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Assessment and Decision Support for Energy Performance Improvement of Dwellings: Framework and Prototype Development

By

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I. Declaration

I declare that this thesis represents my own work, except where due acknowledgement is made, and that it has not previously been included in a thesis, dissertation or report submitted to this University or any other institution for a degree, diploma or any other qualifications.

Signed:

Amit Mhalas

Date: 8th April 2013

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III. Abstract

The target for carbon dioxide (CO_2) emissions reduction in the UK is set at 20% by 2020 and 80% by 2050. The UK housing stock is one of the least energy efficient in Europe. The energy used in homes accounts for more than a quarter of energy use and carbon dioxide emissions in Great Britain. Therefore, it is imperative to improve the energy performance of the existing housing stock and fully exploit energy efficiency and renewable energy interventions.

Several tools have been developed particularly in the last decade for energy assessment of dwellings, largely to inform policy development. However, when it comes to policy implementation stages, stakeholders such as local councils, energy suppliers, social housing providers and planners lack an effective tool, which assists them in estimating the potential for energy performance improvement through implementation of energy efficiency and renewable energy interventions. The UK government has several policies and initiatives to improve the energy performance of the housing stock. This research discusses the development of framework and a prototype tool to assist in implementation of these policies.

There are a number of databases that hold information about the condition of the housing stock. This is in the form of digital maps, aerial and terrestrial imagery and statistics from census and housing surveys. This research presents an innovative way of integrating this information to undertake energy performance assessment on various geographical levels. The framework and the prototype allow stakeholders to determine the baseline energy performance of the dwellings based on their existing characteristics. This information is then used to estimate the potential for reduction in energy consumption and CO_2 emissions and associated costs. Also integrated within the framework and the prototype is analytical hierarchy process based multi-criteria decision analysis technique that supports stakeholders in selection of energy performance improvement interventions suited to their requirements.

The developed framework and prototype are calibrated and validated with empirical data to determine the accuracy, reliability and trustworthiness. To demonstrate the practical applicability of the framework and the prototype, two separate case studies are undertaken involving the stakeholders. The results from the case studies indicate a potential to reduce CO_2 emissions from dwellings by 70% through installation of energy performance improvement interventions.

The developed framework and the prototype are expected to assist stakeholders in making informed decisions with regard to the implementation of energy policies and initiatives and contribute to meeting CO_2 emission reduction targets.

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VII. Abbreviations and Units

AEEI	Autonomous Energy Efficiency Index
AHP	Analytical Hierarchy Process
ASHP	Air Source Heat Pump
BRE	Building Research Establishment
BREDEM	BRE’s Domestic Energy Model
BREHOMES	BRE’s Housing Model for Energy Studies
CCC	Committee on Climate Change
CDA	Conditional Demand Analyses
CDEM	Community Domestic Energy Model
CEP	Climate and Energy Package
CERT	Carbon Emissions Reduction Target
CESP	Community Energy Savings Programme
CO_2	Carbon dioxide
COP	Coefficient of Performance
DECC	Department of Energy and Climate Change, UK
DECoRuM	Domestic Carbon Counting and Carbon Reduction Model
DoE	Department of Energy, USA
ECCP	European Climate Change Programme
ECO	Energy Company Obligation
EEP	Energy and Environmental Prediction
EHS	English Housing Survey
ELECTRE	Elimination and Choice Translating Reality
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EU	European Union
GIS	Geographic Information System
GSHP	Ground Source Heat Pump
GT	Gigatons
GW	Gigawatt
HEED	Homes Energy Efficiency Database
IC Engine	Internal Combustion Engine
IPCC	Intergovernmental Panel on Climate Change
kW	Kilowatt
kW_e	Kilowatt Electric

kWh	Kilowatt hour
kW_{pk}	Peak Power Generated in kW.
kW_{th}	Kilowatt Thermal
LDF	Local Development Framework
LLSOA	Lower Layer Super Output Area
Low-e	Low Emissivity
m^2	Meters square (area)
m^3	Meters cube (volume)
μ-CHP	Micro-Combined Heat and Power
MCDA	Multi-Criteria Decision Analysis
MLSOA	Middle Layer Super Output Area
MW	Megawatt
MWh	Megawatt hours
NCM	National Calculation Methodology
NEA	National Energy Action
NHER	National Homes Energy Rating
NN	Neural Network
^{o}C	Degree Celsius
ONS	Office of National Statistics
OS	Ordnance Survey
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
PV	Photo Voltaic
RCEP	Royal Commission on Environmental Pollution
SAP	Standard Assessment Procedure
SEDBUK	Seasonal Efficiency of Domestic Boilers in UK
SMART	Simple Multi Attribute Rating Techniques
TOPSIS	Technique for Order Preference by Similarity to Ideal Solutions
TW	Terawatt
TWh	Terawatt hour
UK	United Kingdom
UKCIP	UK Climate Impacts Programme
UKDCM	UK Domestic Carbon Model
UNFCC	United Nations Framework Convention on Climate Change
YHN	Your Homes Newcastle

Chapter 1 Introduction

1.1 Context

Of the several gases present in earth's atmosphere, the greenhouse gases such as carbon dioxide (CO_2), nitrous oxide, methane, water vapour, ozone, chlorofluorocarbons, etc. are known to increase the ambient temperature (Houghton, et al., 2001). There is a general consensus that anthropogenic activities have contributed to a disproportionate increase in the amount of these greenhouse gases. This has led to a phenomenon commonly known as climate change (Solomon, et al., 2007).

Each of the greenhouse gases has varying amounts of global warming potential. However, considering the quantity and the atmospheric lifetime, CO_2 contributes significantly to the rise in global temperatures (Frolkis, et al., 2002; Zámostný, et al., 1999). Annual emissions of CO_2 have increased by 80% between 1970 and 2004, from 21 to 38 gigatons (GT). This accounts for 77% of total anthropogenic GHG emissions in 2004 (Metz, et al., 2007). This increase in CO_2 emissions and the resultant increase in global temperature are expected to have significant consequences, some of which include:

- Increase in Global Mean Surface Temperature between 1.1-6.4^{o}C by the end of 21st century. Warming is expected to be greatest over the higher northern latitudes and over the Southern Ocean (Solomon, et al., 2007).
- Mean Sea Level rise of 18-59 cm by the end of 21st century. Sea ice is expected to shrink in both the Arctic and Antarctic (Solomon, et al., 2007).
- Frequency of hot extremes, heat waves and heavy precipitation events will increase. The intensity of tropical cyclones (typhoons and hurricanes) will be higher, with larger peak wind speeds and heavier precipitation (Solomon, et al., 2007).
- Approximately 20-30% of plant and animal species are at an increased risk of extinction. In dry and tropical regions, crop

productivity is projected to decrease, increasing the risk of hunger (Parry, et al., 2007).
- Coastal regions will be at increased risk of flooding due to rise in mean sea level affecting the densely populated and low lying deltas and small islands (Parry, et al., 2007).
- Millions of people will be affected through malnutrition, diseases and injury due to extreme weather events, diarrhoeal diseases, cardio-respiratory diseases due to higher concentrations of ground-level ozone in urban areas, etc. amongst others (Pachauri & Reisinger, 2007).

With the effects of climate change expected to be experienced worldwide, the United Kingdom (UK) is no immune to these impacts. The UK Climate Impact Programme (UKCIP) have projected impacts of climate change in the UK, the significant amongst others include (Jenkins, et al., 2009):

- Rise in summer and winter temperature all over the UK with the greatest rise of approximately 4.2ºC in Southern England and the least rise of 2.5ºC in Scottish Islands.
- Increase in winter precipitation, with the highest rise of 33% in Western UK and decrease in summer precipitation, down by about 40% expected in South of England.
- Seasonal mean and extreme waves are generally projected to increase in the South West UK, reduce to the north of the UK and experience little change in the Southern North Sea. Changes in the annual maxima are typically in the range –1.5 to +1 m.
- The shelf seas around the UK are projected to be 1.5 to 4ºC warmer and approximately 0.2 practical salinity units (p.s.u.) fresher (i.e. lower salinity)

All these global and national effects due to climate change are not only expected to impact the environment but also the socio-economic scenario. If the severe consequences of climate change are to be avoided, the response needs to include reduction in the greenhouse gases, especially CO_2 emissions (Pachauri & Reisinger, 2007). Studies by the Intergovernmental

Panel on Climate Change (IPCC) (Metz, et al., 2007) indicate that there is a substantial potential over the coming decades to reduce emissions below current levels. However, it is expected that any amount of reductions will only minimise the amount of climate change rather than prevent it. Even if it was hypothetically possible to stop all the anthropogenic emissions of CO_2, the existing concentration of CO_2 to decline will take several decades due to the slow decay rate of CO_2 (Houghton, et al., 1997).

Studies undertaken by IPCC indicate that by 2050, CO_2 emissions will need to be reduced between 60% to 80% to stabilise the CO_2 concentrations at the current levels (Richels, et al., 2004; Van Vuuren, et al., 2006; Corfee-Morlot, et al., 2005). It is in this context that this research is being undertaken.

1.1.1 Kyoto Protocol

The United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1992 after IPCC released its First Assessment Report in 1990. The message was clear:

> *"global warming is happening and something has to be done about it"*

By 1995, several countries party to the UNFCCC had realised the need to strengthen their response to climate change. This led to several negotiations, and on 11th December 1997, the Kyoto Protocol was adopted by 192 members of UNFCCC. The key outcome of this protocol is that it set legally binding carbon emission reduction targets on the industrialised countries and those in transition to a market economy (Countries listed in 'Annex I' of Kyoto Protocol). Kyoto Protocol came into force in 2005. The convention hopes to limit the CO_2 concentration to 450 ppm, which will in turn limit the temperature rise by 2ºC, from pre-industrial levels. This is the highest rise we can afford if we want a 50% chance of avoiding the worst effects of climate change (United Nations Framework Convention on Climate Change, 2012a).

The Kyoto Protocol commits the 'Annex I' nations to reduce their carbon emissions by an average of 5.2% between 2008-2012 over 1990 levels. The carbon emission reduction target however varies – for most European Union (EU) countries it is 6-8% while for the UK it is 8% (United Nations, 1998). The protocol also establishes the following market based mechanisms to enable the countries to meet their reduction targets (United Nations Framework Convention on Climate Change, 2012b):

- Emissions Trading: Allows countries that have emission units to spare i.e. emissions permitted to them but have not been used - to sell this excess capacity to countries that are over their targets.
- Clean Development Mechanism: Allows a country to implement an emission-reduction project in developing countries. Such projects can earn saleable certified emission reduction credits, each equivalent to one tonne of CO_2, which can be counted towards meeting Kyoto targets
- Joint Implementation: Allows a country to earn emission reduction units from an emission-reduction or emission removal project in another ‘Annex I’ country. Each equivalent to one tonne of CO_2 can be counted towards meeting its Kyoto target. Joint implementation offers ‘Annex I’ countries a flexible and cost-efficient means of fulfilling a part of their Kyoto commitments, while the host country benefits from foreign investment and technology transfer.

Subsequent to the first period of emissions reductions ending, the Parties to the Kyoto Protocol adopted an amendment at the eighth session of the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol held in Doha, Qatar, in December 2012. The amendment quantifies the emission reductions for several of the previous ‘Annex I’ countries for the period 2013-2020. Collectively these nations aim to reduce their emissions by 18% over the 1990 levels. Most countries of the EU and the UK now have a commitment of 20% emission reduction by 2020 (United Nations, 2012).

1.1.2 The EU Commitment

Parallel to being a party to the Kyoto Protocol, the EU has been taking initiatives to reduce greenhouse gases. One such initiative was establishment of the European Climate Change Programme (ECCP) in 2000. The goal of the ECCP is to identify and develop all the necessary elements of an EU strategy to implement the Kyoto Protocol (Liakopoulos, 2001). The 15 nations that were part of the EU when Kyoto Protocol was adopted in 1997 (since known as EU-15) then redistributed the reduction targets between the member states to better reflect their individual circumstances, requirements for economic growth, and the scope for further emission reductions. The UK was thus re-assigned a target of 12.5% reduction between 2008-2012 over the 1990 baseline as part of this (European Environment Agency, 2006). The EU however in its Strategic Energy Review, 2007, goes beyond the requirements of the Kyoto Protocol and sets itself an ambitious target of 20% greenhouse gas emission reduction by 2020 or 30% reduction if the other industrialised, developed and developing nations agree to do so (Maslin, et al., 2007). Several countries in the EU including the UK have set themselves stringent long-term goals summarised in Table 1-1 below (Boardman, et al., 2005).

Table 1-1: Climate Change Targets for Some EU Countries

Country	**Commitment Level**
France	Limit per capita emissions to 0.5 tons of carbon by 2050.
Germany	Reduce energy-related CO_2 emissions by 45-60% compared to 1990 levels by 2050; commit to 40% reduction by 2020 if EU commits to a 35% reduction over that period.
Sweden	Reduce per capita consumption of CO_2 and other greenhouse gases from the current level of 2.3 tons to 1.2 tons by 2050 and reduce further subsequently.
UK	Reduce national CO_2 emissions by 80% on 1990 levels by 2050.

The EU has subsequently developed the Climate and Energy Package (CEP), a binding legislation which along with the 20% reduction in greenhouse gas emission, further aims to raise the share of renewable energy sources to 20% of the total energy consumed and 20% improvement in EU’s energy efficiency (European Commission, 2010) commonly known as the 20-20-20 targets. The CEP further introduces legislations in following areas which intend to deliver these targets (European Commission, 2012).

- EU Emissions Trading System: Works on the ‘cap and trade’ principle. This means there is a ‘cap’, or limit, on the total amount of certain greenhouse gases that can be emitted by the factories, power plants and other installations in the system. Within this cap, companies receive emission allowances which they can sell to or buy from one another as needed. If a company reduces its emissions, it can keep the spare allowances to cover its future needs or else ‘trade’ (sell) them to another company that is short of allowances.
- Effort Sharing Decision: Under this legislation EU member states have taken on binding annual targets for reducing their greenhouse gas emissions from the sectors not covered by the emissions trading system, such as housing, agriculture, waste and transport (excluding aviation). The targets, covering the period 2013-2020, are differentiated according to member states' relative wealth. They range from a 20% emissions reduction by the richest Member States to a 20% increase by the least wealthy.
- Renewable Energy Directive: Member States have taken on binding national targets for raising the share of renewable energy in their energy consumption by 2020. The national targets will enable the EU as a whole to reach its 20% renewable energy target for 2020. This again depends upon a member states’ wealth ranging from a minimum increase in renewables production of 10% for Malta to a maximum 49% increase for Sweden.
- Carbon Capture and Storage: This involves creating a legal framework to create safe technologies for capturing the carbon dioxide emitted by industrial processes and storing it in underground geological formations where it does not contribute to global warming.
- Energy Efficiency Plan: This directive aims at promoting an economy that respects the planet’s resources. This is mainly achieved by

implementing a low carbon system, improving the EU's energy independence and strengthening security of energy supply.

1.1.3 The UK Perspective

The UK in 1970 established the Royal Commission on Environmental Pollution (RCEP), to advise the Queen, the Government, Parliament and the public on environmental issues. The RCEP and the erstwhile Performance and Innovation Unit undertook several studies to understand UK's position on the Climate Change and the necessary mitigation measures to tackle it. One of the major recommendations of their studies was that the greenhouse gas emissions needed to be reduced at least by 60% by the mid-21st century (Royal Commission on Environmental Pollution, 2000). This recommendation was adopted by the UK Government in their 2003 Energy White Paper (Department of Trade and Industry, 2003). However, when the Climate Change Act, 2008 was introduced, a higher goal of 26% reduction by 2020 and 80% reduction in greenhouse gas emissions was committed to be achieved by 2050 on the 1990 levels (Department of Energy and Climate Change, 2008). These targets are much higher than those required to be met by the EU legislations and directives described in the previous section.

The Climate Change Act, 2008 established a Committee on Climate Change (CCC), an independent body which advises the Government on emissions targets and reports to the Parliament the progress made in reducing greenhouse gas emissions. The CCC has released a series of 'carbon budgets' to delineate a pathway to the 2050 carbon target by identifying contributions from each sector, and within these the reductions expected from specific policy measures (Committee on Climate Change, 2008).

In their 2008 report, the CCC advised on the level of the first three carbon budgets for the periods 2008-2012, 2013-2017, and 2018-2022 and set out an Interim and Intended budget for the period from 2008-2022. For the first three budgets, the CCC follows the EU framework applicable to all greenhouse gases including CO_2. The Figure 1-1 below presents the indicative emissions requirements. Thus, by the end of the third period in

2022, a reduction by 34% over the 1990 levels (or 21% relative to 2005) is budgeted.

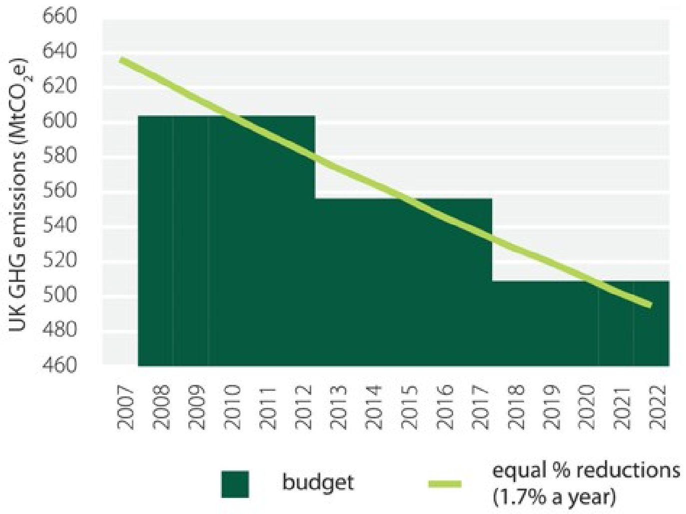

Figure 1-1: Indicative Annual Percentage Emissions Reductions Budget[1]

By adopting these budgets, the UK has become a unique country around the world that has introduced a long-term legally binding framework to tackle the dangers of climate change.

1.1.4 Emission Patterns

In 2004, CO_2 contributed approximately 75% of global greenhouse gas emissions, CH_4 about 14%, N_2O about 8% and the fluorinated gases about 1% (Olivier, et al., 2005). Figure 1-2 further shows that over 56% of the CO_2 emissions in particular come from the burning of fossil fuels for energy generation.

Looking at the sector wise CO_2 emissions, in 2005, the manufacturing was the biggest sector contributing 38%, followed by the transport with 25% and the household sector with 21% of the total emissions (OECD/IEA, 2008) as presented in Figure 1-3.

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[1] Source: (Committee on Climate Change, 2008)

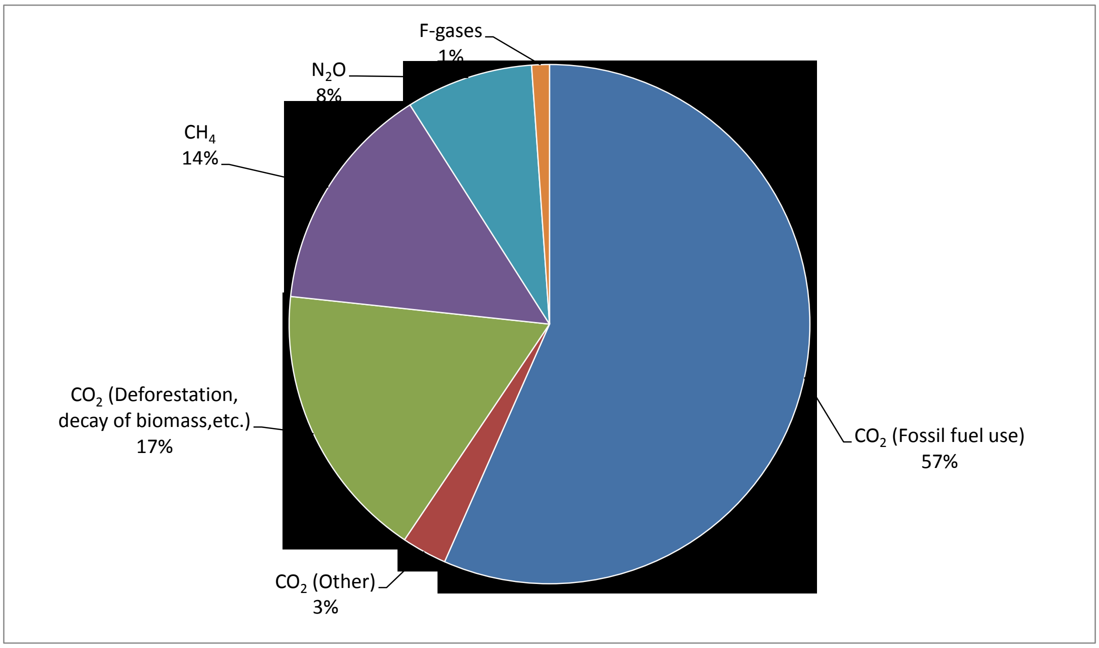

Figure 1-2: Global Greenhouse Gas Emissions[2]

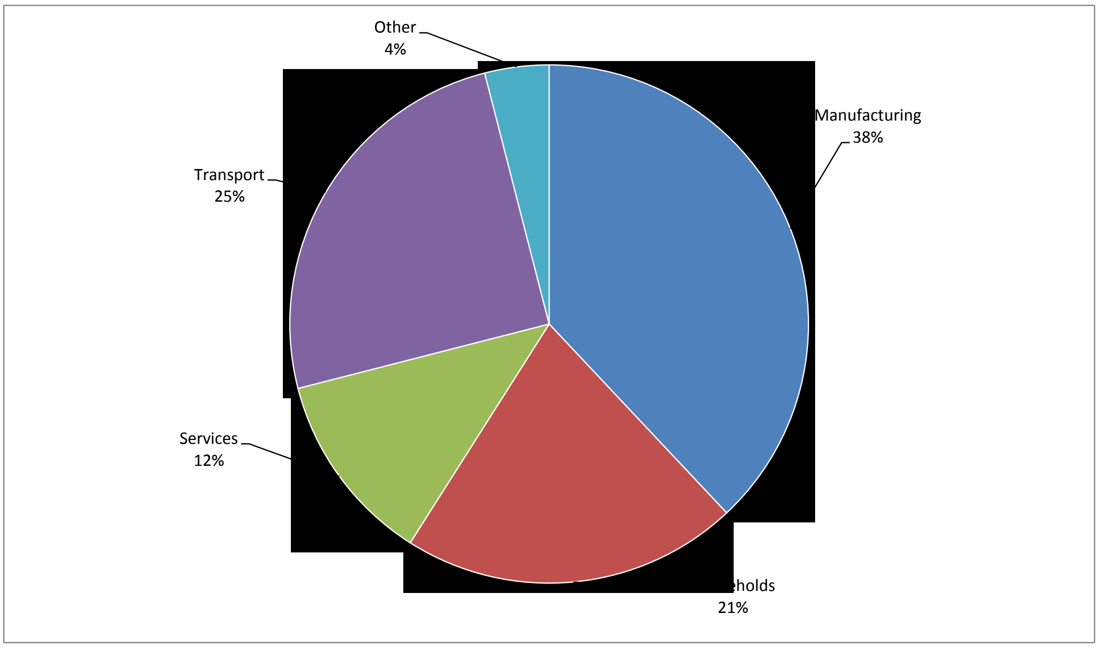

Figure 1-3: Global Greenhouse Gas Emissions by Sector[3]

The emissions from the residential sector primarily come from the energy used for electricity, space heating and cooling (Owen, 2006). Globally, the residential sector accounts for 29% of total the energy consumption

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[2] Source: (Olivier, et al., 2005)

[3] Source: (OECD/IEA, 2008)

(OECD/IEA, 2008). The IPCC Special Report on Emission Scenarios projects this share to increase to 34% of the total energy consumption.

There are about 24 million homes in the UK. It is estimated 75% of the current stock will still exist by 2050 (Wright, 2008). The existing residential building stock can play a major role in mitigating climate change in the short- to medium-term, since substantial reductions in CO_2 emissions from their energy use can be achieved over the coming years (Urge-Vorsatz, et al., 2007).

1.2 UK Obligation to the Existing Dwellings

The UK housing stock makes up for one of the oldest and the least efficient building stock in Europe (Boardman, et al., 2005) (Wright, 2008). Figure 1-4 indicates that this poor quality housing stock means space heating consumed an average of above 60% of the total delivered energy in the last four decades (Palmer & Cooper, 2011).

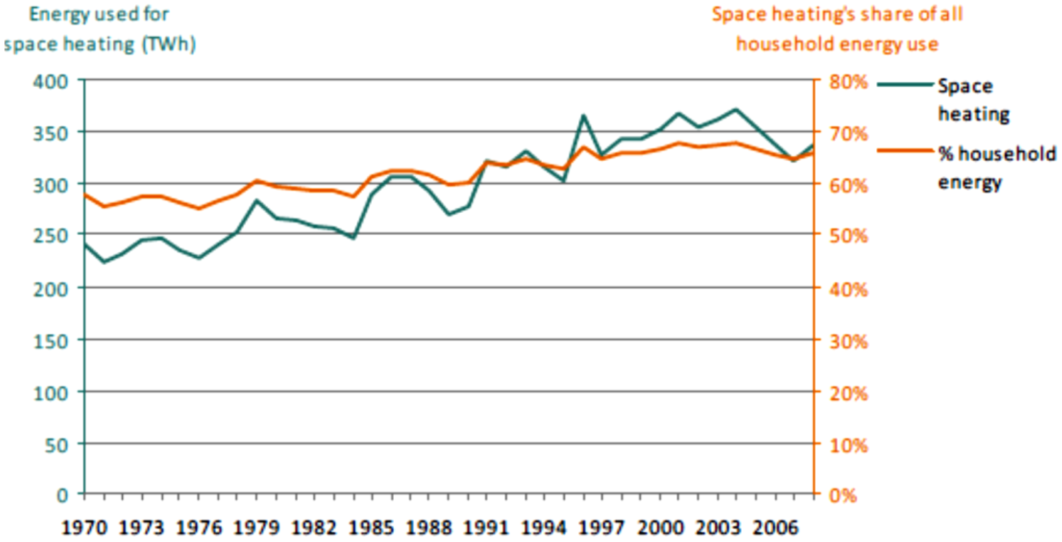

Figure 1-4: Domestic Final Energy Consumption by End-use[4]

Over 30% of the dwellings in England are thought to be 'non-decent' i.e. they are unhealthy, in disrepair, in need of modernisation. A further 80% of these

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[4] Source: Adapted from (Palmer & Cooper, 2011)

dwellings fail to meet the criteria for providing thermal comfort (Communities and Local Government, 2012).

The largest tenure type in 2010-11 was owner occupied with 66% households followed by the private rental and social rental each at 17% (Communities and Local Government, 2012). A range of improvements through energy efficiency and renewable energy measures is promoted through variety of Government programmes. These include grants and advice programmes to achieve short and long term targets. The initiatives not only target reduction in energy consumption but also improve the standard of living and eliminate fuel poverty[5]. Some of the key initiatives are:

- Carbon Emissions Reduction Target (CERT): All domestic energy suppliers with a customer base in excess of 250,000 needs to make savings in the amount of CO_2 emitted by households. 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 (DECC, 2011a).
- Community Energy Savings Programme (CESP): CESP targets households across Great Britain, in areas of low income, to improve energy efficiency standards, and reduce fuel bills. There are 4,500 areas eligible for CESP. CESP is funded by an obligation on energy suppliers and electricity generators (DECC, 2011a).
- Green Deal: The Green Deal allows customers to make their homes and businesses more energy efficient at no upfront cost. Payment for the energy efficiency improvements will be made through instalments added to the customer's energy bill. The level of the instalments can't be higher than the expected saving for the customer as a result of the improvements. If that Green Deal customer leaves a property, the next occupant will be responsible for continuing to make the Green Deal payments. This means that no customer should pay more for the energy efficiency improvements than the savings that will result from

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[5] A dwelling is considered fuel poor if needs to spend more than 10% of its income on fuel for adequate heating (usually 21°C for the main living area, and 18°C for other occupied rooms)

these improvements. This is called the Golden Rule (DECC, 2010) (DECC, 2011b).

- Energy Company Obligation (ECO): The ECO will be replacing CERT and CESP after the introduction of the Green Deal in early 2013. ECO focuses on providing energy efficiency measures to low income and vulnerable consumers and those living in 'hard to treat' properties. ECO ensures that 15% of each supplier’s obligation is used to upgrade more hard-to-reach low-income households in rural areas. ECO requires energy suppliers to provide heating and insulation measures to consumers living in private tenure properties that receive particular means-tested benefits. ECO is financed by the energy suppliers and also covers the installation of measures like solid wall and hard-to-treat cavity wall insulation, which ordinarily can’t be financed solely through the Green Deal (DECC, 2011b).

In the Climate Change Act, 2008, the councils[6] are tasked with reducing per capita energy consumption within their administrative boundaries. The above listed initiatives provide the mechanism to achieve this task, however, much of the obligations are on the energy suppliers. Councils have a responsibility to prepare annual reports on energy efficiency of all the housing in their geographical area, all tenures, under the Homes Energy Conservation Act 1995 (Act of Parliament, 1995). A close coordination is thus necessary between the stakeholders such as councils, local energy companies and the social housing providers if these initiatives are to be implemented effectively (Boardman, 2007). This research attempts to assist these stakeholders in making informed decisions related to implementation of energy performance improvement measures within their administrative areas on a neighbourhood level. This will enable effective implementation of energy related policies and meeting the carbon emissions reduction targets.

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[6] The term ‘Council(s)’ is used to denote County Councils, Borough Councils, Metropolitan District Councils and Unitary Authorities in the United Kingdom who are typically entrusted with planning decisions

1.3 Aims and Objectives of the Research

The research aims to:

- Assess energy performance of dwellings in neighbourhood using innovative techniques.
- Develop decision support tool to enable stakeholders make informed selection of energy performance improvement interventions.

To achieve the above aims, the following objectives are met by this research:

1. Identification of the existing energy assessment tools and methods used for estimating the energy performance of domestic dwellings.
2. Identification of the main characteristics and variables that influence the energy performance of domestic dwellings.
3. Identification of available data sources to estimate the existing condition and energy performance of the dwelling stock.
4. Identification of the energy performance improvement interventions applicable for the dwellings and CO_2 reduction potential of domestic dwelling stock in a neighbourhood.
5. Identification of decision support method to assist stakeholders in selection of energy performance improvement measures.
6. Development of a framework that integrates the databases and the visual aid techniques for assessment and decision support for energy performance improvement of dwellings.
7. Development a proof-of-concept prototype based on the framework.
8. Calibration and validation of the prototype; and undertaking case studies with stakeholder engagement to demonstrate the innovative framework and prototype.

1.4 Research Methods

The key research methods adopted to achieve the abovementioned aims and objectives are literature review, stakeholder engagement, framework and prototype development and empirical validation and case studies.

1.4.1 Literature Review

Literature review was undertaken to identify the methods currently being used to estimate the energy profile of dwellings at various geographical scales (satisfy objective 1 in Section 1.3). The review identified the input parameters required for energy profiling and hence established the characteristics on which the energy performance of dwellings typically depends (satisfy objective 2 in Section 1.3). The sources are identified that hold information on the condition of the existing dwelling stock (satisfy objective 3 in Section 1.3).

The literature review identified the applicable domestic energy efficiency and renewable energy interventions and their potential in reducing CO_2 emissions (satisfy objective 3 in Section 1.3). A review of the existing multi-criteria decision support methods was undertaken to determine the technique that could be used by the stakeholders (satisfy objective 5 in Section 1.3). The technique will assist the stakeholders in making informed selection of energy efficiency and renewable energy interventions based on multiple criteria.

The literature review identified various stages of urban energy planning, the tools used in those stages and the stakeholders involved. The literature review identified the gaps, established the areas where this research makes a contribution and helped in developing a framework for the prototype.

1.4.2 Stakeholder Engagement

The context presented in Section 1.1 and the key initiatives and obligations presented in Section 1.2 have identified the councils, planning authorities, energy suppliers and social housing providers as the key stakeholders for this research. One-to-one discussions are undertaken with these stakeholders as the users of energy profiling tools. The discussions identified how the currently available energy profiling tools are being used and understand what their limitations are (satisfy objectives 1 and 2 in Section 1.3). Stakeholder engagement enabled capturing the user requirements and framework development for the prototype tool (satisfy objectives 6 and 7 in Section 1.3).

Subsequent to the development of the prototype, discussions were again undertaken with stakeholders during case study to evaluate the alternatives based on multiple criteria (satisfy objective 8 in Section 1.3).

1.4.3 Framework and Prototype Development

Based on the literature review and the discussion with stakeholders, a framework is developed that describes the way in which the databases and the visual aid techniques can be integrated. The framework assists in estimating the baseline energy performance, quantification of energy and carbon reduction potential and enable decision making.

A prototype tool is developed to demonstrate the above approach and describe how the information from various databases and visual aid techniques can be used to undertake energy profiling calculations for the dwellings and make informed decisions on implementation of energy efficiency and renewable energy interventions (satisfy objectives 6 and 7 in Section 1.3).

1.4.4 Calibration, Validation and Demonstration

The developed prototype is first tested for calibration. Empirical validation of the tool is undertaken to compare the results from the developed prototype and that obtained from traditional methods. Case studies are then undertaken to demonstrate how the developed framework and prototype can be used in practical situations. The case studies also demonstrate the effectiveness in meeting CO_2 emission reduction targets though informed decision making with regards to implementation of energy performance improvement interventions (satisfy objective 8 in Section 1.3).

1.5 Research Scope and Limitations

The energy calculation model used to develop the prototype is based on the National Calculation Methodology (NCM) adopted for the UK as per the requirements of the Energy Performance of the Buildings Directive (European Parliament and the Council, 2003). The equations in NCM and the prototype developed are thus specific to the UK geographic, social and economic environment.

One of the major inputs into the prototype is the dwelling footprint from the Ordnance Survey (OS) maps. Most of these OS maps typically do not have the footprint of individual flats especially in blocks of high rise apartments (Ordnance Survey, 2010), (Ordnance Survey, 2011). Hence the tool is only applicable to terraced, semi-detached and detached houses and bungalows, which however, represents more than 83% of the total UK dwelling stock (Communities and Local Government, 2009).

1.6 Key Contributions of the Research

The literature review and the discussions with the stakeholders have helped to establish the limitations and gaps within the existing energy models. The review and discussions have also confirmed the requirement of a tool to assist in implementation of energy policies. It is in this respect that the research makes following contributions:

- This research makes innovative use of information from imagery, digital maps and national databases to establish the characteristics and variables that define energy consumptions of dwellings.
- The innovative use of this information enables user to define the archetypes of dwellings rather than relying on standard archetypes. It also eliminates the need for drive-by surveys. This significantly decreases the modelling time by reducing the amount of time required to input and process the data.
- The baseline energy performance assessment tool uses the UK Government’s National Calculation Methodology as per the requirements of Energy Performance of Building Directive so that the results generated are consistent with the requirements for implementation of energy policy.

- The identification of the data sources and structures and the inherent algorithms has increased the transparency of the framework and prototype.
- The research has developed models for quantification of energy consumption and CO_2 reduction potential which take into consideration the specific characteristics of dwellings. Cost models are developed which take into consideration the cost of installation, cost savings from reduced energy demand and income generated from feed-in-tariff and renewable heat incentives.
- The prototype tool developed as a part of this research allows stakeholders to generate baseline energy performance information for various geographic levels and also develop tailor-made scenarios for assessment of energy efficiency and renewable energy interventions. This will enable them to develop strategies for neighbourhood, town or regional level and implement energy policies efficiently.
- A decision support tool based on analytical hierarchy process is also integrated within the framework and prototype. It assists stakeholders in making informed decisions on implementation of energy performance improvement interventions based on environmental, technical, economic and social criteria.
- The validation process has confirmed that the results from the framework and prototype are within ±5% of the traditional methods. Thus the developed framework and prototype is reliable and trustworthy.
- The case studies have demonstrated the effectiveness of the tool amongst the stakeholders. The scenarios considered in each case study achieved about 80% reduction in space heating through fabric change. About 80% of electricity demand can be met by installing solar panels. Other interventions can further contribute depending on their applicability. This translates to approximately 70% reduction in CO_2 emissions.

1.7 Structure of the Thesis

The structure of the thesis is summarised in Figure 1-5 and described below:

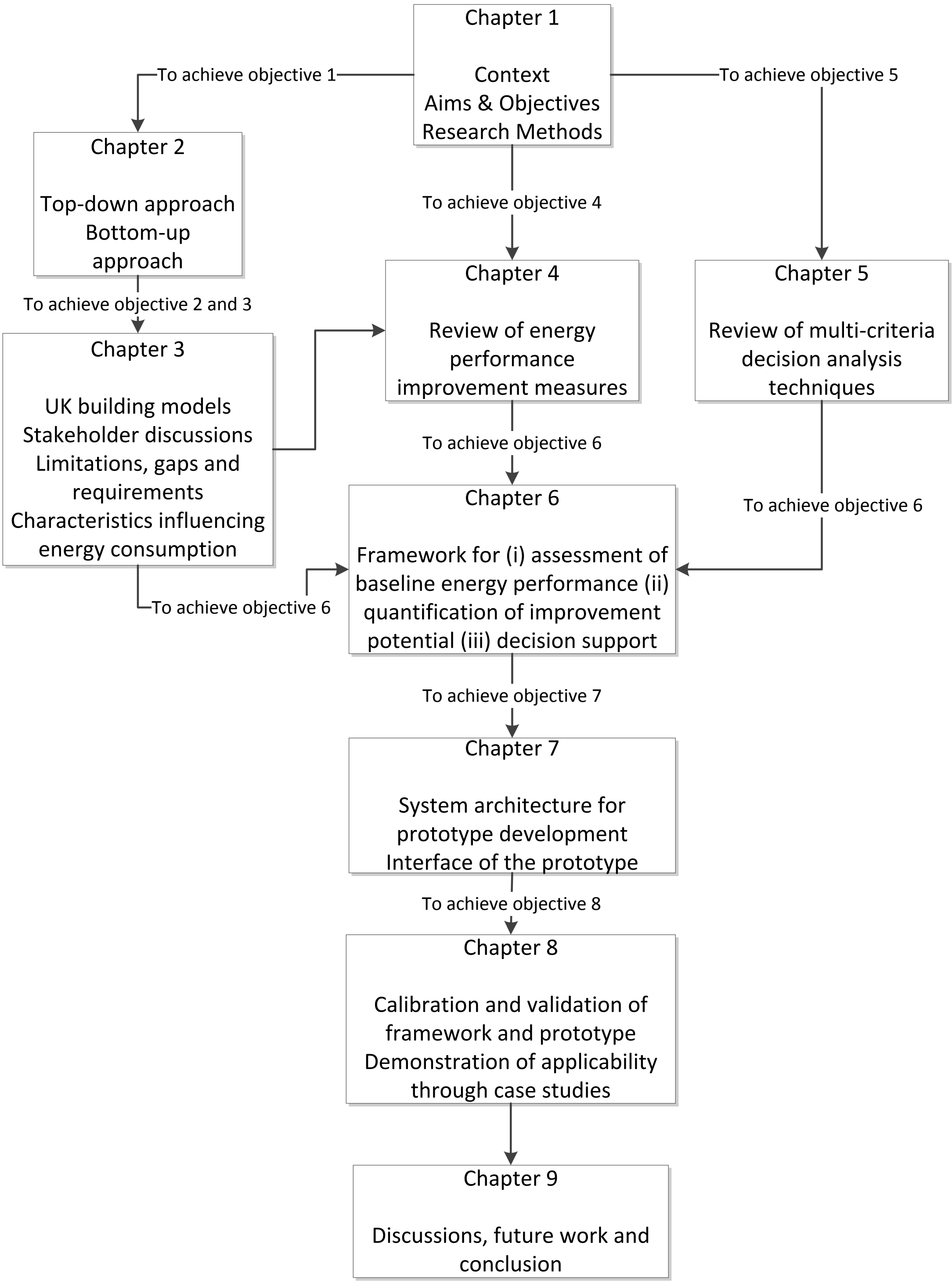

Figure 1-5: Structure of the Thesis

Chapter 1 introduces the background for this research; presents the aims and objectives of this research; describes the research methods adopted; and establishes the contribution to knowledge that this research makes.

Chapter 2 describes the modelling tools developed to estimate the energy performance of dwellings. The chapter critically reviews the two most common approaches: top-down and bottom-up approach. The benefits and limitations of various models that fall in these categories are discussed.

Chapter 3 describes in detail the energy modelling tools predominantly used in the context of dwellings in the UK. The chapter presents the findings from the discussions with the stakeholders regarding the use of existing modelling tools and understand their requirements. The literature review and the stakeholder discussions helped to establish the gaps in the existing models. The chapter describes the characteristics that influence energy consumption which inform the development of various energy models.

Chapter 4 presents a review of various measures that improve energy performance of dwellings and are applicable for the UK dwelling stock. These include energy efficiency improvement measures such as changes to the fabric of the dwelling and existing heating system and; installation of renewable or low carbon energy generation techniques such as solar panels, micro-wind turbines, micro-combined heat and power units and heat pumps.

Chapter 5 reviews the various techniques used to support decision making and selects a technique that can be integrated in this research. The chapter also extensively reviews various energy planning projects to identify the criteria that most of the decisions are based on. A chosen set of criteria are then discussed with the stakeholders to identify which of them are to be included in the decision support tool within this research.

Chapter 6 focuses on the structural aspect of the prototype development process and presents a framework for development of the tool to (i) estimate the baseline energy performance of dwellings; (ii) estimate impact of energy performance improvement scenarios; and (iii) assist stakeholders in decision making.

Chapter 7 presents how the framework that is developed in earlier chapter is applied to develop a ‘proof-of-concept’ prototype and thus demonstrate the suggested approach. The chapter describes ‘how’ the activities describes within the framework relate with each other and are put into real work practice to assess current and future energy performance of dwellings.

Chapter 8 describes the calibration and validation of the prototype. The chapter also presents the results and analysis of case study undertaken to demonstrate the approach of this research.

Chapter 9 presents the conclusion where the major outcomes of this research are discussed. The chapter also discusses the scope for work that can be undertaken in future research activities.

1.8 Summary

This chapter introduces the context in which this research is being undertaken. The phenomenon of climate change is discussed along with its causes, impacts and the necessary mitigation measures. The aims and objectives represent one of the means of responding to climate change. The chapter describes the research methods adopted to meet these aims and objectives and the contribution to knowledge that this research makes. The next chapter discusses the findings of the literature review undertaken to identify the existing energy profiling tools and then select a tool applicable for this research.

Chapter 2 Existing Energy Assessment Methods

2.1 Introduction

The techniques to model energy consumption in residential sector can be broadly classified into 'top-down' and 'bottom-up' approaches (Tuladhar, et al., 2009). Figure 2-1 below displays a schematic of the general methodological philosophy and the adopted perspective.

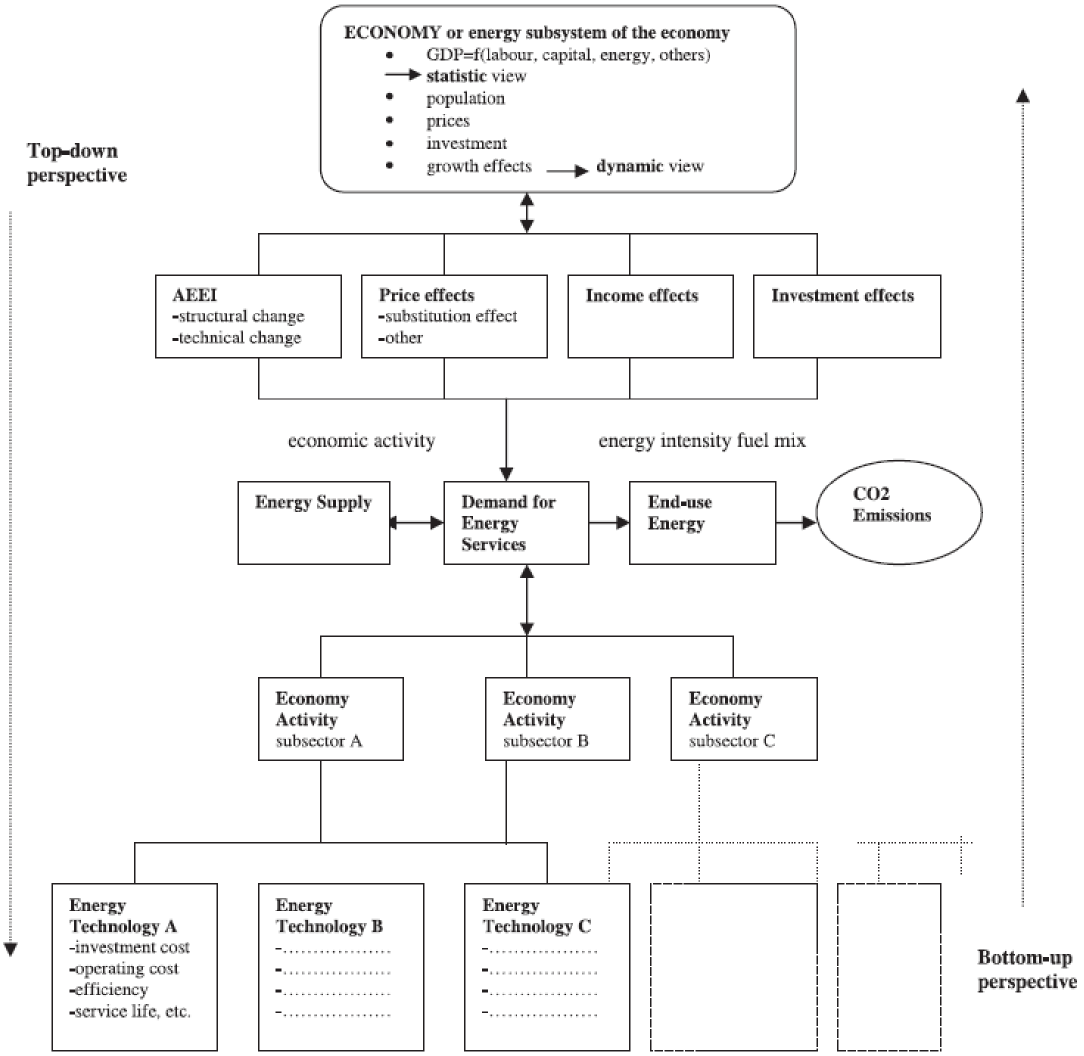

Figure 2-1: Top-down and Bottom-up Approaches[7]

The approaches have a vast diversity in terms of their level of detail, their complexity, the data input required from the user, the time periods covered

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[7] Source: Adapted from (IEA, 1998)

and their geographical coverage (Hourcade, et al., 2006). The following sections discuss the strengths, weaknesses and applicability of these models.

2.2 Top-down Approach

The top-down approach works on a macro-economic scale to model energy supply and energy demand. The development and use of this approach grew significantly during the energy crisis in the late 1970s. The models require little details of the consumption process and treat dwellings as an energy sink and regress or apply factors that affect consumption to determine the trends (Swan & Ugursal, 2009). This approach aims at fitting historical time series of national energy consumption or CO_2 emissions data on an aggregated level. Top-down models investigate the inter-relationship between the energy sector and the economy at large (Kavgic, et al., 2010). The top-down approach can be further categorised into econometric and technological models.

2.2.1 Econometric Models

The econometric models are largely based on parameters such as income, fuel prices and gross domestic product to establish a relationship between energy sector and economic output. The models can also include parameters on climatic conditions such as population weighted temperature of a nation (MIT, 1997). An example of the principle of econometric model is for instance, the higher the energy prices, the lower is the demand for energy (Johnston, 2003). Hirst, et al., (1977) initiated an econometric housing energy model in USA which included a component on growth/contraction of housing stock. Bentzen & Engsted (2001) developed an energy consumption model for Denmark based on disposable income, price of energy and the number of heating degree days. The annual delivered energy price and temperature is another model developed in UK for annual domestic energy consumption since 1970. This is a regression model based on average heating season temperature and inflation adjusted energy price (Summerfield, et al., 2010).

2.2.2 Technological Models

Technological models attribute the energy consumption to broad characteristics of the entire dwelling stock for e.g. appliance ownership trends in a particular decade (Swan & Ugursal, 2009). These models may also consider other parameters such as saturation effects and technological change (Johnston, 2003).

Saha & Stephenson (1980) developed a technological model for New Zealand with parameters based on appliance ownership and rating and their use factor as a function of housing stock to determine energy demand for space heating, domestic hot water and cooking.

Hirst, et al., (1977) described in Section 2.2.1 further developed their model to include technological parameters. The added component varies the energy intensiveness of the appliances as a function of their capital cost (O'Neal & Hirst, 1980).

2.2.3 Strengths and Weaknesses of the Top-down Approach

The major strength of the top-down approach is the need for only the aggregate data which is widely available and simple. The housing sector rarely undergoes paradigm shift and hence the models can thus provide good prediction capability for small changes in the sector. These models typically evaluate on regional or national level and are useful for estimating the required energy supply with implications of changes to the economy (Swan & Ugursal, 2009). Model developed by (Saha & Stephenson, 1980) showed some excellent prediction capacity with continuity in economic and technological development.

The major weakness of the top-down approach is its incapability to model irregular advances in technology. These models parameterise technological development, which often follows no certain pattern (Johnston, 2003). Model developed by Hirst, et al., (1977) is sensitive to major demographic and economic factors. The model however needs to update the assumed information periodically to improve its prediction quality. Haas & Schipper

(1998) in their study identified “non-elastic response due to irreversible improvements in technical efficiency”.

The reliance on the past energy-economy interactions to predict future scenarios may not be appropriate while dealing with issues such as climate change. This is because the environmental, social and economic conditions may be significantly different to that experienced in the past (Kavgic, et al., 2010).

Several economists rely overly on the Autonomous Energy Efficiency Index (AEEI) (see Figure 2-1) leading to the top-down approach estimating high implementation costs for measures to mitigate CO_2 emissions (Jaccard, et al., 1996).

The top-down approach lacks the details of energy consumption and efficiency of individual dwellings. This clearly excludes the use of this approach for identifying key areas for improvements in the demand side energy consumption (Swan & Ugursal, 2009). Table 2-1 below summarises the benefits and limitations of the top-down approaches.

Table 2-1: Benefits and Limitations of the Top-down Approach

Benefits	• Focuses on the interaction between the energy sector and economy at large • Use of aggregated economic data which is simple to obtain and input • Includes macroeconomic and socioeconomic effects
Limitations	• Reliance on historical data to project future trends • Incapable of modelling irregular advances in technology due to parameterisation of technological development • No clear presentation of end-use consumption or efficiency of individual dwellings • Less suitable for examining energy reduction policies

2.3 Bottom-up Approach

The bottom-up approach consists of all the models that use input data from a hierarchical level lower than that of a sector as a whole i.e. data from disaggregated components. The variety of data inputs results in the groups and sub-groups of the bottom-up approach as described in Figure 2-2 and described in detail in the following sections.

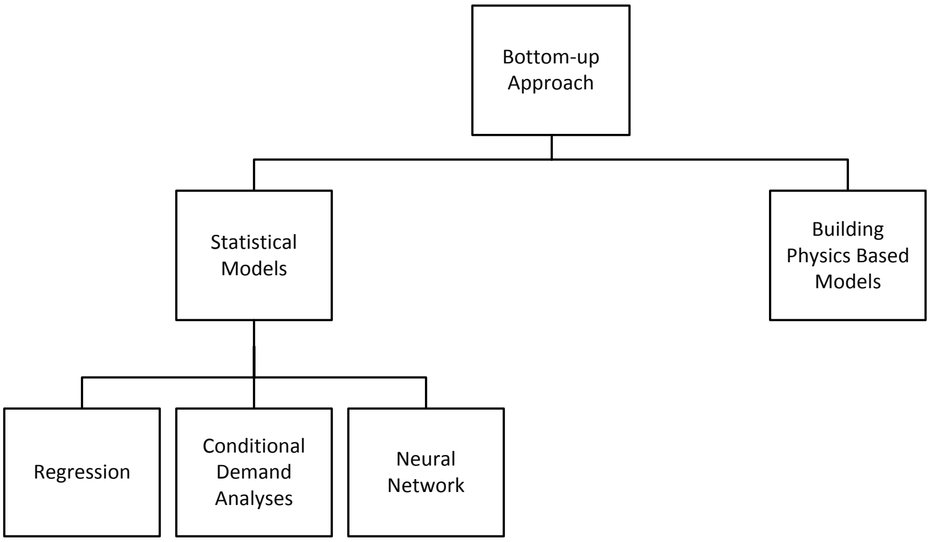

Figure 2-2: Types of Bottom-up Approaches

2.3.1 Statistical Models

A large amount of customer energy billing information is available worldwide which provides exceptional data source for modelling. Significant research has been undertaken to apply various statistical techniques to utilise this data. Statistical models also rely on information gathered from a sampling of houses (Swan & Ugursal, 2009). The three major statistical techniques are regression, conditional demand analyses and neural network.

2.3.1.1 Regression

This technique uses the regression analyses to determine the coefficients of the model corresponding to the input parameters. (Hirst, et al., 1986) used the Princeton Scorekeeping Model with monthly and bi-monthly energy supplier billing data. They examined the weather and non-weather sensitive elements of the dwellings by regression based on the number of heating degree days.

A model containing four simultaneous equations was developed by (Tonn & White, 1988) consisting with space heating, appliance and lighting, wood use and indoor temperature. Data was collected from 100 homes through extensive survey and 30 regression models were developed.

2.3.1.2 Conditional Demand Analysis (CDA)

The CDA regresses the total dwelling energy consumption onto appliances owned by the householders. Data is obtained through survey of occupants and energy billing information from suppliers (Parti & Parti, 1980). Information gathered is indicated as binary or count variable and coefficients are determined to represent use level and rating (Caves, et al., 1987; Bartels & Fiebig, 1990; Fiebig, et al., 1991). Typically CDA provides reliable results from various samples consisting of hundreds or thousands of dwellings (Lafrance & Perron, 1994).

2.3.1.3 Neural Network (NN)

The NN techniques utilise simplified mathematical models based on densely interconnected parallel structure of biological neural networks (Issa, et al., 2001). The NN technique allows all the end-uses to affect one another through a series of parallel neurons (Mihalakakou, et al., 2002). Interconnectivity between different characteristics is structured within the neurons.

The neurons have scaling and activation functions which adjust the vector and bias term hidden within the neurons (Swan & Ugursal, 2009). The use of NN technique in residential energy modelling is limited due to computational and data requirements and the lack of physical significance of the coefficients relating dwelling characteristics to total energy consumption (Aydinalp, et al., 2002).

2.3.2 Building Physics Based Models

The Building physics based models calculate the energy consumption based on physical characteristics of the buildings or its components. Building physics based models are the only methods that can fully estimate energy consumption of a sector without any historical energy consumption information.

Building physics based modelling techniques generally sample houses from representatives of the housing stock and consider building energy calculation method to estimate the delivered energy consumption (Aydinalp-Koksal & Ugursal, 2008). The energy calculation requires quantitative data on physically measurable variables such as the efficiency of space heating systems and their characteristics, information on the areas of the different dwelling elements (walls, roof, floor, windows, doors) along with their thermal characteristics (U values[8]), internal temperatures and heating patterns, ventilation rates, energy consumption of appliances, number of occupants, external temperatures, etc. (Johnston, 2003).

The building physics data along with the empirical data from various housing related surveys coupled with information regarding operation of the building help in estimating energy consumption of dwellings for past, present and future (Wilson & Swisher, 1993). The bottom-up building physics based models have been widely used in Europe to enable policymakers estimate the effectiveness of their policies and further identify the technological measures for end use efficiencies.

A mass, energy, and monetary flow model of the German building sector recognized the building stock as the largest economic, physical, and cultural capital of industrialized countries (Kohler, et al., 1997). The stock being not well quantified was segregated into basic elements and classed them. The research states they are “reference” buildings and not “typical”. They are associated with “age-use” classifications characteristic of archetypes. Each

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[8] U value is a measure of heat loss in a building element. It is also referred as ‘overall heat transfer co-efficient’ and measures how well parts of a building transfer heat.

group was broken down into detailed elements such as window type. Using these elements they developed building specifications which comprise the materials and operations with respect to the building.

Petersdorff, et al., (2006) developed a model for building stock for 15 EU countries by examining five standard buildings with eight insulation standards. Ecofys's built environment analysis model is used to calculate the heating demand for three climatic regions. The three house types included in the model were terrace, small apartment, and large apartment. The eight insulation standards applied to the buildings were determined based on typical values for the climatic conditions and building vintage found in EU countries. Different scenarios of retrofit and construction/demolition are modelled and an attempt is made to extend the model to smaller housing types. They found their models corresponded well with statistical data.

A model was developed for Nova Scotia by (MacGregor, et al., 1993) using three insulation/infiltration levels and nine dwelling types resulting in 27 archetypes. The model uses typical values of occupancy, appliances and lights, and evaluated the energy consumption of each archetype using an hourly analysis program. Energy consumption values are extrapolated to provincial levels based on the estimated number of dwellings represented by each archetype. The results are consistent with top down estimates for the region. The model evaluates the potential for energy savings and economic benefits through introduction of small-scale fluidized-bed furnaces for residential space and domestic hot water heating.

A model was developed for American building stock to determine space heating and cooling loads by (Huang & Broderick, 2000) using 16 multifamily and 45 single-family prototypical residential buildings. The model uses the DOE-2.1 building energy simulation programme supported by the USA Department of Energy (Department of Energy, 2008). Building heating and cooling loads are disaggregated to show the contributions from the walls, roof, windows, infiltration, and internal gains by setting the thermal conductivity of each component to zero. The model also utilizes building population estimates provided in (Energy Information Administration, 2001) to scale their results up to a national value. The scale-up was undertaken by normalising each archetype’s energy consumption by heated floor area and multiplying by the national floor area value.

A residential end-use energy consumption model for Osaka city scale was developed by (Shimoda, et al., 2004) consisting of 20 dwelling types and 23 occupant types representing variety of houses within the city. Each dwelling type was modelled using conductive heat transfer analysis based on identical insulation levels. Occupant types consisted of family members, appliance ownership levels and the appliance ratings. Each archetype was simulated and multiplied by the number of dwellings it represented. The study revealed two interesting results from their approach: the total estimated residential energy use is less than historical values because “unreasonable” energy use (e.g. leaving lights on) was not accounted for, and estimated unit energy consumption is larger than statistical values which they attribute to surveys focusing on larger families.

A number of building physics based models have been developed in the UK to determine domestic energy demand. The core calculation engine of these models is the Building Research Establishment’s Domestic Energy Model (BREDEM). It consists of several heat balance equations and empirical relationships to produce an estimate of the annual (BREDEM-12) or monthly (BREDEM-8) energy consumption (Dickson, et al., 1996; Anderson, et al., 2002a; Anderson, et al., 2002b). The calculation is based on factors contributing to energy balance such as materials used for construction, insulation levels, ventilation characteristics, efficiency and control of heating systems, solar gains, fuel type and use of any renewable energy technologies.

BREDEM forms the energy calculation engine of Standard Assessment Procedure (SAP), In 1994 SAP was cited in Part L of the Building Regulations as a means of assessing dwelling performance. SAP was further designated as the national calculation methodology for UK as per the requirements of the Energy Performance of Buildings Directive (European Parliament and the Council, 2003; BRE, 2011). Reduced Data SAP (RDSAP) was introduced in 2005 for assessing the performance of existing dwellings (BRE, 2011).

2.3.3 Strength and Weaknesses of the Bottom-up Approach

Bottom-up statistical techniques are capable of determining the effects of regional or national economic changes while representing the energy intensity of particular end uses. The primary information for statistical models is however energy supplier billing data which is private information and affected by data protection in several countries including UK. Of the three statistical techniques discussed earlier, regression is the least favoured as the utilised inputs vary widely among models, limiting their comparison. The CDA on the other hand focuses on simplification of end-uses and hence can be easily used for different locations with comparable predictions from various studies (Swan & Ugursal, 2009). The NN approach allows for the most variation and integration between end-uses, resulting in the highest prediction capabilities. The coefficients of the neurons however have no physical significance leading to a huge drawback. A bias of the energy estimation error was found when using the NN technique (Aydinalp-Koksal & Ugursal, 2008).

The building physics based models rely on detailed housing information and hence can estimate the energy consumption with most clarity. Further, they do not depend upon historical values; however, the historical data can be used to calibrate the models. The major advantage of building physics based models such as BREDEM is modular structure of its algorithms. This means the model users can easily modify these algorithms to suit particular needs (Kavgic, et al., 2010). Building physics based models are currently the only models that can evaluate the impact of new technologies. Assessing the impact of technologies is important because, compared to taxes or energy price policies, technological solutions are more likely to gain public acceptance in reduction of energy consumption and associated greenhouse gas emissions (Swan & Ugursal, 2009).

There are however, some notable limitations of the building physics based model. The building physics based models make assumption regarding occupant behaviour which can have significant impact on energy consumption. Further requirements of large amount of site specific data and expertise required to develop modular equations can be a significant drawback. SAP requires an input of over 90 different items of data for each dwelling. This data is available for new developments; however, for existing dwellings, most of this data has to be gathered through site surveys. A detailed property survey by a trained assessor can last for at least 30 minutes (Rylatt, et al., 2003). Thus collecting this data for each dwelling and then aggregating for 1,200 households in an LLSOA or 24 million dwellings in UK can be time consuming and expensive (Office of National Statistics, 2012).

A summary of the benefits and limitations of bottom-up approaches is presented in Table 2-2.

Table 2-2: Benefits and Limitations of the Bottom-up Approach

Benefits	• Determines typical end use energy consumption at a highly disaggregated level • Describes current and prospective technologies in detail • Assess and quantifies the impact of different technologies on energy consumption • Includes macroeconomic and socioeconomic effects
Limitations	• Large amount of input data and expertise required • Assumptions regarding occupant behaviour

2.4 Approach for this Research

It is clear from the discussions in Section 2.2 and Section 2.3 that building physics based bottom-up approach is more appropriate for this research. Bottom-up methods adequately identify differences in the energy consumption of various end-use technologies. They further take into account technological changes to end-use systems or changes to the energy efficiency of such systems. We have also seen in Section 1.2, the policies and initiatives require practical decisions and are directed towards the level of the physical factors which influence energy use. Bottom-up approach, more specifically the building physics based models specifically help in addressing these needs. As the data is physically measurable and explicit, the building physics based methods can be more robustly extrapolated to allow for future changes in technical efficiency or technical change (Boardman, et al., 1995).

2.5 Summary

This chapter discussed the two basic methods of energy profiling and their applications. Based on the strength, weaknesses and the applications identified through the literature review, this research uses the building physics based bottom-up approach. In the next chapter, we will discuss in detail the building physics based models developed for the UK residential sector based on literature review and stakeholder engagement. The next chapter identifies the gap in the current methods and the contribution this research makes.

Chapter 3 Domestic Energy Modelling in UK

3.1 Introduction

In the previous chapter we have seen that building physics based tools are more appropriate to achieve the aims and objectives of this research. In this chapter we review the building physics based tools developed for energy modelling in the UK. Based on the review of these tools, the factors that influence energy performance of dwellings are identified. These factors enable estimating the baseline energy performance of dwellings and also quantify the energy and carbon emissions reduction potential, which is discussed in later chapters. Discussions are undertaken with the stakeholders regarding the use of existing domestic energy modelling techniques. The review of these models and the discussions with stakeholders helped in identifying the limitations of the existing models and establishing the contributions this research can make.

3.2 UK Building Physics Based Models

Several building physics based models have been developed in the UK over a number of years to estimate the current and future residential demand. Some of the key models are:

- Building Research Establishment's Housing Model for Energy Studies (BREHOMES) (Shorrock & Dunster, 1997)
- The Johnston Energy and CO_2 Emission Model (Johnston, 2003)
- The UK Domestic Carbon Model (Boardman, et al., 2005)
- The DECarb Model (Natarajan & Levermore, 2007)
- The Energy and Environmental Prediction (EEP) Tool (Jones, et al., 2007)
- The Domestic Energy Carbon Counting and Carbon Reduction Model (DECoRuM) (Gupta, 2009)
- The Community Domestic Energy Model (CDEM) (Firth, et al., 2010)

3.2.1 Energy Calculation Engine

All the seven models described above share the same core energy calculation engine BREDEM, modified to varying degrees. BREHOMES and DECoRuM use the annual version BREDEM-12. Johnston and EEP use the simplified version BREDEM-9, whereas the UKDCM, DECarb and CDEM use the monthly version BREDEM-8 (Shorrock & Dunster, 1997; Gupta, 2009; Johnston, 2003; Boardman, et al., 2005; Natarajan & Levermore, 2007a; Jones, et al., 2007; Firth, et al., 2010).

3.2.2 Disaggregation Levels

The disaggregation levels vary significantly amongst the seven models. The Johnston model is developed around two notional types of dwellings – pre and post 1996 (Johnston, 2003). UKDCM comprises 20,000 different dwelling combinations by 2050 defined by geographical area, age, construction type, number of floors and tenure, with each type given an appropriate weighting to describe the overall carbon and energy profile for a given scenario (Boardman, et al., 2005). BREHOMES disaggregates the housing stock into over 1,000 categories, defined by built form, construction age, tenure and the central heating ownership. However, it uses a single composite dwelling to predict future trends in the overall stock, which results in simplified calculations at the cost of the full diversity (Natarajan & Levermore, 2007).

The EEP model uses built form and age to group properties into 100 different types. Each type has an associated CO_2 emission, energy rating and yearly energy cost associated with it. The DECarb contains 8,064 unique combinations of dwellings in 6 age bands whereas CDEM consists of only 47 archetypes based on built form and age. CDEM however is the only model that investigates the uncertainties on the results associated with input variables. The study makes a stark finding that potential exists for creating simpler domestic energy models functioning with a limited set of input parameters with associated sensitivity coefficients (Firth, et al., 2010).

3.2.3 Applications

The five of the seven models described above (i.e. BREHOMES, Johnston, UKDCM, DECarb and CDEM) have been developed to test various scenarios to achieve medium (up to year 2020) and long term (up to year 2050) goals. The models use a standard baseline year based on which projections are made. BREHOMES has 1993 as the baseline year, while, the Johnston, UKDCM and DECarb have 1996 as the baseline year. CDEM identified the energy demand for 2001 while the EEP and the DECoRuM do not specify a base year.

BREHOMES constructed two scenarios ‘reference’ based on business-as-usual considering the current population and consumption trends and ‘Efficiency’ where population and consumption trends remain the same, but the uptake of efficiency measures, such as loft insulation, is increased (Shorrock & Dunster, 1997). The Johnston model in addition to the business-as-usual scenario further considers ‘demand side’ and ‘integrated’ scenario. Demand side identifies what could happen if the current rate of uptake of fabric and end-use efficiency measures is increased. Integrated scenario is similar, but also considers the implications of additional measures on the energy supply side (Johnston, 2003).

The UKDCM tests scenarios where domestic dwellings achieve 60% emission reduction by 2050. The scenarios have energy efficiency measures and a shift towards low and zero carbon technologies that are retrofitted or integrated to the building or community (Boardman, et al., 2005). DECarb model does not add any further scenarios however, examines, the scenarios developed by BREHOMES, Johnston, and UKDCM.

Results from DECarb indicate that scenarios developed by Johnston fail to achieve 50% reduction by 2050 as it only considers the existing trend in uptake of building refurbishment (Johnston, 2003). The scenarios presented by UKDCM can achieve 60% reduction, only if the major changes to the existing housing stock were accepted soon (Natarajan & Levermore, 2007a).

3.3 Stakeholder Engagement

Based on extensive literature review undertaken in Chapter 2 and Section 3.2, several limitations and gaps have been identified in the existing tools and methodologies and presented in Section 3.4. However, to supplement these findings, stakeholder engagement was undertaken. In Section 1.2 and 1.4.2 we identified that the onus of implementation of the various policies on reduction of energy consumption and carbon emissions related to dwellings lies with the councils, planning authorities, energy suppliers and social housing providers amongst others. One-to-one discussions were undertaken with selected participants listed in Table 3-1 at their respective offices. The participants chosen were from the identified stakeholders.

Four participants are currently working with Middlesbrough council. Participants from Studio Urban Area LLC and Deep Green Solutions have more than 20 years of previous work experience each with four local councils are currently engaged in various town planning, sustainability and building related services across various councils in the UK. Two participants represented Erimus Housing, a Social Housing Provider with over 15,000 dwellings across Middlesbrough and Stockton. They are one of the largest social housing providers in UK. One participant from National Energy Action (NEA) has over 50 years of work experience while the other participant from NEA has 25 years. NEA is a national charity who works in partnership with central and local government, utility companies, housing providers, consumer groups and voluntary organisations throughout UK to provide advice, improve and promote energy efficiency and eradicate fuel poverty. Considering these credentials, these stakeholders are considered to be representative of stakeholders related to implementation of energy performance improvement measures in the UK.

The discussions focussed on obtaining information related to the methods of energy profiling and identify their effectiveness in decision making related to policy implementation. A semi-structured questionnaire was developed to aid this discussion and is included in Appendix A. Semi-structured interviews was chosen as a method as it does not follow a rigorous set of questions. It allows new ideas to be brought as a result of what is being discussed (Hague & Hague, 2004).

Discussions with the participants revealed that none of the tools discussed in Section 3.2 are currently being used by any of the stakeholders. Erimus Housing and NEA use the NHER Plan Assessor developed by the National Energy Services. NHER Plan Assessor is BRE approved software capable of producing SAP ratings. The Housing Act, 2004 requires Energy Performance Certificate (EPC) (which displays the SAP rating) to be issued for each dwelling that is being rented or sold to a new tenant (Act of Parliamnent, 2004). The data required for undertaking the SAP assessment is gathered through inspection of each property.

The participants confirmed that while the tool was easy to use, the amount of data required for SAP assessment is large and hence time consuming. This is particularly significant for Erimus Housing which manages large number of properties. The NHER Plan Assessor can only be used when an EPC is to be issued. Thus the tool cannot be used to predict scenarios of energy consumption or SAP rating from implementation of improvement measures.

Participants from Studio UrbanArea LLC and Deep Green Solutions indicated that they use NHER Plan Assessor to issue EPCs. The participants had similar opinions to that from Erimus Housing and NEA regarding the amount of data required, time consumption and inability to simulate scenarios. The participants also indicated use of CarbonMixer®, software developed by Bobby Gilbert and Associates to run scenarios for carbon savings.

Table 3-1: Profile of Participants from Stakeholder Engagement

	Participant	Company	Profile
1	Programme Manager	Erimus Housing, Middlesbrough	Over 35 years of investment related experience. Currently leads the Asset Management Team and is responsible for decent homes and decisions related to energy investment.
2	Sustainability Coordinator	Erimus Housing, Middlesbrough	Part of the Asset Management Team. Involved in development of sustainable strategy and delivery across staff, customers and offices.
3	Technical Development Manager	National Energy Action, Newcastle-upon-Tyne / Warm Zone	Over 25 years of experience in resource efficiency and carbon reduction. Work involves managing a team of technical staff and projects to evaluate the effect of technology as a solution to improving the lives of people living in fuel poverty. This work involves building fabric improvement, resource efficiency improvement, and evaluating and modelling new technologies used to generate heat and power
4	Technical Coordinator	National Energy Action, Newcastle-upon-Tyne / Warm Zone	Over 50 years of experience in construction industry. Role focuses on the technical issue involved in improving thermal efficiency and reducing energy consumption particularly to hard-to-treat properties. Current and recent projects include providing technical assistance and mentoring support to a wide range of organizations

	Participant	Company	Profile
			and consumer group particularly to the vulnerable groups potentially in fuel poverty.
5	Town Planner and Urban Designer	Studio UrbanArea LLP, Newcastle-upon-Tyne	Over 20 years work experience in strategic planning, community engagement, urban regeneration and sustainable development. Worked for Newcastle City Council as the Head of the Urban Design Section on a range of inner city regeneration projects
6	Managing Director	Deep Green Solutions, Gateshead	Over 27 years of experience in sustainability and building services engineering including that with Durham County Council, Chester-le-Street District Council, Northumbria Energy Efficiency Advice Centre
7	Senior Housing Needs and Enabling Officer	Middlesbrough Council	Over 10 years of experience in Strategic Housing, which has involved preparing strategies, procuring works and services, supporting and delivering regeneration projects and new housing developments
8	Housing Needs and Enabling Officer	Middlesbrough Council	Over 6 years working for the Housing Needs and enabling team for Middlesbrough Council. Currently one of the lead officers for the Council on the GoWarm Gresham scheme which is delivering Community Energy Saving Programme (CESP) to over 1100 properties. It is the largest private sector scheme of its kind in the

	Participant	Company	Profile
			Country.
9	Community Protection Officer	Middlesbrough Council	Specific responsibilities for Middlesbrough`s Carbon reduction programme and facilitate Middlesbrough Climate Change Community Partnership. Supports the delivery of the Council's commitment to sustainable living through its One Planet Living Programme and work closely with Environmental and health Charity Middlesbrough Environment City.
10	Director of Middlesbrough Environment City and Chair of the Middlesbrough Affordable Warmth Group.	Middlesbrough Environment City/ Affordable Warmth Group	Over 20 years of experience in delivering projects and management in the voluntary sector. Currently Director of Middlesbrough Environment City, a charity that promotes healthy and sustainable living and encourages behaviour change to more sustainable behaviours.

A separate investigation was undertaken on CarbonMixer® to understand its capabilities. CarbonMixer® can undertake SAP assessment similar to NHER. It is however, not BRE approved software as it gives only a “ball park” figure as the SAP rating is for archetype rather than for the actual dwelling (BG&A, 2011). It does allow scenarios to be simulated; however, building models need to be developed using standard archetypes defined in the software. The tool is being promulgated to even estimate baseline for neighbourhood level. The demonstration videos indicated that while this is possible, model for each dwelling has to be developed individually as CarbonMixer® does not make use of any available topography base maps. Developing dwelling models for up to 1,200 houses in LLSOA or approximately 24 million dwellings in UK however is a huge ask.

The participants confirmed that the improvement of the properties is typically undertaken when funding is available for a particular area, for e.g. a CESP area or energy companies along with the installation companies approach the housing provider as per the requirements of the CERT. The most common improvement measures include changes to the built fabric (insulation and double glazing), heating system and fuel including boiler, heating controls and installation of solar photo voltaic and solar water heaters. However, no formal methods are currently used to choose between these interventions or undertake trade-off analysis. Thus in a hypothetical situation, an installation company may get install external insulation to filled cavity walls in a CESP area if they approach the housing provider first, when more energy could be saved by changing to an A rated[9] boiler from a G rated boiler.

The participants indicated that they lack a tool that can be used to effectively assess baseline energy performance of large dwelling stock, assess various scenarios of improvement and help them in making decisions based on environmental benefit, associated costs and social perceptions.

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[9] Boiler rating as defined in the SEDBUK rating scheme

3.4 Limitations and Gaps of the Existing Energy Models

Based on the extensive literature review and the discussions with the stakeholders, following limitations and gaps are observed with regards to the UK building physics based models. These are summarised in Table 3-2.

The transparency of models in terms of data sources and model structures is recognised by most authors as a crucial issue for the future deployment of the models. Further, no access is available to the core calculation algorithms of almost all the models, including the modified BREDEM-type modules. (Kavgic, et al., 2010). Unfortunately, access to either the raw input data or the model algorithms is currently limited for the majority of the models; hence, their outputs cannot be accurately replicated (Natarajan & Levermore, 2007a).

Except for EEP and DECoRuM, all other models work well as policy advice tools due to their inherently built in archetypes and the author specified futuristic scenarios. These tools lack the ability to be used by stakeholders for implementation of policy or initiatives described in Section 1.2. This is because dwelling characteristics may be different from those in the standard archetype. Also, the energy efficiency and renewable energy interventions scenarios that the stakeholder wants to test may be different than those defined as standard within these models.

EEP and DECoRum have an ability to be used for policy implementation due to their ability to model individual dwellings. However, these models develop their archetypes based on drive-by surveys in addition to the publicly available information. The EEP for their model surveyed 55,000 dwellings in Neath Port Talbot District Borough Council for which 18 person months were required (Jones, et al., 2007). DECoRuM undertook a case study in Oxford, UK for 318 dwellings. Much of the 95 parameters required for BREDEM-12 model were identified using data reduction techniques, however, 22 parameters were identified through walk-by survey (Gupta, 2009).

The Local Development Framework (LDF) requires local governments to involve local community, utility providers, environmental groups and housing corporations amongst others in their appraisal and management process of the framework (Office of the Deputy Prime Minister, 2010). None of the models discussed earlier assist stakeholder in meeting this requirement.

Table 3-2: Summary of Limitations of the Existing Models and Tools

	Limitation / Gap	Description
1	Transparency of Models	• Most models fail to identify their data sources and present their structures • Access to core energy calculation algorithms is not available
2	Dwelling Archetypes	• All models except for EEP and DECoRuM consider only standard archetypes of dwellings • These archetypes are author defined and may not present the actual characteristics of dwelling providing misleading energy consumption details
3	Drive-by / Walk-by Surveys	• EEP and DECoRuM try to overcome the above limitation, however undertake drive-by surveys are time consuming and costly • Any error during data collection requires revisit
4	Policy Implementation	• All the models developed above were developed to inform energy policy and none of them assist stakeholders in implementation of energy policies • The models lack the capability of undertaking performance improvement scenarios through use of actual dwelling characteristics on different geographic levels • None of the models predict the changes to the SAP ratings or consider feed-in-tariffs.
5	Decision Support	• None of the models discussed assist the user/stakeholder in making decisions with regards to the selection criteria • The LDF requires stakeholder engagement during appraisal process which all models fail to consider

3.5 Characteristics Influencing Energy Performance

There are about 24 million homes in the United Kingdom. Of these 21.8 million are in England, comprising 29% terraces, 27% semi-detached, 17% detached, 9% bungalows, 3% converted flats and 14% purpose-built flats (Communities and Local Government, 2009).

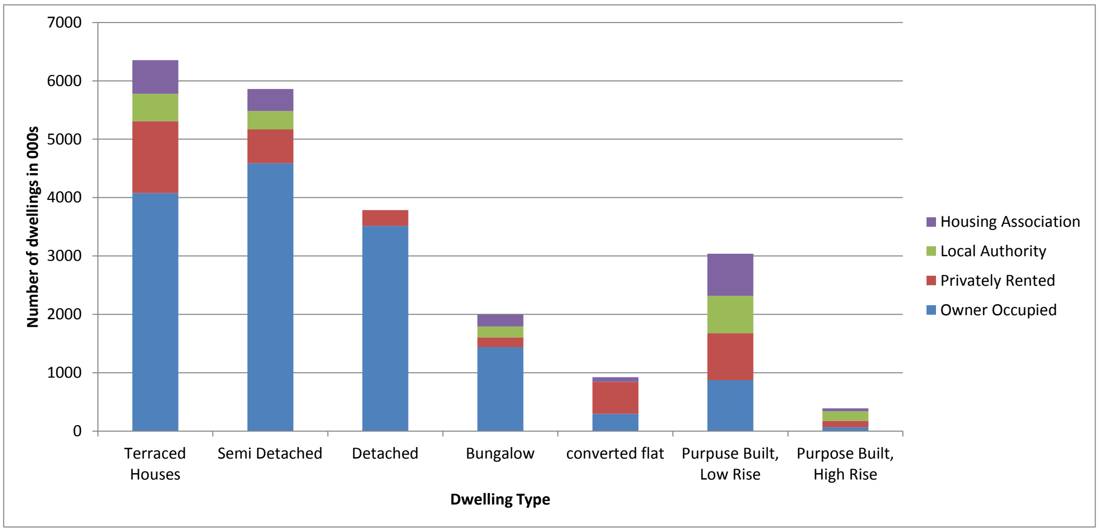

Figure 3-1: Dwelling Type and Ownership Statistics

Figure 3-1 presents the statistics for the proportion of dwellings in each type managed by the housing associations or local councils, privately owned or privately rented. So, unlike many countries, more than 86% dwellings in UK are houses.

Figure 3-2 presents the statistics on the age of the dwellings and their ownership type in England. The statistics indicate that the stock is fairly old with 39% predating 1944, 40% were built between 1945 and 1980, and 21% after 1980. The statistics indicate that most of the dwellings are either privately owned or rented and built prior to 1980s, before the thermal standards started improving as a part of reforms to the Building Regulations (Wright, 2008).

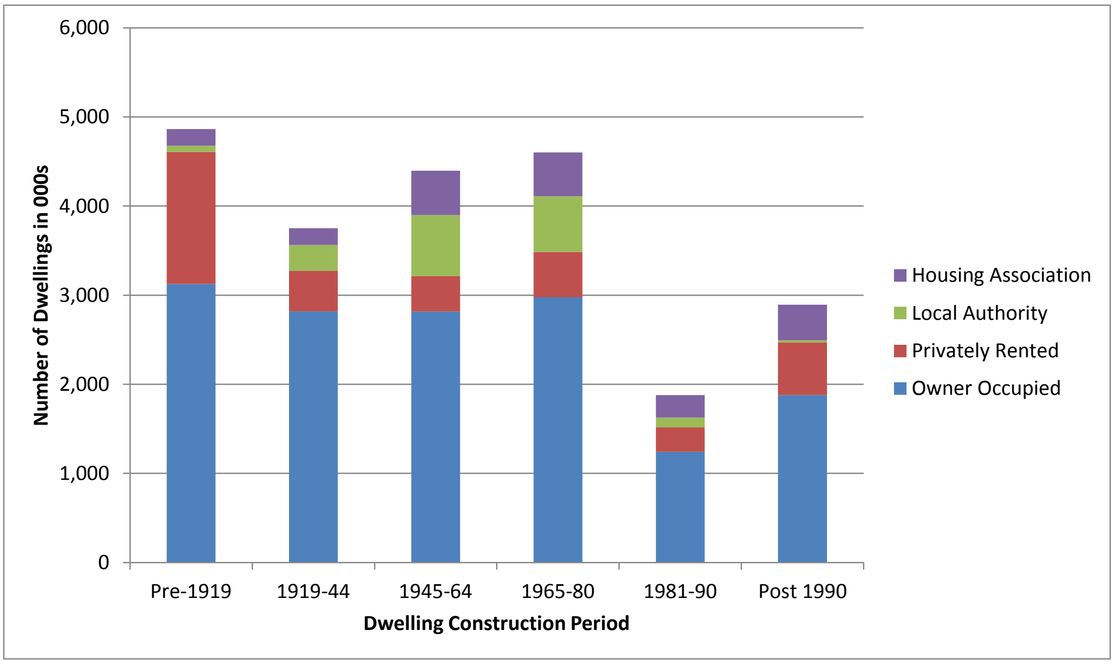

Figure 3-2: Dwelling Age and Ownership Statistics

Energy in dwellings is used for space heating, hot water, lighting and power appliances. The actual amount of energy used for these tasks results from a complex interaction between built form, location, energy-using equipment and occupancy type. According to Palmer & Cooper, (2011), 83% of energy use in the home is accounted for by space and non-electric water heating, and the vast bulk of this is done by gas. The remainder is accounted for by electricity use for other purposes, including electric water heating (Owen, 2006).

3.5.1 Building Fabric

Heat is lost from dwellings through the fabric, by air infiltration and ventilation. Fabric heat loss is directly related to the amount of area exposed to the atmosphere and the type of the fabric such as walls, and roof (Anderson, et al., 2002a). The ratio of wall area to exposed roof area depends on the building type – terraced houses, with two party walls, have a lower ratio than semi-detached houses; while detached houses and bungalows have the highest ratios. Figure 3-1 indicates that more than 52% dwellings in UK are either semi-detached or detached houses or bungalows thus amounting to significant heat loss. The insulation levels depend on age and subsequent improvements (Utley & Shorrock, 2008).

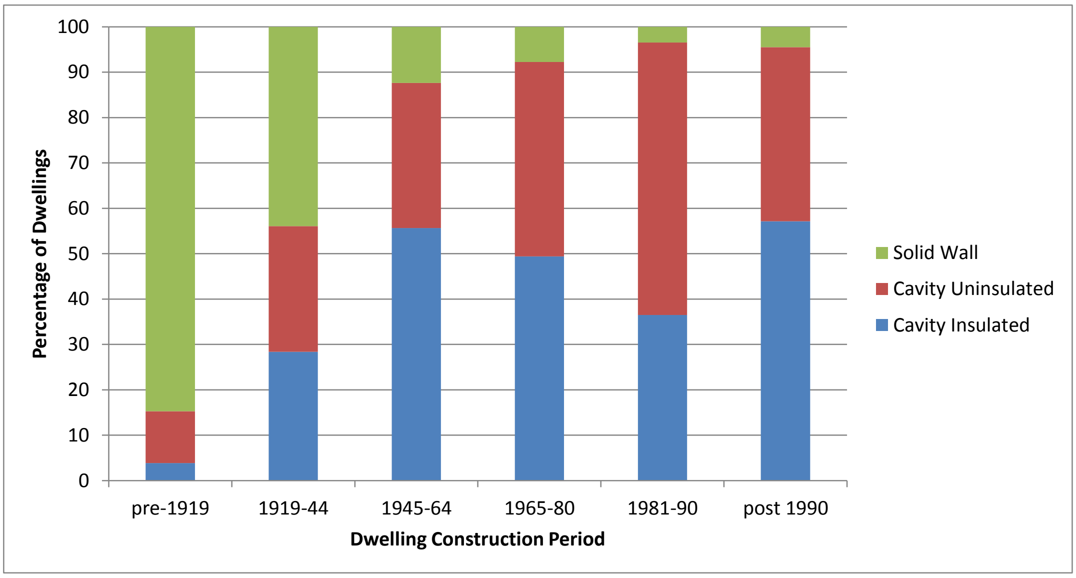

Figure 3-3: Wall Types and Construction Periods

Figure 3-3 presents the wall types based on construction periods (Communities and Local Government, 2012). Dwellings built prior to the 1940s are most likely to have solid walls which have effect most heat loss. Dwellings post 1940s, are likely to have cavity walls which perform better than the solid walls. Insulated cavity walls however perform the best amongst all; however they represent less than 30% of total dwelling stock.

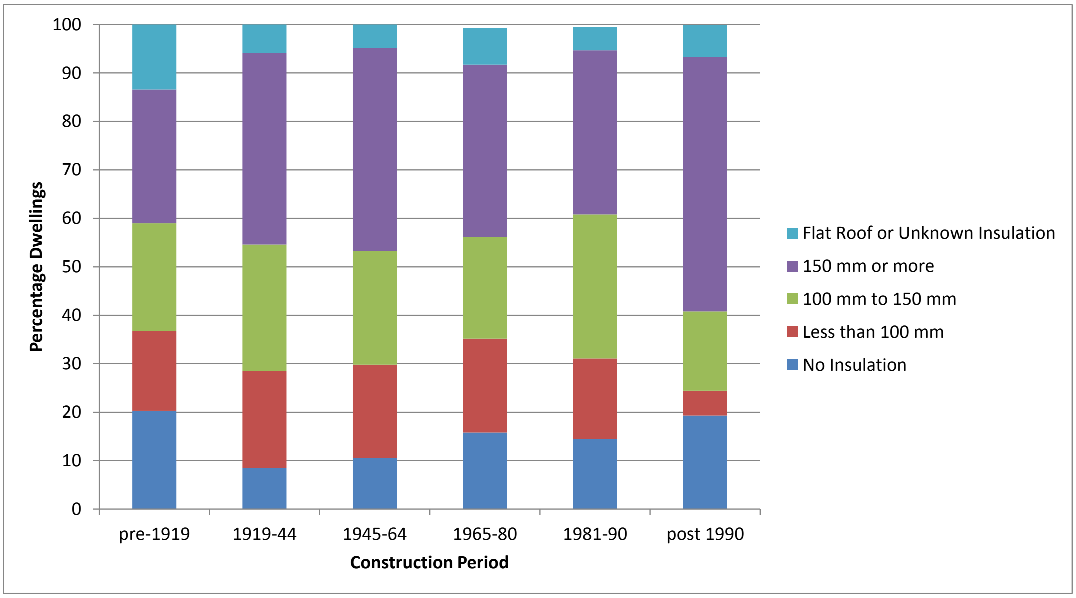

Figure 3-4: Roof/Loft Insulation and Construction Periods

Heat loss through roof depends on the insulation levels. Dwellings built prior to 1970s were unlikely to have any insulation; however, due to the popularity of roof insulation since then, the uptake has increased through dwellings of all ages as indicated by Figure 3-4 (Communities and Local Government, 2012). By 1990, about 80% dwellings had some roof insulation, though it was most likely to be only 100 mm in depth (Utley & Shorrock, 2008).

Another source of heat loss is thermal bridging at junctions, through lintels, timber framework etc. This becomes more important as the thermal transmission (U-value) of building elements is reduced, as the bridging accounts for a higher proportion of heat loss (Lowe, et al., 2000). Most Northern European countries have built reasonably airtight dwellings for a long time, but the UK dwellings tend to be much leakier buildings, with heat loss as a consequence (Wright, 2008).

3.5.2 Heating Systems

Poor dwelling fabric of most UK dwelling has led to a huge demand for space heating requirements. Further the average living room temperature has increased from 19.9°C in 1990 to 20.1°C in 2005 (Summerfield, et al., 2007). Figure 3-5 presents the means by which space heating demand is met in dwellings (Communities and Local Government, 2012). The figure indicates that majority of UK houses are heated by central heating systems fired by a natural gas boiler. The boiler heats up water and circulates it through radiators in different rooms. The amount of fuel used by the boiler depends on the efficiency of the boiler. Though the penetration of central heating is high amongst dwellings of all construction periods, boilers became popular only in the 1970s and typically had efficiency of just over 50% (Owen, 2006). Dwellings prior to 1980s are likely to have older boilers. Most of these boilers or the radiators have no controls to detect temperature and hence switch the heating on or off (Wright, 2008). This further leads to uncontrolled use of heating systems. Dwellings which do not have gas boilers are most likely to have electrical heating which is much more carbon intensive than gas central heating as seen from Figure 3-5. Poor building fabric coupled with low efficiency boiler or electrical heating contribute to significant carbon emissions.

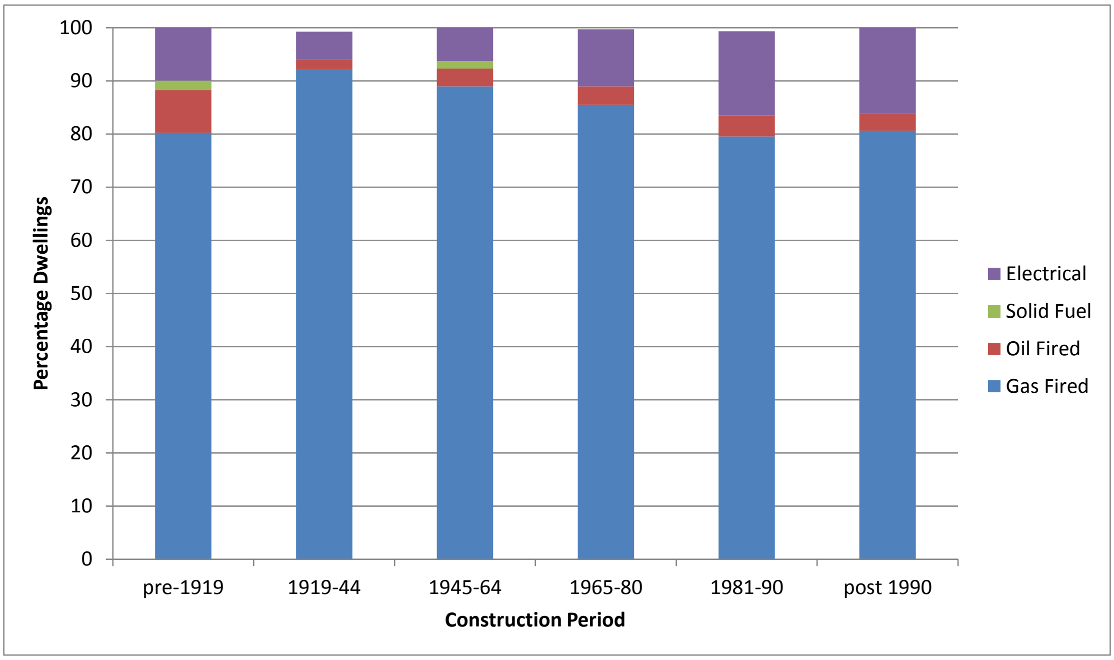

Figure 3-5: Type of Space Heating

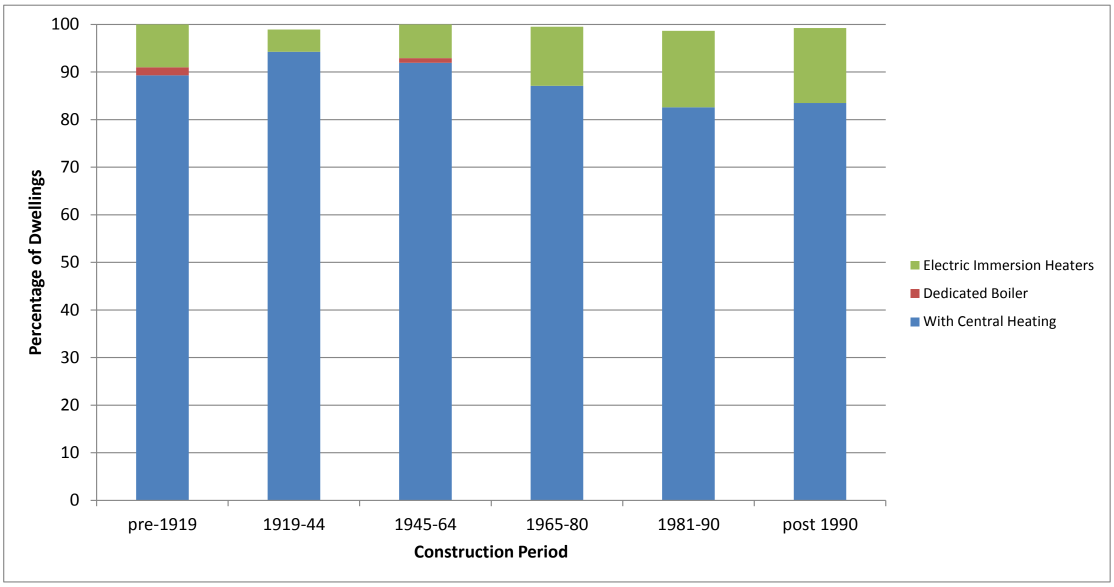

Figure 3-6: Type of Water Heating

The demand for hot water in dwellings is typically met by the same central heating system that meets the space heating demand as indicated by Figure 3-6 (Communities and Local Government, 2012). Hot water use is not linked to dwelling type or age. It is largely dictated by the number of people in the home and personal preferences, capability of the hot water system and presence of hot water storage cylinder (Wright, 2008).

3.5.3 Lights and Appliances

Unlike space and water heating, where energy is generated on-site by conversion of fuel, energy used for lighting and appliances is delivered and used directly in the form of electricity. Though electricity use accounts for only 17% of the total energy consumed by the dwelling, it is a growing home-based activity (Owen, 2006; Utley & Shorrock, 2008).

Electricity consumption doubled from 44 TWh in 1970 to 89 TWh in 2004. (Department of Trade and Industry, 2007). This is mainly because each household has more appliances. In the 1970s, a UK household on an average had 17 appliances, which has almost tripled to 47 appliances in 2004. Further, the numbers of most commonly used appliances have increased by an average of over four times for most appliances as seen from Figure 3-7 (DTI, 2008).

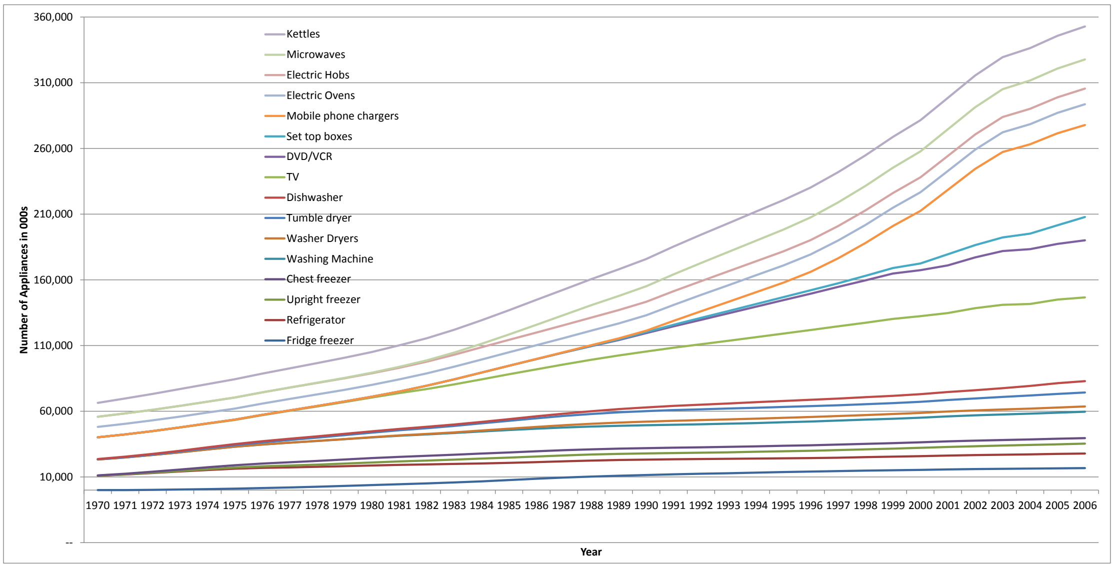

Figure 3-7: Number of Appliances Owned by Households

Research by Crosbie & Guy (2006) has shown that choice of fittings is strongly influenced by fashion and by TV style programmes, with lighting rightly seen as having a central influence on the internal ambience. Tungsten halogen spotlights are very popular, despite being inefficient, because of their small size and the bright white spotlight effect they produce. Most homes, regardless of size or built form, now have a refrigerator, freezer, automatic washing machine, microwave oven, hob and oven (ovens and hobs sometimes use gas, with gas hobs more common than gas ovens). But larger homes with more kitchen or outbuilding space often either have larger appliances or more of them, particularly for refrigeration and cooking. Similarly in infotainment; the family TV or radio has been replaced by an array of bedroom TVs, computers, MP3 players, mobile phones with mains chargers, CD players, computer game consoles, etc. leading to increased electricity consumption (Wright, 2008).

Because lights and appliances are retail traded goods, the maximum savings that could be achieved depends largely on policy initiatives regarding the efficiency rating and sale of these equipment. Informing or implementing retail policy is beyond the scope of this study. The way electricity is currently generated however can be influenced. This research focuses on electricity generated using renewable energy techniques on domestic level to power the growing demand from lights and appliances and reduce the dependence on conventional means of electricity generation.

3.6 Summary

A critical review of the building physics based bottom up models discussed in subsequent chapters reveals that the energy consumption of dwellings is broadly influenced by the following:

- Geometry of the dwelling
- Materials used for construction of the dwelling
- Thermal insulation of the building fabric
- Ventilation characteristics of the dwelling and ventilation equipment
- Efficiency and control of the heating system
- Solar gains through openings of the dwelling
- Fuel used to provide space and water heating, ventilation and lighting
- Installed renewable energy technologies

Based on the extensive literature review and the discussions with the stakeholders it is now evident that a clear gap exists between the vast arrays of methods when it comes to making energy policy implementation decisions with regards to assessing and improving the energy performance of existing dwellings. This research intends to address some of these issues through:

Through literature review and stakeholder engagement, this chapter has identified the models developed and tools used to assess the energy performance of the UK dwelling stock. The research has identified that potential exists for a tool to be developed that can assist the councils, planners, energy suppliers and social housing providers in making decisions with regards to implementation of the policy. The chapter also presents the contribution this research hopes to make towards improving energy performance of the dwellings. The next chapter discusses the energy performance improvement measures applicable to domestic dwellings.

Chapter 4 Energy Performance Improvement Measures

4.1 Introduction

The use of building physics model described in the previous chapter establishes the existing energy performance characteristics of dwellings. Reduction in energy related carbon emissions from dwellings can be achieved through two methods viz. supply side management and demand side management. Supply side management includes changes to large scale power generation and distribution. This research has chosen a building physics based bottom-up approach; hence, supply side management is beyond the scope of this research. The demand side management is achieved through improving the quality of the building stock and use of zero or low carbon energy generation techniques on a domestic level also known as micro-generation. Micro-generation is currently considered as demand side management and forms an important part of energy strategy, as it is a way to improve energy security by reducing fuel imports (Hawkes, et al., 2009). To improve the uptake of micro-generation, the UK Government has introduced feed-in-tariffs for renewable electricity systems with a declared net capacity of 50kW or less (HM Government, 2013a). A similar scheme of providing incentives is in consideration for use of renewable heat generation techniques (HM Government, 2013b).

It is in this respect that this chapter presents a review of various measures that improve energy performance of dwellings and are applicable for the UK dwelling stock. The options include energy efficiency improvement measures such as changes to the fabric of the dwelling and existing heating system and; installation of renewable or low carbon energy generation techniques such as solar panels, micro-wind turbines, micro-combined heat and power units and heat pumps. District heating network is one of the low-carbon energy generation techniques; however, it is not considered a micro-generation technology (Staffell, et al., 2010) and thus not considered in this research.

4.2 Fabric Change

Reducing heat loss through the building fabric is one of the most practical and efficient ways of reducing the energy demand of the dwelling. It involves improving the performance of walls, floor and roof through adding insulation layers and replacing windows with multiple glazing. The following sections describe the options available in each of these categories. Improving building fabric is one of the requirements of the Energy Performance of Building Directive.

4.2.1 Wall Insulation

Houses in the UK have either solid wall or cavity wall which are responsible for about 35% heat lost through the dwelling (Hopper, et al., 2012). A cavity wall is made up of two walls with a gap in between; the outer leaf is usually made of brick, and the inner layer of brick or concrete block. A solid wall has no cavity and each wall is a single solid wall, usually made of brick or stone. Cavity walls were introduced in the 1930’s, hence all dwellings constructed earlier than that have solid walls (Everett, 2007). Non-insulated solid walls have a typical U value of 2.1 W/m^{2}K whereas unfilled cavity walls have a typical U value of 1.6 W/m^{2}K (Firth, et al., 2010). The options for insulating solid wall include internal or external wall insulation and that for cavity wall is filling the cavity with insulation to reduce their U value (Roberts, 2008).

4.2.1.1 External Wall Insulation

External wall insulation involves lining the external face of the wall. There are various types and thickness of external wall insulation available. The larger the thickness, the lower is the U value and hence lower is the heat loss rate. Table 4-1 below shows the different types of external wall insulation available, their thickness and respective U values. For any upgrades to existing dwellings, the Building Regulations (2010) require a U value of 0.30 W/m^{2}K to be achieved. It is seen from Table 4-1 that some insulation types achieve this standard only above 120 mm thickness. External wall insulation costs between £45/m^2 and £65/m^2 depending on the insulation type and thickness selected (Dowson, et al., 2012).

Table 4-1: Wall Insulation Thickness and U Values[10]

Insulation Type	Typical U Values (W/m^{2}K)					
	40 mm	**60 mm**	**80 mm**	**100 mm**	**120 mm**	**140 mm**
Phenolic	0.44	0.32	0.25	0.21	0.18	0.16
Polyisocyanurate and polyurethane	0.45	0.33	0.26	0.22	0.19	0.16
Expanded polystyrene and mineral wool (slab)	0.65	0.49	0.39	0.33	0.28	0.25
Cellular glass and woodfibre	0.67	0.51	0.41	0.34	0.30	0.26

External wall insulation not only improves the thermal performance but also improves the appearance where properties are in a poor decorative state of repair, reduce condensation and prevent dampness. External wall insulation can reduce heat loss from walls by over 70%. It can be applied without any disruption to the household and has no effect on the floor area of the dwelling (Energy Saving Trust, 2012a).

Adding external wall insulation will however significantly alter the appearance of the dwelling and hence may be subject to local planning regulations. There are currently more than 8,000 designated conservation areas in UK which are designated for specific architectural and historic interest (English Heritage, 2012). For such areas where this aspect is important, external wall insulation may be applied to side and rear walls, which often account for most of the overall wall area (UCL, 2007).

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[10] Source (BRE/EST, 2006a)

4.2.1.2 Internal Wall Insulation

Internal wall insulation involves lining the internal face of the wall. Similar materials presented in Table 4-1 are also used for internal wall insulation. The Building Regulations (2010) require a U value of 0.30 W/m^{2}K to be achieved and hence a thickness of 120 mm is typically required. Internal insulation also reduces the heat loss from walls by over 70% and is cheaper than external insulation costing between £35/m^2 and £42/m^2 depending on the type and thickness chosen. Internal insulation however, can marginally reduce the floor area of the rooms in which they may be applied (Dowson, et al., 2012). Further, it is disruptive to the household and requires internal fittings such as skirting boards, door frames and items hanging on the wall to be removed and reattached (Energy Saving Trust, 2012a). Internal insulation however can be an option for dwellings in conservation areas where there may be planning restrictions on external insulation.

4.2.1.3 Cavity Wall Insulation

Improving the thermal performance of cavity walls includes filling the cavity between the two layers of the wall with insulating material. Unlike solid wall insulation, the choice for this type insulation is limited as the material needs to be injected into the cavity through holes or slots made in inner or outer leaf of the wall (Shu & Orlandi, 1986). The common types are blown mineral wool, urea-formaldehyde foam and bonded polystyrene beads and achieve a U value of 0.55 W/m^{2}K as required by the Building Regulations (2010). Cavity wall insulation can reduce heat loss from walls by over 50% and typically costs £6/m^2 (REAP Scotland, 2011). Holes around 22 mm in size are drilled at intervals of around 1m in the wall. With specially designed equipment, insulation is then blown into the cavity. Once all the insulation is in, the holes in the brickwork are closed (Energy Saving Trust, 2012b). Cavity wall insulation takes only a few hours to install and does not change the appearance of the dwelling. Cavity wall insulation however has higher U value than solid wall insulation as the typical thickness of the cavity is 50-75 mm which limits the amount of insulation that can be injected. The performance however can be improved through adding internal or external insulation.

4.2.2 Floor Insulation

Heat loss from floor adjacent to the ground or above an unheated floor such as garage, accounts for about 10% of the total heat lost (Hopper, et al., 2012). The net U value of the floor depends on the size, shape, type and thickness of the installation and the conductivity of the ground beneath. Heat losses are more around the edges of the floor and hence an end-terrace house may have a higher heat loss than a mid-terrace house (BRE/EST, 2006a).

Table 4-2: Floor Insulation Thickness and U Value[11]

Insulation Type	**Typical U Values (W/m^{2}K)**					
Timber floor	**100 mm**	**125 mm**	**150 mm**	**175 mm**	**200 mm**	**-**
Concrete Floor	**40 mm**	**60 mm**	**80 mm**	**100 mm**	**120 mm**	**140 mm**
Phenolic	0.30	0.23	0.19	0.16	0.14	0.13
Polyisocyanurate and polyurethane	0.31	0.24	0.20	0.17	0.15	0.13
Extruded Polystyrene	0.35	0.28	0.23	0.20	0.18	0.16
Expanded Polystyrene	0.39	0.32	0.28	0.24	0.21	0.19
Cellular Glass	0.42	0.34	0.29	0.26	0.23	0.21

The choice and thickness of insulation selected also depends on the type of floor. Table 4-2 shows typical U values for insulation types and thickness for timber and concrete floors. The Building Regulations require a U value of 0.25 W/m^{2}K to be achieved and hence a thickness of 80 mm for concrete

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[11] Source (BRE/EST, 2006a)

floor and 150 mm for timber floor is typically required for most insulation types. Insulating floors can reduce heat loss from the floors by 50%. For timber floors are most likely to be suspended with access from void below for safe installation; concrete floors are however unlikely to have this access and need to be insulated above which may cause disruption to the householder (Roberts, 2008). Floor insulation is quick to install and typically costs between £8/m^2 and £12/m^2 depending on the type and thickness selected (Mackenzie, et al., 2010). In view of the amount of reduction in heat loss achieved and low cost of installation, floor insulation is considered as one of the improvement option.

4.2.3 Roof Insulation

Roofs are the second largest heat loss aspect of the dwelling after the walls responsible for about 25% of the total losses (Hopper, et al., 2012). Reducing heat losses from the roofs involve lining the joists of the loft with insulating material or lining the rafters with insulating material in case of dwellings with roof rooms. Dwellings without any added insulation built prior to the enforcement of Building Regulations in 1965 are likely to have a U value of 2.3 W/m^{2}K. The roof performance has subsequently improved and the average U value post 1960s dwellings is 0.44 W/m^{2}K (Firth, et al., 2010).

Table 4-3: Roof Insulation Thickness and U Value[12]

Insulation Type	**Typical U Values (W/m^{2}K)**				
	150 mm	**200 mm**	**250 mm**	**275 mm**	**300 mm**
Cellulose	0.24	0.18	0.14	0.13	0.12
Flax	0.25	0.19	0.15	0.14	0.13
Sheep's Wool	0.26	0.20	0.16	0.14	0.13
Mineral Wool	0.28	0.21	0.17	0.16	0.14

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[12] Source (BRE/EST, 2006a)

Table 4-3 describes the insulation types and thickness that can achieve the recommended best performance value of 0.16 W/m^{2}K for joists and 0.18 W/m^{2}K for rafters (Office of Deputy Prime Minister, 2010). Insulation liner between joists or rafter can reduce heat loss from the roof by over 50%. Roof installations are quick to install, cause no disruption to the householder and typically costs between £7/m^2 and £10/m^2 depending on the type and thickness selected (Energy Saving Trust, 2012c).

4.2.4 Double Glazed Windows

Heat loss from windows account for about 20% of the total heat lost from dwelling. Reducing heat lost from the windows involves replacing them with double glazed and low-emissivity (low-e) windows. Dwellings prior to 1970s had single glazed windows with a typical U value of 4 W/m^{2}K. Double glazed windows were first invented in 1930s; however, they became more popular in the UK in 1970s and have a typical U value of 3 W/m^{2}K (Milne & Boardman, 2000; Dowson, et al., 2012). Double glazed windows consist of two layers of glass sealed along a spacer frame thus creating a narrow gap between them. The gap acts as an insulator reducing the heat loss (Osborne, 1985). With advances in glass coating and filling the layer with inert gases, the performance of the windows has significantly improved.

Table 4-4 describes the various types of double glazed windows available and their respective U values. The Building Regulations (2010) require all windows fitted as a part of refurbishment to at least have a Window Energy Rating of Band C[13] which equates to a U value of 1.6 W/m^{2}K. Replacing existing windows with double glazing can reduce heat loss from windows by about 50% and depending on the type of window chosen can typically costs between £200/m^2 and 250/m^2 (Dowson, et al., 2012). Double glazed windows are quick to install and cause minimal disruption to the household. Long with the reduction in heat loss, the low-e double glazed windows also reduce condensation and glare and noise entering the dwelling (Energy Saving Trust, 2012d).

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[13] Window Energy Rating Bands as defined by British Fenestration Rating Council (Glass and Glazing Federation, 2013)

Table 4-4: Double Glazed Window Types and U Value[14]

Frame Type	Gas Fill	Spacer Type	Band[13]	U Value
PVC-U	Argon	Silicone Rubber	B	1.4 W/m^2K
Timber	Argon	Corrugated Metal Strip	C	1.5 W/m^2K
PVC-U	Argon	Hard Polyurethane	C	1.6 W/m^2K
Timber	Air	Silicone Rubber	D	1.6 W/m^2K
PVC-U	Argon	Aluminium	D	1.6 W/m^2K
Aluminium	Argon	Silicone Rubber	D	1.8 W/m^2K

4.3 Changes to Heating System

Of the total energy supplied to dwelling, on an average, 62% is utilised for space heating and another 21% is utilised for hot water (Cheng & Steemers, 2011; Palmer & Cooper, 2011). As heating energy is the largest contributor to the total energy demand, efficient heat provision is the major aspect of energy performance improvement. One of the most efficient ways of providing heat demand is installation of condensing boilers and heating controls within the dwelling (Peacock, et al., 2007). The English Housing Survey estimates that currently only 8% of all dwellings have a condensing boiler, which are the dwellings also likely to have installed heating controls (Communities and Local Government, 2012). Thus installation of condensing boilers and heating controls present an enormous potential towards reducing heat demand the options for which are described in sections below.

4.3.1 Condensing Boilers

Installation of boilers peaked in Britain in the late 1960s when central heating started replacing fireplaces. Most boilers installed then had efficiency of about 55-60%, which increased to about 70% by the early 1980s (Utley & Shorrock, 2008; Everett, 2007). Condensing boilers are high efficiency gas-

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[14] Source (BRE/EST, 2007)

fired air or water heaters that were introduced in the 1980s, and are very similar to the standard boilers popular throughout Europe. An enlarged or secondary heat exchanger is used to reduce the flue exit temperature from around 150°C to 50°C; thus extracting more energy from the fuel and increasing the efficiency of the boiler (Energy Saving Trust, 2003).

Condensing boilers offer the highest efficiency of any gas-based heating technology, with manufacturers claiming to attain up to 98% higher heating value (Veissman, 2007). Seasonal Efficiency of Domestic Boilers in the UK (SEDBUK) laboratory tests indicates seasonal efficiencies up to 93% from the best performing boilers (DEFRA, 2012). There are two types of condensing boilers viz., regular and combination. The regular boilers use a storage tank for hot water, whereas combination boilers provide hot water and space heating on demand and require no storage. The efficiency of regular boilers is about 3% higher than the combination boilers. However, the regular boilers are expected to deliver 5% less useful energy due to losses from storage tank and pipework (Orr, et al., 2009).

Condensing boilers have become mandatory in the UK owing to their improved efficiency. The Building Regulations require all new and replacement boilers to be condensing 'A' rated[15] boilers with a minimum efficiency of 88% (Office of the Deputy Prime Minister, 2005). Installing condensing boiler not only increases the efficiency of the operation, but forms a good alternative for dwellings having electrical storage heating as the CO_2 emissions factor for gas or biomass boiler is significantly less.

The principle of operation of condensing boilers is relatively simple. Further, with the increased scale of manufacturing, condensing boilers are one of the cheapest of all available heating technologies and come with a life time of about 15 years (Staffell, et al., 2010). A typical 24 kW_{th} boiler costs about £800 with an £20 per additional kW_{th}. Replacing existing boilers with condensing may require upgrade to the existing fuel supply, plumbing and electrical systems. There are extensive safety regulations, which the installers and the boiler manufacturers need to comply, which are labour

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[15] Boiler rating as defined in SEDBUK (DEFRA, 2012)

intensive. Depending on the amount of work required, this may increase cost of installation by another £1,200-£1,500 (Staffell, et al., 2010). As with standard boilers, it is a good practice to undertake annual maintenance of the condensing boilers which can cost an additional £25-£50 per annum to prevent any breakdowns (Which?, 2012).

4.3.2 Heating Controls

Although most dwellings now have some form of central heating, a significant amount of heat is lost due to lack of heating controls (Shipworth, 2011). Dwellings may have either central, room or storage heating. However, the heating needs to operate only when required and should produce heat adequate to meet the required temperature. It is mentioned earlier that regular boilers loose heat from storage tank and pipe work. These losses can be significantly reduced by installing boiler interlocks, storage cylinder and room thermostats, insulating cylinder and pipework and installing thermostatic radiator valves.

Boiler interlock is an arrangement of the heating system controls (room thermostats, programmable room thermostats, cylinder thermostats, programmers and time switches) in such a way to ensure that the boiler does not operate when there is no demand for heat (Pushkar, 2011).

Storage cylinder thermostat switches on and off the heat supply from the boiler to the hot-water cylinder. It works by sensing the temperature of the water inside the cylinder, switching on the water heating when the temperature falls below the thermostat setting, and switching it off once this set temperature has been reached (Isaacs, et al., 2008). Room thermostats are similar to the cylinder thermostats; however they sense the temperature of the air in the room. Room thermostat switches on the central heating when the temperature falls below the thermostat setting, and switching it off once this set temperature has been reached (Scott, et al., 2011). Larger houses should be divided into zones with time and temperature controls for each. Programmable thermostats further allow for different time and temperature settings for each day of the week. Thermostatic radiator valves sense the temperature of the air around and regulate the flow of the water through the radiator they are attached to. Thermostatic radiator valves do not control the operation of the boiler and hence are not considered an alternative to room thermostats, but an additional heating control (Tahersima, et al., 2011).

Pipe and cylinder insulation work on the same principles as wall, roof and floor insulation i.e. by adding a layer to reduce losses. The materials used for pipe and cylinder insulation are similar to that described earlier. Pipe insulation typically comes in 20 mm thickness and cylinder insulation comes in 80 mm thickness (Energy Saving Trust, 2012e).

Installing various heating controls above can reduce the heat loss from storage and distribution by over 20%. Boiler interlocks, thermostats and thermostatic radiator valves can cost up to £200 for purchase and installation. They not only help in reducing heat loss but also increase the comfort level in the household. The pipe insulation and cylinder jacket cost about £25 and do not need services of a professional installer. The life times of these heating controls can be several decades and require no maintenance.

4.4 Solar Panels

Installation of solar panels is one of the most prolific and well-publicised forms of renewable micro-generation technologies. There are two solar technologies available viz., solar photovoltaic (Solar PV) for generation of electricity and solar thermal for generation of hot water. Solar panels offer zero-carbon energy with no reliance on fuel purchase. The UK receives an average of 1050‑1250 kWh/m of solar energy per year (on an optimally inclined plane, annual horizontal irradiance is around 875‑1075 kWh/m (Šúri, et al., 2005). Though solar power varies throughout the day and seasons, it has a predictable manner and the energy yield can be estimated with reasonable accuracy (Jardine & Lane, 2002). The durability and reliability of solar panels is high as there are no moving parts or organic materials involved. It is typical for PV modules to have a guaranteed lifetime of at least 25 years, and advanced ageing techniques suggest that modules could last more than 50 years before falling below their guaranteed output voltage (Wohlgemuth, et al., 2005).

Of the 24 million dwellings in UK, only 120,000 dwellings currently have any form of solar panels installed (Palmer & Cooper, 2011). Solar panels thus represent a huge potential for generating zero-carbon energy. Solar panels require little maintenance such as occasional cleaning the surface to remove dust or bird droppings and over-shading due to trees (Energy Saving Trust, 2012f).

4.4.1 Solar PV

Solar PV consists of semiconducting materials that convert energy from sunlight into electricity. The panels generate direct current which is then fed to an inverter which converts it into alternating current for use within the house or export to the grid. The PV cells have traditionally been made of silicon, however several other types of materials are described in Table 4-5.

The first generation materials are currently the ones most widely installed and have higher efficiencies; however, these materials are costly. The second generation materials were developed to lower the cost and offer easy integration into the roof tiles; however, they also offer less efficient (Ekins-Daukes, 2009). Solar PV modules are available in 1 m×1.6 m size with a peak power generating capacity of around 0.22 kW. Thus a typical dwelling roof-top installation may have 9-18 modules arranged in an array, depending on available roof area thus offering a 2-4 kW_{pk} power generating capacity (Staffell, et al., 2010; Peacock, et al., 2007).

Depending on the size of installation, Solar PV can supply two-thirds of the total annual electricity demand of the dwelling. It is noticed from several installation studies that the long-term rate of power loss of Solar PV is very low, with 0.6% and 0.3% decrease per year seen over 27 and 14 years respectively (Tang, et al., 2006).

Table 4-5: Solar PV: Types, Efficiency and Yield[16]

Material	Typical Efficiency (%)	Highest Efficiency (%)	Annual Energy Yield (kWh/kW$_{pk}$)
First Generation			
Mono-crystalline Silicon	15	23	710-790
Multi-crystalline Silicon	8-12	15.5	690-800
Heterojunction with Intrinsic Thin Layer	16-23	-	~750
Second Generation			
Amorphous Silicon	4-6	10.5	620-900
Cadmium Telluride	7	11	560-760
Copper Indium and Galium	9	13.5	820-1000

Solar PV along with its components and installation currently cost £5,000-£9,000 depending on the type of panel and number of modules (Bergman & Jardine, 2009). The electricity generated from the Solar PV not only offsets the electricity that needs to be drawn from the grid but is also eligible for feed-in-tariff and the current rate is £0.1544/kWh. Electricity that is not used within the house can be exported to the grid and is eligible for an additional export tariff of £0.045/kWh (HM Government, 2013a).

4.4.2 Solar Thermal

The concept of using solar energy to heat water has been around for several decades, even pre-dating the widespread use of electricity and gas for heating (Perlin, 1999). Heat from the sun is absorbed by the black surface of a solar collector. A working fluid (often water plus antifreeze) is pumped to

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[16] Source (Staffell, et al., 2010)

the surface of this collector, transferring heat to the exchange coil at the bottom of a water storage tank inside dwelling.

There are two main types of solar collector: flat plate and evacuated tube. In a flat plate system, solar heat is absorbed by a flat metallic surface with a selective black coating, to allow good absorption and low re-radiation of the heat. Evacuated tube systems vary in their design, but all contain several partially evacuated glass tubes with a selectively coated heat absorber. They offer higher efficiency than flat plate collectors, and can deliver higher temperature water as heat losses in the collector are reduced. However, they are more complex and energy intensive to manufacture, making them more expensive. The only energy input required for operation is for the control system and pump that circulates the working fluid (Staffell, et al., 2010).

Solar thermal panels are available in module sizes similar to that described for Solar PV. Domestic installations typically use about 4-8 m^2 of panel or tubes, and generate up to 1000 kWh of hot water per annum (Martin & Watson, 2001). Solar thermal panels are suitable for houses that have storage cylinder or have space to install storage cylinder. Solar thermal panels can cost £5,000-£8,000 including installation and plumbing depending on the type and number of modules (Bergman & Jardine, 2009). Solar thermal panels may in future be eligible for renewable heat incentive and a rate of £0.173/kWh is currently under consultation (HM Government, 2013b).

4.5 Micro-Combined Heat and Power Units

Micro-Combined Heat and Power (µ-CHP) units are means of cogeneration – a process of heating water and producing electricity simultaneously, however on a domestic level instead of large industrial scale and hence the term ‘micro’. Several µ-CHP technologies have been developed over the years that convert chemical energy within fuel into useful heat and electricity (Kopanos, et al., 2013). They can be classified into combustion and electrochemical technologies. Combustion technologies consist of internal combustion engines (IC) and Stirling engines. They are based on principle of combustion and the subsequent conversion of heat into mechanical energy through a piston-cylinder arrangement that drives a generator for electricity generation. Electrochemical technologies consist of solid oxide fuel cells and polymer electrolyte membrane fuel cells and are based on the direct conversion of the fuel’s chemical energy into electrical energy (Pehnt, et al., 2006).

4.5.1 IC Engines

IC engines are similar to automobile engines and hence are reliable and a proven technology. They are based on spark ignition typically fuelled by natural gas. The fuel is ignited by a spark which forces the piston to drive a crankshaft mechanism connected to an alternating current generator (Onovwiona & Ugursal, 2006). Field trials of μ-CHP based on IC engines have demonstrated up to 25% electrical and 85% total efficiency (Carbon Trust, 2007). Emissions from IC engines are typically the highest of any micro-CHP technology owing to the combustion within the engine with up to 270 mg nitrogen oxide and 50 mg carbon monoxide produced per kWh of fuel burnt. Some IC engines however have catalytic converters that reduce nitrogen oxide to 80 mg and carbon monoxide to zero. IC engines have high operating noise levels, making them unsuitable for dwelling installations. Complete systems are generally larger and heavier than a condensing boiler and thus need to be floor-standing units. IC engine units currently available generate upto 36 kWth and 5 kWe energy and cost about £14,000 including installation (Teekaram, 2005). Electricity generated from IC engines is currently not eligible for feed-in tariffs. Due to high initial costs, no incentives for electricity generation and limitations in installation due to excessive size, IC engines are not considered as an improvement measure in this study.

4.5.2 Stirling Engines

In Stirling engines, the combustion of fuel occurs outside the cylinder, which are completely sealed and filled with light pressurised gas. Combustion is continuous and more tightly controlled than with explosive internal combustion, removing the need for catalytic converters and reducing engine noise levels (Onovwiona & Ugursal, 2006). Combustion chambers are smaller and hence the size of the Stirling engine is smaller and is comparable to traditional wall mounted boilers. The predominant fuel used in Stirling engine is natural gas. However, as the combustion is happening outside the cylinder, the choice of fuel used is wide and includes use of biomass, having much less CO_2 emissions factor than conventional fuels. Stirling engines produce significantly more heat than electricity, and being heat driven can only produce electricity intermittently during summer (Staffell, et al., 2010). Field trials of Stirling engines have indicated an electrical efficiency up to 12% and total efficiency of up to 88% (Carbon Trust, 2007). Sterling engines though being expensive due to precision engineering are highly subsidised in the UK market and hence cost around £3,000 including installation (Harrison, 2010). The costs are hence comparable to condensing boilers. Sterling engines require annual maintenance which can cost an additional £50 over conventional maintenance costs. The durability of Stirling engine is currently under investigation as the technology is only a few years old. However the units are expected to last for over 15 years (Staffell, et al., 2010). The electricity generated from Sterling engine based μ-CHP units is eligible for feed-in-tariff at the current rate of £0.1544/kWh and an additional £0.045/kWh for export to the grid (HM Government, 2013a).

4.5.3 Fuel Cell

Fuel cells work on a completely different principle to the combustion technology. They convert fuel into direct current instead of mechanical energy. Fuel cells not only require precision engineering but also exotic materials. Polymer electrolyte membrane fuel cells use hydrated fluoropolymer composites and small quantities of platinum as a catalyst. Solid oxide fuel cells (SOFC) use fragile, 10 – 100 μm thick ceramic composites and chromium alloys (Hawkes & Brandon, 2009). Fuel cells offer significantly higher electrical efficiency than combustion engines with some trials measuring up to 33%. Their total efficiency is currently lower than combustion engines at 75%, owing to their relative immaturity and difficulties in capturing low-grade waste heat (Hawkes, et al., 2009). Fuel cells however are currently the most expensive form of micro-CHP at present costing over

£16,000/kWe including installation. The reasons for high cost are most models are pre-commercial designs and mass production is expected to bring this cost down in future (Staffell & Green, 2009). As the technology is still under development, the reliability of this technique is unknown. Further, fuel cells are currently not eligible for feed-in-tariff and hence have no incentive for financial returns. This technology is therefore not considered as an improvement measure in this study.

4.6 Micro-Wind Turbines

Wind energy has been harnessed for over centuries now and works on the principle of wind rotating blades (or rotor) connected to a turbine that generates electricity. It is one of the cleanest forms of energy and currently the fastest growing energy industry in the world (Shea, 1988). By the end of 2012 more than 200,000 turbines are operating worldwide with power generation capacity in excess of 282 GW (GWEC, 2013). The UK is estimated to have more than 40% of Europe’s land-based wind energy potential and currently ranks as the world’s 6th largest wind energy producer with over 8 GW generation capacity (BRE/EST, 2005; GWEC, 2013). Most of this energy is generated through large scale wind turbines. Micro-wind turbines for dwellings thus present a large untapped potential for energy generation (BWEA, 2008). Mean wind speeds at 50 m above open ground have been measured about 6.5 - 7.5 m/s over most of the country (Petersen & Troen, 1990).

Wind turbine having less than 25 m^2 swept area is classified as micro-wind turbine. μ-wind turbines (<0.5 kWp) have historically been used in the UK for off-grid battery charging applications, most notably on sailing boats and hence is an established technology (James, et al., 2010). Contrary to the traditional 3 blade design of large scale turbines, μ-wind turbines are available in several types including 2-6 bladed, horizontal, vertical and cross-flow axis and building augmented turbines (Allen, et al., 2008). μ-turbines are now designed to minimise noise and vibration, and are able to operate in more turbulent conditions, with rapid changes in wind speed and direction (Staffell, et al., 2010).

Horizontal axis wind turbines are the most common and well-developed types of micro-wind turbines, offering the greatest performance at present. These turbines have typical blade diameter of 1.1 – 5.6 m blade diameter. Table 4-6 below shows the typical rated power of turbines with various blade diameters.

Table 4-6: Wind Turbine: Size and Rated Capacity

Blade Diameter (m)	Rated Power (kW)	Minimum Wind Speed (m/s)
1.1	0.4	2.0
2.1	1.5	2.4
3.5	2.5	3.0
5.4	5.0	3.0
5.5	6.0	2.5
5.6	6.0	2.7

Turbines with blade diameter up to 2.1 m can either be roof mounted or pole mounted, but turbines with blade diameter more than 2.1 can only be pole mounted (Sissons, et al., 2011). Table 4-6 indicates that a minimum wind speed is required for wind turbine to operate. This is because at very low wind speeds, the turbine torque is insufficient to overcome friction and power conversion losses, so no net power is produced. μ-wind turbines are typically designed for wind speed between 3-13 m/s. The turbine power approximately increases with the cube of wind speed, and operate close to optimum efficiency between these speeds. As the wind speed approaches maximum rated design speed (e.g. 13 m/s), the power output levels off as the generator and gearbox are at maximum capacity. In some models, the turbine shuts down at higher wind speeds to protect itself from damage (Staffell, et al., 2010).

Wind turbines are currently subject to Planning Regulations and can only be installed on detached dwellings or within the compounds of detached dwelling if it is a pole mounted turbine (Planning Portal, 2012). The installed cost of μ-wind turbine is between £2,000 for roof mounted to £22,000 for pole mounted. The electricity generated from μ-wind turbines is eligible for feed-in-tariff at the current rate of £0.1544/kWh and an additional £0.045/kWh for export to the grid (HM Government, 2013a). The durability of μ-wind turbines is currently unknown as the technology has no long term experience. However, several manufacturers and organisations expect the lifetime between 15-23 years (Allen, et al., 2008).

4.7 Heat Pumps

Heat pumps operate on the same principle as refrigeration; however in reverse i.e. they extract ambient heat from the environment and upgrade its temperature for space and water heating (Staffel, et al., 2012). Although they require electricity to operate, the majority of the energy harnessed is 'renewable' heat drawn from the environment. Figure 4-1 presents the schematic operation of a heat pump.

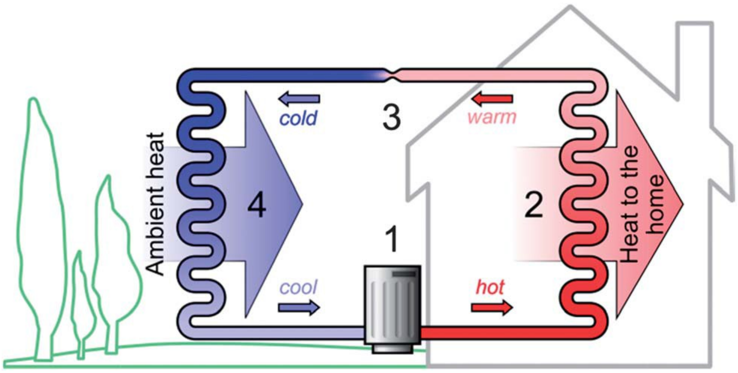

Figure 4-1: Schematic of Heat Pump Components and Cycle[17]

There are four key components in a heat pump: a compressor unit that increases the pressure and temperature of the refrigerant making ambient heat into a useful commodity; an internal heat exchanger, or condenser, that distributes heat to the home or to hot water; an expansion valve, that returns the refrigerant back to below ambient temperature and; an external heat exchanger, or evaporator, which collects heat from the environment.

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[17] Adapted from (Staffel, et al., 2012)

In process (1) (which corresponds to item 1 in Figure 4-1), the working fluid in the dry vapour phase undergoes isentropic compression, heating the gas to a superheated state. This is associated with the introduction of work to the system in the form of electrical power via the compressor. Process (2) first involves removing the superheat and then the heat of condensation. This occurs at constant pressure and is where heat is harvested and delivered to the hotter location. The now liquid working fluid then goes through an expansion valve (3) where its pressure abruptly decreases, causing evaporation with associated absorption of heat from the low temperature reservoir. The liquid-vapour mixture is then completely vaporised by heat input from the cooler environment (4), returning the working fluid to a dry vapour (Banks, 2008).

Heat pump can be divided into two main categories depending on where the outside heat exchanger is placed. When the heat exchanger draws heat from ambient air, it is termed as air source heat pump (ASHP) and when it draws heat from the ground it is termed as ground source heat pump (GSHP) (Staffel, et al., 2012). ASHP are similar to widely used commercial air-conditioners, using a small external heat exchanger and circulating fan. GSHP use plastic tubes laid underground as an external heat exchanger. These can be laid horizontally at a depth of up to 2 m, which requires extensive digging for trenches (400-800 m^2 of land) (Greening & Azapagic , 2002).

Heat pumps typically have a compressor that operates on electricity similar to refrigerator compressors. However, alternative designs of heat pump have now been commercialised which are gas driven. Gas engine heat pumps use an internal combustion engine to drive the compressor instead of an electric motor. They utilise the principle of combined heat and power (CHP) by moving the conversion of fuel into mechanical work closer to the end point of use, so that waste heat can be captured rather than lost to the environment (Bakker, et al., 2010).

The efficiency of a heat pump is typically represented by the coefficient of performance (COP) which the amount of heat output per unit of energy consumed. A COP greater than 1 indicates an efficiency of more than 100% i.e. more heat is generated per unit of energy supplied to the heat pump. Table 4-7 shows the annual average COP for types of heat pumps and the compressor power source.

Table 4-7: Coefficient of Performance for Heat Pump Types[18]

Type of Heat Pump	Power Source for Heat Pump Compressor	
	Electricity	Gas
Air Source	2.5	1.1
Ground Source	3.2	1.2

The COP of any heat pump is highly dependent on the temperature difference between the external heat exchanger that collects heat and the output to the home and hot water. In practice COP drops by between 0.6 and 1.0 for every 10^{o}C difference. During the winter there is the greatest demand for heating, when UK air temperatures average around 0^{o}C (Met Office, 2012). GSHPs benefit from the fact that below 2 m depth, ground temperature shows little variation during the year, remaining at around 10^{o}C (Veissmann, 2012).

Heat pumps have long life times as compared to conventional boilers because of their reliability and low maintenance requirements. Compressors can typically last for over 25 years and the heat collectors can last for over 50 years (Bergman & Jardine, 2009). The installed cost of an ASHP of 5-20 kW_{th} capacity is approximately £7,000. GSHP are more expensive at about £10,000 due to added labour costs of trenching the ground for laying of pipes (Energy Saving Trust, 2012g). The operating cost for heat pumps can be high if the compressor is electric powered as electricity is more than four times expensive than gas (BRE, 2011). The heat generated from the heat pumps may in future be eligible for renewable heat incentive and a rate of £0.069-£0.115/kWh is currently under consultation for air source heat pumps

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[18] Source (BRE, 2011)

and a rate of £0.125-£0.173/kWh is currently under consultation for ground source heat pumps (HM Government, 2013b).

4.8 Summary

This chapter presented a review of the interventions that improve the energy performance of dwellings and thus reduce carbon emissions. The interventions presented and their benefits are summarised in Table 4-8.

Table 4-8: Summary of Interventions and their Benefits

	Interventions	Benefit
1	Fabric change	• Installing/external/cavity wall insulation significantly reduces heat loss and reduces the space heating requirement by up to 60%. • Low-e double glazed windows also reduce heat loss and reduce space heating requirement by up to 20%.
2	Heating systems	• Condensing boilers can increase the operating efficiency by up to 20% over conventional boilers thus resulting in less fuel demand • Replacing electrical heating with condensing boilers results in reducing the cost of fuel by over 50% and also reducing the intensity of carbon emissions by over 60%. • Thermostatic radiator valves, cylinder thermostats and jackets can further improve the boiler performance by up to 5%.
3	Solar panels	• Solar panels are zero carbon renewable energy generation technology. • Solar PV generates electricity and can supply up to 100% of dwellings electricity demand. Excess electricity generated can be exported to national grid and receive feed-in-tariff. • Solar thermal panels generate hot water and can supply up to 50% of dwellings hot water requirements. The heat generated may be

	Interventions	Benefit
		eligible for renewable heat incentive in future.
4	Micro-combined heat and power units	• μ-CHP is a low carbon energy generation technology. • It generates electricity while meeting the heating demand of the dwelling. • It can supply up to 50% of dwellings electricity demand and any excess generation can be exported to grid and receive feed-in-tariff.
5	Micro-wind turbine	• μ-wind turbine is a zero carbon renewable electricity generation technology. • It can supply up to 100% of dwellings electricity demand. Excess electricity generated can be exported to national grid and receive feed-in-tariff.
6	Heat pumps	• GSHP and ASHP are low carbon energy generation technologies due to their higher COP. • They can supply entire heat demand of the dwellings and may be eligible for renewable heat incentive in future.

The impact of these technologies in improving the performance such as decrease in U value, increase in efficiency and ability to harness natural resources has been discussed in detail. The expected lifetimes, capital cost and annual maintenance costs for all these interventions have been presented in this chapter. These details are used in later chapters to enable construction of scenarios for improvement and quantify the energy and carbon reduction potential.

Chapter 5 Decision Support Tools

5.1 Introduction

In the previous chapter we have seen that there are several interventions available to improve the energy performance of dwellings. These interventions come with varying levels of efficiency improvement, CO_2 emission reductions and associated costs. The decision on what interventions are to be chosen for a particular area is complex as it relies on the emission targets to be reached, investment potential and social perception. Selecting the alternatives can thus be challenging for stakeholders involved in decision making process. The review of existing energy models has identified that none of them adequately assist stakeholders in appropriate decision making. One of the outcomes of the discussions with the stakeholders is the necessity of an integrated decision support tool with the energy assessment technique. This chapter reviews the various techniques currently being used to support decision making and select a technique that can be integrated in this research. Integration of decision support tool will also assist stakeholders in meeting the requirements of the LDF.

5.2 Overview of Techniques

Traditional single criteria decision making is normally aimed at maximization of benefits with minimization of costs. During the 1970s, energy planning efforts were directed primarily towards energy models aimed at exploring the energy–economy relationships established in the energy sector. The main objectives followed were to accurately estimate future energy demand. A single criteria approach aimed at identifying the most efficient supply options (Samouilidis & Mitropoulos, 1982). In the 1980s however, considerations regarding the environmental and social awareness greatly improved and decision making efforts had to be modified which resulted in development of multi-criteria approaches (Nijcamp & Volwahsen, 1990).

Complex decision making methods deal with the process of making decisions in the presence of multiple parameters. A decision-maker is required to choose among quantifiable or non-quantifiable and multiple criteria (Putrus, 1990). The parameters may be conflicting and therefore, the solution is dependent on the preferences of the decision-maker which could be a compromise. In most of the cases, different groups of decision-makers are involved in the process. Each group brings along different criteria and points of view, which must be resolved within a framework of understanding and mutual compromise (Afgan, et al., 1998).

Although multi-criteria decision making approach appears to be an ideal method to support the trade-off for this research, the selection process for the right method itself is fairly complex. It is crucial for decision makers to select the right method because a wrong choice of method may cause a misleading solution, a waste of time and resources and the users might lose confidence in the implementation of technique (Tecle, 1992). Hence, a comprehensive review of multi-criteria decision making techniques is undertaken.

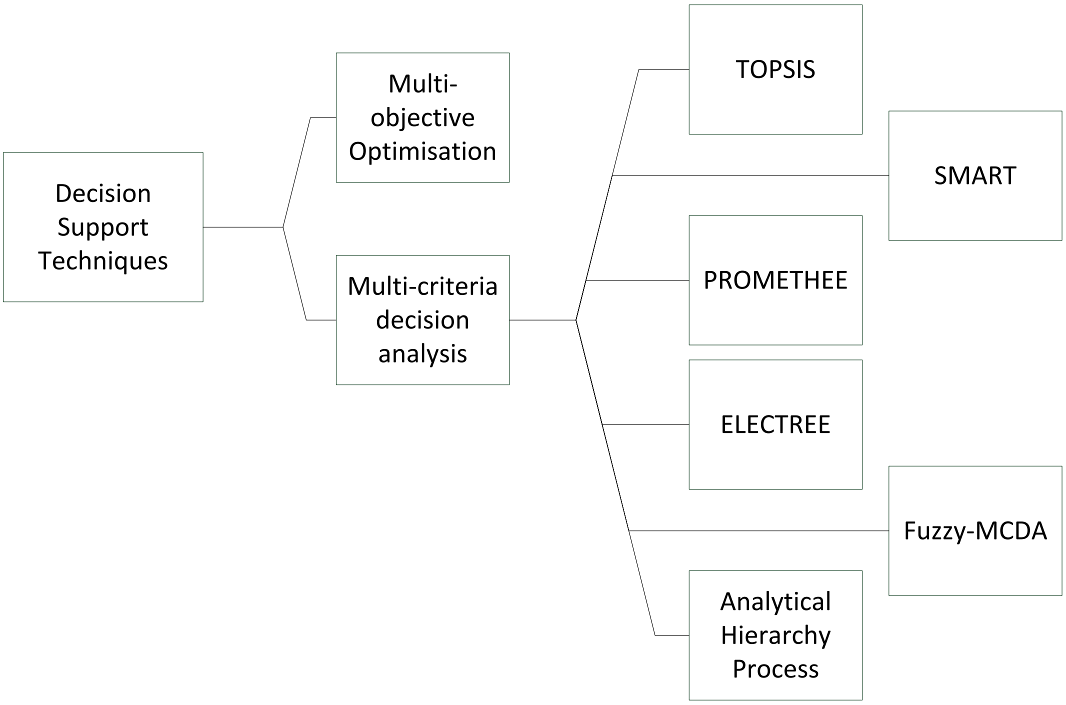

Figure 5-1: Classification of Decision Support System

Figure 5-1 presents the general classification of decision support techniques and is described in detail in sections below (Jahan, et al., 2010; Wu, et al., 2009).

5.3 Multi-Objective Optimisation

Multi-objective optimisation as the name suggests, is used in problems which have more than one objectives involved and have to be optimised against a particular function. This method is very widely used in energy resource allocation, energy planning and electric utility applications. Maximization of cost benefit ratio to arrive at optimum resource allocation in rural areas and national level energy planning are amongst a few applications (Christensen & Vidal, 1990). The application areas have common features of higher investment costs, higher project durations, conflicting objectives and uncertainty (Lootsma, et al., 1990).

Genetic algorithm is the most commonly applied technique in multi-objective optimisation and has been used for regional energy supply optimization, electricity distribution planning and desalination power plant selection (Amagai & Leung, 1989; Akash, et al., 1997; Levitin, et al., 1995). The algorithms are similar to the natural evolution process where a population of a specific species adapts to the natural environment under consideration. A population of designs is created and then allowed to evolve in order to adapt to the design environment under consideration. The key feature of genetic algorithm is the manipulation of a population whose individuals are characterized by possessing a chromosome. It can later be coded as a string of characters of given length. Each string represents a feasible solution to the optimization problem. A chromosome is composed of strings of symbols called bits (in this case binary). Each bit is attached to a position within the string representing the chromosome to which it belongs. If, for example, the strings are binary, then each bit can take any value of 0 and 1. The link between the genetic algorithm and the problem at hand is provided by the fitness function. The fitness function establishes mapping from the chromosomes to some set of real numbers. The greater the fitness function, the better is the adaptation of the individual (Haldenbilen & Ceylan, 2005).

The advantage of multi-objective techniques such as genetic algorithm is the ability to use accumulating information about initially unknown search space in order to bias subsequent searches into useful subspaces. This can however also be a drawback as these techniques work well only when the alternatives are not pre-determined and set of objectives are optimised for given constrains. In this research, there are no multiple objectives that need to be optimised as the only objective is to improve energy performance. Further, the interventions through which this can be achieved are also known and discussed in Chapter 4. Multi-objective optimisation techniques and genetic algorithms are therefore not suitable for this research.

5.4 Multi-Criteria Decision Analysis

Multi-Criteria Decision Analysis (MCDA) are also commonly known interchangeably as Multi-criteria Decision Aid, Multi-criteria Decision Making and Multiple Criteria Decision Methods (Mysiak, 2006). It differs from the Multi-objective optimisation techniques, as MCDA techniques do not optimise the input data. The output of the MCDA instead informs which alternatives are best suited for particular conditions of criteria. MCDA have been widely used in renewable energy planning, energy resource allocation, building energy management, transportation energy management, planning for energy projects and electric utility planning (Huang, et al., 1995; Hobbs & Meirer, 1994). The commonly applied MCDM methods are Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS); Simple Multi Attribute Rating Techniques (SMART); Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE); Elimination and Choice Translating Reality (ELECTRE); Fuzzy-MCDA and Analytical Hierarchy Process. More than one MCDA method is also applied in many application areas (Mirasgedis & Diakoulaki, 1997; Salminen, et al., 1998). A review of these techniques is presented in the following sections. Some of the features are:

- MCDA offers creating a structure of framework for decision making.
- Multiple sets of criteria can be created in MCDA to trade-off between alternatives.

- MCDA allows stakeholders to consider more than one potential use of alternatives.
- MCDA often allow for a better evaluation consistency in situations of risk/uncertainty.
- MCDA assists in generating common interest among multiple stakeholders’ criteria and alternatives and facilitates negotiation.
- MCDA can be well documented and hence the decision processes enables efficient communication.

5.4.1 TOPSIS

The technique for order preference by similarity to ideal solutions (TOPSIS) is developed by Huang & Yoon (1981). The basic concept of TOPSIS is that the selected alternative should have the longest distance from the negative ideal solution in geometrical sense. The method assumes that each attribute has a monotonically increasing or decreasing utility. This makes it easy to locate the ideal and negative ideal solutions. Thus, the preference order of alternatives is yielded through comparing the Euclidean distances. A decision matrix of *M* alternatives and *N* criteria is formulated firstly. The normalized decision matrix and construction of the weighted decision matrix is carried out. This is followed by the ideal and negative-ideal solutions. For benefit criteria the decision maker wants to have maximum value among the alternatives and for cost criteria he wants minimum values amongst alternatives. This is followed by separation measure and calculating relative closeness to the ideal solution. The best alternative is one which has the shortest distance to the ideal solution and longest distance to negative ideal solution.

TOPSIS is a useful technique in dealing with multiple attribute decision making problems. It has been successfully applied to the areas of human resources management, transportation, product design, manufacturing, water management, quality control, and location analysis (Lee & Lin, 2011). TOPSIS however has its drawbacks. The alternative preference is generated through Euclidean distances. If other distance measurement techniques are used, then the preference ranking could be different. The system does not compensate for this (Triantaphyllou, 2000). TOPSIS however relies on an assumption that the criteria for decision making are monotonically increasing or decreasing (Huang & Yoon, 1981). This means that an analytical or empirical function exists or should be established between the criteria. This may be possible for criteria solely relying on tangible parameters. As this research relies on intangible parameters, where such function cannot be established, TOPSIS does not fit the requirements of this research.

5.4.2 PROMETHEE

Preference ranking organization method for enrichment evaluation (PROMETHEE) was developed by Brans, et al., (1986) and uses the outranking principle to rank the alternatives. It performs a pair-wise comparison of alternatives in order to rank them with respect to a number of criteria (Pohekar & Ramachandran, 2004). The method uses preference function $P_j(a,b)$ which is a function of the difference d_j between two alternatives for any criterion j, i.e. $d_j = f(a,j) - f(b,j)$, where $f(a,j)$ and $f(b,j)$ are values of two alternatives a and b for criterion j. The indifference and preference thresholds q' and $p'$are defined depending upon the type of criterion function. Two alternatives are indifferent for criterion j as long as d_j does not exceed the indifference threshold q'. If d_j becomes greater than p', there is a strict preference. Multi-criteria preference index, $\pi(a,b)$ a weighted average of the preference functions $P_j(a,b)$, for all the criteria is defined as:

$$\pi(a,b) = \frac{\sum_{j=1}^{J} w_j P_j(a,b)}{\sum_{j=1}^{J} w_j}$$

$$\Phi^{+} = \sum_{A} \pi(a,b)$$

$$\Phi^{-} = \sum_{A} \pi(b,a)$$

$$\Phi(a) = \Phi^{+}(a) - \Phi^{-}(a)$$

Where,

w_j is the weight assigned to the criterion.
$\Phi^+(a)$ is the outranking index of a in the alternative set A.
$\Phi^-(a)$ is the outranked index of a in the alternative set A.
$\Phi(a)$ is the net ranking of a in the alternative set A.

The value having maximum $\Phi(a)$ is considered as the best. a outranks b if and only if $\Phi(a) > \Phi(b)$.

The advantage of PROMETHEE is that, with this method is possible to put in order a set of alternatives based on their preferences from the best to the least quality. However, the drawback of this method is that it considers six generalized criteria functions viz., usual criterion, quasi criterion, criterion with linear preference, level criterion, criterion with linear preference and indifference area, and Gaussian criterion. The user of this method has to tailor their criteria to suit these requirements (Ocelíková & Klimešová, 2010). It is due to this requirement, that PROMETHEE gives incorrect or inconsistent results compared with other techniques such as Analytical Hierarchy Process (Pohekar & Ramachandran, 2004). This technique is thus not considered for this research.

5.4.3 SMART

Simple Multi Attribute Rating Techniques (SMART) is based on Ward Edwards' work introduced in 1971. SMART is a 10 step technique that includes a process of identifying objective and organising these into a hierarchy (Edwards, 1971; 1977):

1. Identify the person or the organisation whose utilities are to be maximised.
2. Identify the issue or issues.
3. Identify the alternatives to be evaluated.
4. Identify the relevant attributes of value for evaluation of alternatives.
5. Rank the attributes in the order of importance.
6. Rate attributes in importance, preserving the ratios.

7. Sum the importance weights and divide each by the sum.
8. Measure the location of each alternative being evaluated on each dimension.
9. Calculate utilities for alternatives.
10. Make a provisional decision.

SMART has been widely used to optimise the alternatives as it is simple to use (Goodwin & Wright, 2004). The technique however comes with severe drawbacks as it works well in single criterion problems (Edwards & Barron, 1994). The ranks provided to the attributes in Steps 6 and 7 described above are related to single dimensional attributes. Where multiple attributes (for criteria as well as alternatives) are involved, such as this research, the process can become extremely complex and also give erroneous results due to human error. It is also due to the simplicity, it may not capture all the details and complexities of a real problem (Goodwin & Wright, 2004).

5.4.4 ELECTRE

The elimination and choice translating reality (ELECTRE) was developed to handle discrete criteria of both quantitative and qualitative in nature and provide a complete ordering of the alternatives (Roy, 1968). The method allows user to formulate a problem such that it chooses alternatives that are preferred over most of the criteria and that do not cause an unacceptable level of discontent for any of the criteria. The concordance, discordance indices and threshold values are used in this technique. Based on these indices, graphs for strong and weak relationships are developed. These graphs are used in an iterative procedure to obtain the ranking of alternatives (Roy, 1985). This index is defined in the range (0–1) and it provides a judgment on degree of credibility of each outranking relation and represents a test to verify the performance of each alternative. The index of global concordance C_{ik} represents the amount of evidence to support the concordance among all criteria, under the hypothesis that A_i outranks A_k. It is defined as follows:

$$C_{ik} = \frac{\sum_{j=1}^{m} W_j C_j(A_i A_k)}{\sum_{j=1}^{m} W_j}$$

Where,

W_j is the weight associated with the jth criteria.

Finally, the ELECTRE method yields a whole system of binary outranking relations between the alternatives. This method has a clearer view of alternatives by eliminating less favourable ones, especially convenient while encountering a few criteria with a large number of alternatives in a decision making problem. However, the major drawback of the technique is that the system is not necessarily complete; the ELECTRE method is sometimes unable to identify the preferred alternative. It only produces a core of leading alternatives (Goicoechea, et al., 1982). To solve this problem some studies have also used ELECTRE with Analytical Hierarchy Process to identify ranks of alternatives (Afshari, et al., 2010).

5.4.5 Fuzzy-MCDA

The fuzzy-MCDA is based on the fuzzy set theory or fuzzy logic. Fuzzy is defined as something that is blurred, indistinct or fluffy (Oxford University, 1993). In modern mathematical society, fuzzy set or logic is a branch of mathematics that was formulated to model vagueness intrinsic in human cognitive process and to solve ill-defined and complicated problems because of ambiguous, incomplete, vague, and imprecise information that characterize the real-world system (Zadeh, 1965). There is no one defined procedure of implementing fuzzy-MCDA as it is described for other methods in this chapter. It is a concept that has been used in several areas to make intuitive judgement (Chan, et al., 2009).

Fuzzy logic is a superset of boolean conventional logic that has been expanded to handle the concept of partial truth and true values between “completely true” and “completely false” (Zimmermann, 2001). Fuzzy control can be defined as the application of fuzzy logic. In general, the design and setting of fuzzy controllers consist of defining three parameters (Lah, et al., 2005):

- Defining the domain for the input and output of linguistic variables for each fuzzy controller.
- Defining the set and the type of membership function for each linguistic value-input of every fuzzy controller. The relations between inputs and outputs of linguistic values have to be provided in the form of fuzzy rules, which represent logical inference.
- Defining the fuzzy logic operators for each If-Then sentence, as a base for final inference.

Fuzzy techniques are popular in construction related project management where there are several uncertainties that a project may face during its lifetime (Chan, et al., 2009). This research has no inherent uncertainties as the objective and the alternatives are well defined. Further, this research generates objective data for analysis and removes uncertainties related to energy performance improvement decisions. The motive of using fuzzy-MCDA is thus contradicted and hence not considered appropriate for this research.

5.4.6 Analytical Hierarchy Process

Analytical Hierarchy Process (AHP) is developed by Saaty (1980; 1992). The essence of the process is decomposition of a complex problem into a hierarchy with goal (objective) at the top of the hierarchy, criterions and sub-criterions at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy. Many decision problems involve tangible and intangible criteria. Tangibles are the criteria that are physical (can be numerically measured), as they constitute some kind of objective reality outside the individual conducting the measurement. Intangibles are the psychological criteria that comprise the subjective ideas, feelings, and beliefs of the decision maker. The AHP is a method that can be used to establish measures in both the tangible (objective) and the intangible (subjective) domains.

Elements at given hierarchy level are compared in pairs to assess their relative preference with respect to each of the elements at the next higher level. The comparisons are either actual measurements or taken from a fundamental scale that reflects the relative strength of preferences and feelings. Saaty's fundamental scale of 1–9 is used to assess the intensity of preference between two elements. The intensities and their explanation is presented in Table 5-1.

Table 5-1: The Fundamental Scale of AHP[19]

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	One activity is between equal and moderately important over other
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	One activity is between moderate and strongly important over other
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	One activity is between strongly and very strongly important over other
7	Very strong importance	Experience and judgement very strongly favour one activity over another
8	Very, very strong	One activity is between very strongly and extremely important over other

---

[19] Source (Saaty, 2008)

Intensity of Importance	Definition	Explanation
9	Extreme importance	Experience and judgement favour one activity extremely important over another
Reciprocals of the above intensities		If i is 3 times j , i.e. $i = 3j$, then $j = \frac{i}{3}$ or $j = \frac{1}{3}i$

To elicit pair wise comparisons at a given level, a matrix A is created by putting the result of pair wise comparison of element i with element j into the position a_{ji} as below.

$$\begin{bmatrix} a_{11} & a_{12} & . & a_{1n} \\ a_{21} & a_{22} & . & a_{2n} \\ . & . & . & . \\ a_{n1} & a_{n2} & . & a_{nn} \end{bmatrix}$$

AHP computes and aggregates the eigenvectors of the matrix until the composite final vector of weight coefficients for alternatives is obtained. After obtaining the weight vector, it is then multiplied with the weight coefficient of the element at a higher level (that was used as criterion for pair wise comparisons). The procedure is repeated upward for each level, until the top of the hierarchy is reached. The entries of final weight coefficients vector reflect the relative importance (value) of each alternative with respect to the goal stated at the top of hierarchy. A decision maker may use this vector to suit their particular needs and interests. One of the major advantages of AHP is that it calculates the inconsistency index as a ratio of the decision maker's inconsistency and randomly generated index. This index is important for the decision maker to assure that the judgments are consistent and that the final decision is made well. The inconsistency index should be lower than 0.10. Although a higher value of inconsistency index requires re-evaluation of pair wise comparisons, decisions obtained in certain cases could also be acceptable (Pohekar & Ramachandran, 2004). AHP does have a limitation of up to 15 attributes in each hierarchy as more attributes lead to inconsistent results (Saaty, 1992).

Pohekar & Ramachandran (2004) have reviewed over a hundred different case studies where some forms of MCDA have been used. Their analysis indicates that AHP is the most widely used technique with over 25% cases preferring it. The application areas include renewable energy planning, energy resource allocation, transportation energy system, project planning and electric utility planning (Akash, et al., 1997; Ramanathan & Ganesh, 1995; Elkarni & Mustafa, 1998).

AHP fits the requirements of this research as the objective, alternatives and the tangible and intangible criteria are well defined and have less than 15 attributes in each hierarchy. AHP also overcomes the limitations presented for the methods described earlier such as: the criteria need not have analytical or empirical relation between them as required for TOPSIS; the criteria are not generalised as in PROMETHEE and are specified and ranked by the user; multiple dimensional attributes and complexities are acceptable contrary to the case in SMART; it not only identifies the preferred alternative but identifies the rank for all which is not the case in ELECTRE; and it enables decision making in certain or uncertain conditions unlike fuzzy-MCDA. AHP is hence selected as a decision support tool for this research.

5.5 Criteria for Selection of Interventions

The selection of interventions depends on several criteria that are of importance to stakeholders. It is therefore essential to understand what these criteria are so that they are included in the decision support tool developed as a part of this research. This requirement is met using two methods: literature review and discussions with the stakeholders. The literature review identified the commonly used selection criteria. The identified criteria are then compared vis-à-vis the requirements of this research and range of criteria are then selected. These criteria are then presented to the stakeholders. Based on the opinion of the stakeholders, the final list of criteria is selected.

Beccali, et al., (1998) undertook a case study for technology selection for energy planning for Sardinia, Italy. The criteria for the selection of technology included: targets of primary energy saving in regional scale; primary energy saved; sustainability in terms of CO_2 and other pollutants; reliability of technology; installation and maintenance requirements and labour impact. The choice of technology included solar energy, wind energy and CHP.

Aras, et al., (2004) adopted a multi-criteria selection approach for projecting wind power stations using analytical hierarchy process. The criteria included: cost for establishment and maintenance; topography of the region; access to infrastructure; and convenience of set-up. The results from their study indicate topography of the region was ranked as the most important criteria for site selection.

Nigim, et al., (2004) undertook a prefeasibility study for prioritising local renewable energy resources using AHP as their MCDA approach. Their criteria for prioritising the alternatives were categorised into: human/environmental impact which consisted of ecological impact, social and economic benefits and educational potential; and project feasibility which consisted of resource availability, technical feasibility and financial viability. The study included solar photovoltaic, solar thermal, wind power, geothermal and micro-hydro as the renewable energy options.

Arán Carrión, et al., (2008) evaluated site options for installation of grid connected solar photovoltaic power plant in Andalusia, Spain. The multi-criteria analysis on this instance was undertaken using AHP. The criteria for site selection are categorised into: environment which included land use and visual impact; orography which included slopes and orientation; location which included access to highways, substations and urban areas; and climate which consists global irradiance, diffuse radiation; equivalent sun hours and average temperature. The analysis of their results indicates that climate is the most important category with equivalent sun hours ranked as the most important criteria.

Terrados, et al., (2009) proposed a methodology for renewable energy planning applicable for regions in Spain based on MCDA. The methodology adopted SWOT and Delphi analysis for options such as electric power generation using biomass, hydroelectricity, isolated and grid-connected photo-voltaic systems, wind energy and thermal energy using solar and biomass. The criteria for selection of the technology were categorised into technical which included primary energy saved, maturity and know-how and resources available; environmental which included sustainability based on CO_2 and other pollutants; and socio-economic which included job creation. The results do not indicate the ranking of the criteria; however, the potential of energy generation using these technologies has been identified and indicates biomass as the most useful resource.

Heo, et al., (2010) and Erol & Kilkiş (2012) have undertaken similar studies for energy source assessment. They inform government policies in meeting energy targets through renewable and conventional sources in Korea and Turkey respectively. Both studies have used AHP to rank the criteria and the alternaties to generate an order of preferred energy technologies. The criteria involved are categorised as: technological covering superiority, completeness and reliability; market covering domestic and national market size and competitive power; economic covering supply capability, feasibility and durability; environmental covering reduction in greehouse gas and pollutants and acceptability by local residents; and policy covering the possibility towards achieving the goals.

The review of the above literature indicates that the selection of alternatives mainly depends on the technological, environmental, social and economic criteria. There are several factors included within these criteria, however, the geographic scale for which these studies have been undertaken also have to be considered. Most studies described above were undertaken to inform national policies or attempt to meet national targets. Hence, the studies described above consider wider economic factors such as the demand and supply in the markets. This rearch attempts to assist stakeholders on implementaiton of energy policies on a neighbourhood to a local council level. The development of energy policies have been undertaken based on the reliability, availability and market economics of various techniques. Based on the review and analysis presented, the following criteria are deemed important for ranking the interventions presented in Chapter 4:

- Technological criteria: Consisting factors such as applicability of technology to the dwelling/area under consideration, the annual energy savings achieved and ease of implementation.
- Environmental criteria: Consisting factors such as the annual reductions in CO_2 emissions achieved.
- Economic criteria: Consisting of factors such as cost of installation, grants available from grovernment or energy suppliers, annual maintenance cost and annual returns based on cost of energy saved from the grid and feed-in-tariff or renewable heat incentive.
- Social criteria: Consisting of factors such as acceptability by local residents and local planning restictions.

The selected criteria and their respective factors were then discussed with all the stakeholders listed in Table 3-1 as a part of the engagement process during this research. All the stakeholders indicated that the criteria presented to them are in line with the requirement of the LDF, energy policies and their expectations. However a common opinion amonsgst all stakeholders involved was that they preferred to have minimum hierarchy levels in decision making process so as to reduce the amount of time required and also eliminate any complexities. The stakeholders indicated that most of their current decision making though ad-hoc is goverened by the economic criteria and hence factors related to them must be given importance. Based on these discussions, it was decided to consider the following criteria for decision support tool:

- Annual reduction in CO_2 levels.
- Initial investment (capital cost and grants received though government policies).
- Return on investment (annual running cost to user and savings made through feed-in-tariff and renewable heat incentive).

- Social Acceptability (personal likeliness towards intervention and local planning restrictions).
- Ease of implementation (access to technology, resources and timeline).

By removing the factors, one level of hierarchy is eliminated from the decision making process. The annual reductions in CO_2 levels has been chosen as a selction criteria over the annual savings in energy as the emission targets are related to reduction in CO_2 levels. Initial investment and the return on investment are both selected as economic factors are an important aspect of decision making process.

5.6 Summary

This chapter has presented an extensive review of the decision support tools most widely used. MCDA techniques were reviewed in further detail as the research deals with multiple criteria rather than multiple objectives. The study of various techniques revealed that AHP is the applicable technique for this research and also it is the most widely used technique in energy planning. Literature reviewed was reviewed to understand the criteria commonly used for ranking the alternatives. A final list of criteria is chosen based on discussions with the stakeholders.

Chapter 6 Framework Development

6.1 Introduction

The previous chapters have presented an extensive review of literature on methods of assessing dwelling energy performance, common energy performance improvement practices and the decision support tool. The next major objective of this research is to develop a framework for prototype development. Developing a software based tool involves decomposing complex problems into a number of simpler problems. The decomposition of the tool can be undertaken in two types based on the structural and behavioural aspects respectively (Schnieders, et al., 2004). The structural aspects define 'what' needs to be provided by the tool (e.g. which tasks, activities, etc.). The behavioural aspects define 'how' the tool acts in order to fulfil a task. It thus provides information about the dynamic behaviour of the system. This chapter focuses on the structural aspect of the development process and presents a framework for development of the tool to (i) estimate the baseline energy performance of dwellings; (ii) estimate impact of energy performance improvement scenarios; and (iii) assist stakeholders in decision making. These functionalities of the tool seek to address the limitations of the existing models, methods and tools and meet the requirements of the stakeholders identified in earlier chapters.

6.2 Framework Methodology

There are two common methods of describing the functional aspects of a tool. One method is using data flow diagrams which have been developed by (Yourdon & Constantine, 1979) and the other is structured analysis and design technique developed by (Marca & McGowan, 1988). Both the methods are based on graphical notations used to describe information flows among processes being documented. There are differences in the graphical symbols being used in each method as well as some differences in emphasis on the kind of information that is to be captured or presented in the documents. A data flow diagram is a good method for depicting the flow of data through a system; however, it has limitations describing the analytical models which form a major part of technique development in this study. Structured analysis and design technique not only has abilities to describe analytical functions, but also physical and manufacturing aspects of a system (Boucher & Yalcin, 2006). This technique has been adapted in the function modelling industry as integrated computer-aided manufacturing definition 0 (or commonly known as IDEF0) (Bider & Johannesson, 2005). The building block of IDEF0 is the activity box and is shown in Figure 6-1. The activity box is used to describe a function that is to be performed. The function could be a physical function such as moving or a material or a mathematical (analytical) function such as conversion of parameter from one form to another. Inputs are shown at the left of the activity box and are those things that are transformed by the function. Outputs are shown at the right of the activity box and are the result of the transformation process provided by the activity. Mechanisms are shown entering an activity box at the bottom and are the means by which a function is realised. Controls are shown entering the activity box at the top and are set of conditions that guide or constrain the performance of the activity (Boucher & Yalcin, 2006). The number inside the activity box describes the activity number and the number outside the box describes the sub-activity that further forms a part of this activity.

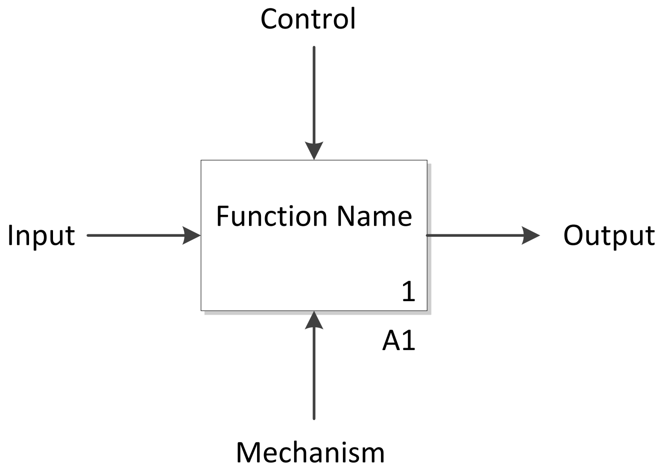

Figure 6-1: IDEF0 Activity Box

6.3 Framework Description

This study considers each dwelling as an object on which the function of energy processing is to be done. The framework for the energy performance assessment and decision support tool is presented as function modelling diagram in Figure 6-2.

The primary stage is to create entities of the dwellings objects within a neighbourhood using digital imagery and maps and national databases and statistics. Dwelling objects share and represent certain characteristics, thus forming various archetypes. A neighbourhood for which energy performance assessment is under consideration may consist of dwellings representing various such archetypes. The benefit of this method over the models and tools described in Section 3.2 is that a user can create as many archetypes as needed based on the characteristics identified within the neighbourhood. This is a significant advantage over the user trying to 'fix the dwelling to author defined archetypes'. Through creation of the dwelling objects, information is stored as attribute for each polygon in the digital maps. These attributes are then used to undertake all energy performance related calculations.

Once the objects for all the dwellings representing various archetypes are developed, the information is accessed by the SAP energy calculation module which calculates the baseline energy performance of the dwelling stock within the neighbourhood. By using the SAP algorithms to estimate the energy performance characteristics, the tool meets the requirements set by EPBD and Part L of Building Regulations. The SAP rating generated for the dwellings is further useful for stakeholders in targeting the most eligible properties while they seek funding for implementation of energy related policy. This satisfies a requirement which has been identified through their engagement and discussed in Section 3.3.

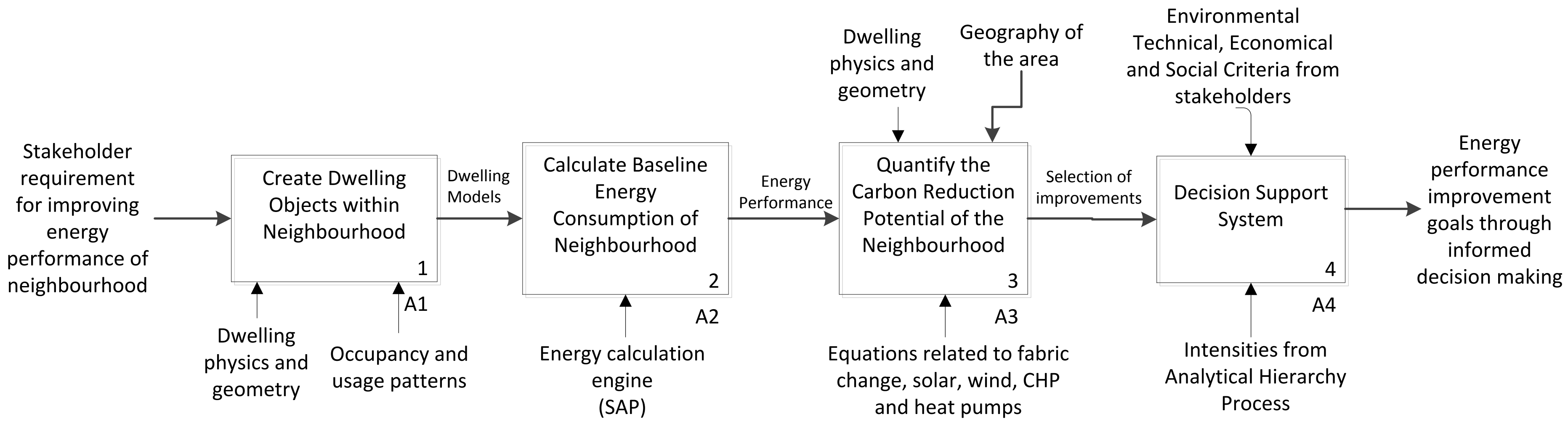

Figure 6-2: Framework for Energy Performance Assessment Tool

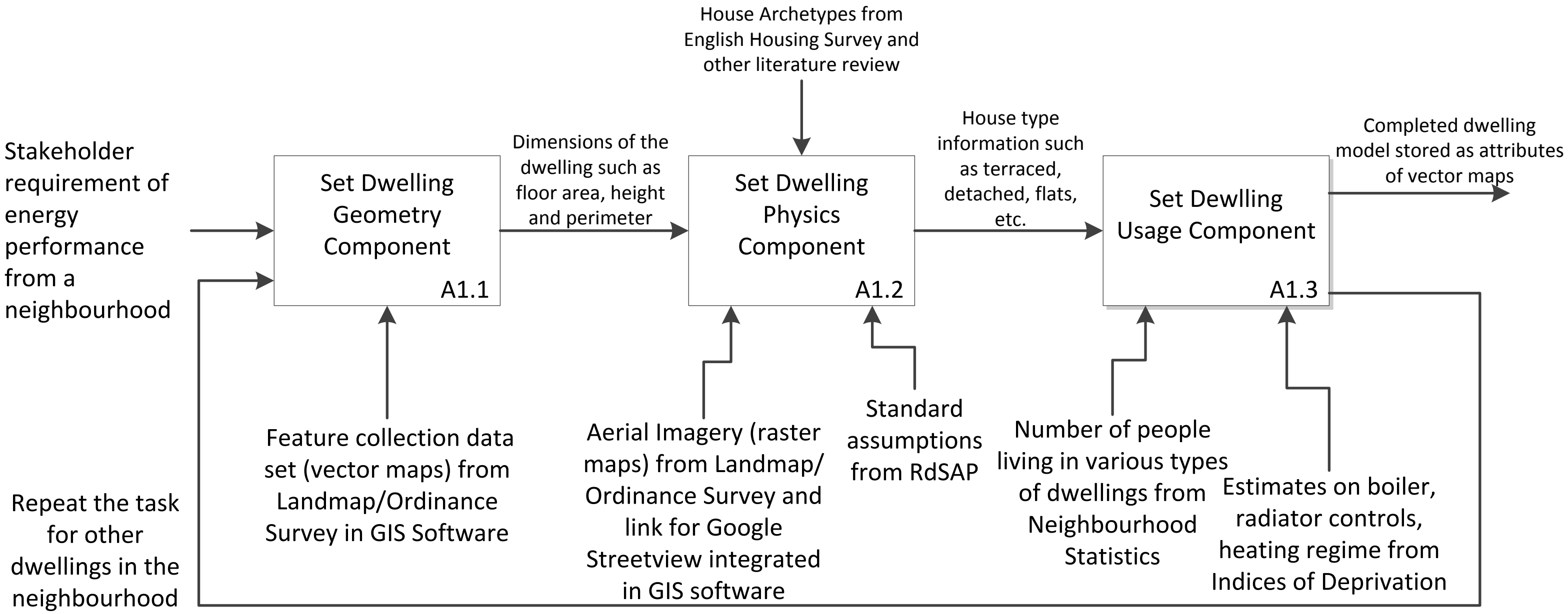

Figure 6-3: Creating Domestic Dwelling Objects

Subsequent to identifying the baseline energy performance, the next task is to quantify the potential of energy efficiency and renewable energy interventions in improving the energy performance and hence reducing the CO_2 emissions of the neighbourhood. This is achieved based on the dwelling objects developed and their baseline energy performance characteristics and energy performance improvement measures discussed in Chapter 4. Mathematical equations are formulated to estimate energy, carbon and cost savings. This overcomes a significant gap in the existing tools which have limitations with regards to simulating scenarios identified in Sections 3.2 and 3.3.

The final stage is to systematically use the information generated during this approach using a decision support tool. Analytical Hierarchy Process is used to rank the energy efficiency and renewable energy interventions based on environmental, technical, economic and social criteria defined by the stakeholders. Decision support system is currently not a part of any models and tools discussed in Section 3.2. By developing such as system as a part of the integrated framework this research makes an attempt to meet the requirements of the Local Development Framework and assist stakeholders in making informed decisions.

6.4 Creating Dwelling Objects

The principal requirement of the tool is to develop domestic dwelling objects which act as source for all calculations related to baseline energy performance and quantification of carbon reduction potential. Investigations of the characteristics and the variables for energy performance assessment from earlier chapters reveal that the data input can be classified into three major categories viz. dwelling geometry data, dwelling physics data and dwelling usage data. A dwelling model is constructed based on the components for each of these categories. The function modelling diagram for creating objects is depicted in Figure 6-3 which consists of setting the following components:

- Geometric component consisting of details on floor area, floor height, exposed perimeter and wall area and roof-area
- Physics component consisting of details on ventilation and U values of walls, windows, roof and floors
- Usage component consisting of details on the type and use of heating system, heating controls and lights and appliances

6.4.1 Geometric Component

The geometric component defines the dimensions of dwellings which are typically unique to each dwelling. The OS MasterMap Topography Layer and Landmap Building Blocks layer contain the features represented by points, lines and polygons (vector maps) that can provide the information for generating a geometric component (Ordnance Survey, 2010; MIMAS, 2012). The detailed parameters required for geometry components and their data sources are presented in Table 6-1.

Table 6-1: Input Parameters and Data Sources for Geometry Component

Parameters Required	Data Sources
• Number of storeys • Floor area and perimeter • Height of each storey • Area of the roof • Area of the exposed walls and windows	• Vector map of the area from Ordinance Survey and Landmap • Aerial and terrestrial imagery from Ordinance Survey and Google Maps

6.4.2 Physics Component

The building physics component defines the thermal characteristics of the material used for construction of dwelling. Dwellings of similar age typically have similar construction characteristics (Dowson, et al., 2012; Killp, 2005). This information is obtained or inferred from default values provided in SAP algorithms, databases such as EHS and HEED (Communities and Local Government, 2012). Each age band is defined as an archetype. The age band is identified using aerial and terrestrial imagery from OS and Google Maps. Since several dwellings may share these characteristics, unlike the geometrical data, the building physics data is attributed to a particular archetype and the physics component is created. The detailed parameters required for physics components and their data sources are presented in Table 6-2.

Table 6-2: Input Parameters and Data Sources for Physics Component

Parameters Required	Data Sources
• Mean wind speed • Mean external temperature • Horizontal solar radiation	• Data tables provided in SAP • Data provided by DECC and MetOffice
• Level of over-shading • Dwelling detachment (mid or end terraced, semidetached, detached, flat, etc.) • Dwelling Age (Before 1900, 1900-1929, 2007 – Onwards, etc.)	• Vector map of the area from Ordinance Survey and Landmap • Aerial and terrestrial imagery from Ordinance Survey and Google Maps
• U Value for doors, walls, windows, floor and roof • Draught proofing • Type of floor and window and door frame • Orientation of windows	• Inferred from age of the building • Aerial and terrestrial imagery from Ordinance Survey and Google Maps
• Number of flues, chimneys • Number of fans and vents	• Inferred from age of the dwelling • Aerial and terrestrial imagery from Ordinance Survey and Google Maps
• Type of water heater (gas, oil or solid fuel boiler, electric immersion) • If hot water tank present its volume, thickness of insulation, thermostat and insulation of pipework	• Inferred from age of the dwelling • Inferred from HEED and EHS

Parameters Required	Data Sources
• Mean internal temperature • Space heating type (gas, oil, solid fuel, electric) and its efficiency • Type of heating controls (programmers, thermostats)	

6.4.3 Usage Component

The building usage data depends on the amenities present within the dwellings and the way they are used by the occupants. Traditionally assumptions made regarding occupancy patterns and usage has been regarded as a drawback in the bottom-up building physics based techniques. Recently (Shipworth, 2011; Kelly, et al., 2013) have investigated relationships between internal space heating and socio-demographics. The usage component identifies the socio-demographic profile of the area from the census and neighbourhood statistics data maintained by the ONS (Office of National Statistics, 2012). The detailed parameters required for usage components and their data sources are presented in Table 6-3.

Table 6-3: Input Parameters and Data Sources for Usage Component

Parameters Required	Data Sources
• Number of occupants • Heating periods • Demand temperatures • Level of use of hot water, lights and cooking (average, below average and above average) • Electrical appliances	• Default data provided in SAP • Inferred based on census data, economic deprivation and Neighbourhood Statistics data from ONS

6.5 Estimate Baseline Energy Performance of Neighbourhood

The SAP manual provides extensive details on the equations involved in estimating baseline energy performance and hence those equations are not presented here. Finding the data sources for obtaining these parameters is one of the objectives of this study and is discussed in detail. The attribute information now added to the vector maps acts as the input data for SAP based energy performance assessment. The function modelling diagram of SAP algorithms is presented in Figure 6-4 which is used to calculate the following:

- Heat losses due to ventilation from the type of floor, number of chimneys, flues, fans, passive vents and storeys and average wind speed in the area.
- Heat losses from building fabric such as doors, windows, roof, floor and walls taking into consideration their area and U value.
- Energy demand for water heating depending on the number of occupants, temperature rise for hot water and losses due to presence of storage cylinder and distribution of hot water through pipes.
- Internal gains from occupant metabolism, lighting and electrical appliances, cooking, water heating and boiler pumps for space and water heating and losses from evaporation; and external gains due to solar radiation through windows.
- Space heating demand depending on the building geometry, heat losses, difference between internal temperature demand and external temperature and fraction of living space to total dwelling area.
- Energy required by the heating system to meet the total (water and space) heat demand depending on the efficiency of the system.
- Electricity required for boiler pumps, fans, lighting and electrical appliances.
- Energy cost depending on amount of electricity required from the grid and type and amount of fuel required for space and water heating.
- CO_2 emissions based on amount of electricity and total amount of fuel for space heating and water and their emission factors.

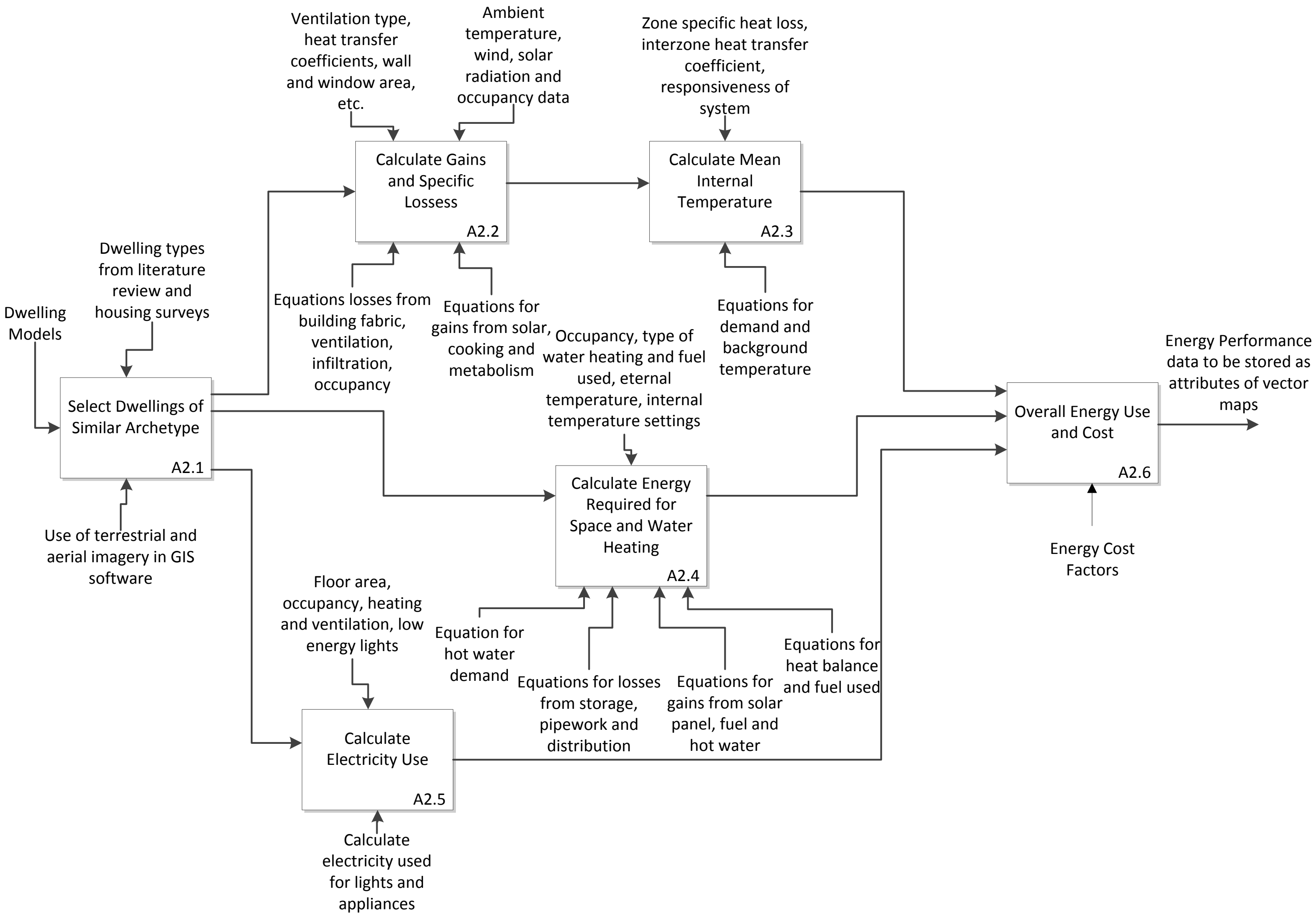

Figure 6-4: Baseline Energy Performance Assessment

Based on the energy costs associated with space heating, water heating, ventilation and lighting energy performance SAP rating and environmental impact (EI) rating are calculated. These ratings are adjusted for floor area so that they are essentially independent of dwelling size for a given built form. The SAP and EI ratings are expressed on a scale of 1 to 100, the higher the number the lower the running costs and CO_2 emissions respectively (BRE, 2011). The resulting energy usage and the ratings for each dwelling are added to the existing attributes on the vector maps. This information is then used to display thematic maps and hence identify energy hot-spots. The information generated is then used to quantify the energy savings and carbon reduction potential of the area though energy improvement measures.

6.6 Carbon Reduction Potential of the Neighbourhood

The existing characteristics of the dwellings essentially define their energy consumption and carbon reduction potential. The lower the baseline energy performance, the higher is the potential for reducing energy consumption and carbon emissions. Equations which are currently not a part of SAP such as those involved in estimating the carbon reduction potential through use of energy improvement measures have been discussed in detail. Chapter 4 has identified the most applicable interventions for improving energy efficiency in dwellings which are described below (Peacock, et al., 2007; Jenkins, 2010). The function modelling diagram for these interventions is presented as Figure 6-5:

- Changes to building fabric such as insulation of roof, walls, floor and installation of low-e double glazed windows.
- Replacing the low efficiency boilers with high efficiency condensing boilers.
- Installation of solar photovoltaic panels for electricity generation and solar thermal for hot water generation.
- Installation of micro wind-turbines for electricity generation.
- Installation of µ-CHP to meet space heating demand and generate electricity as a by-product of heat generation.

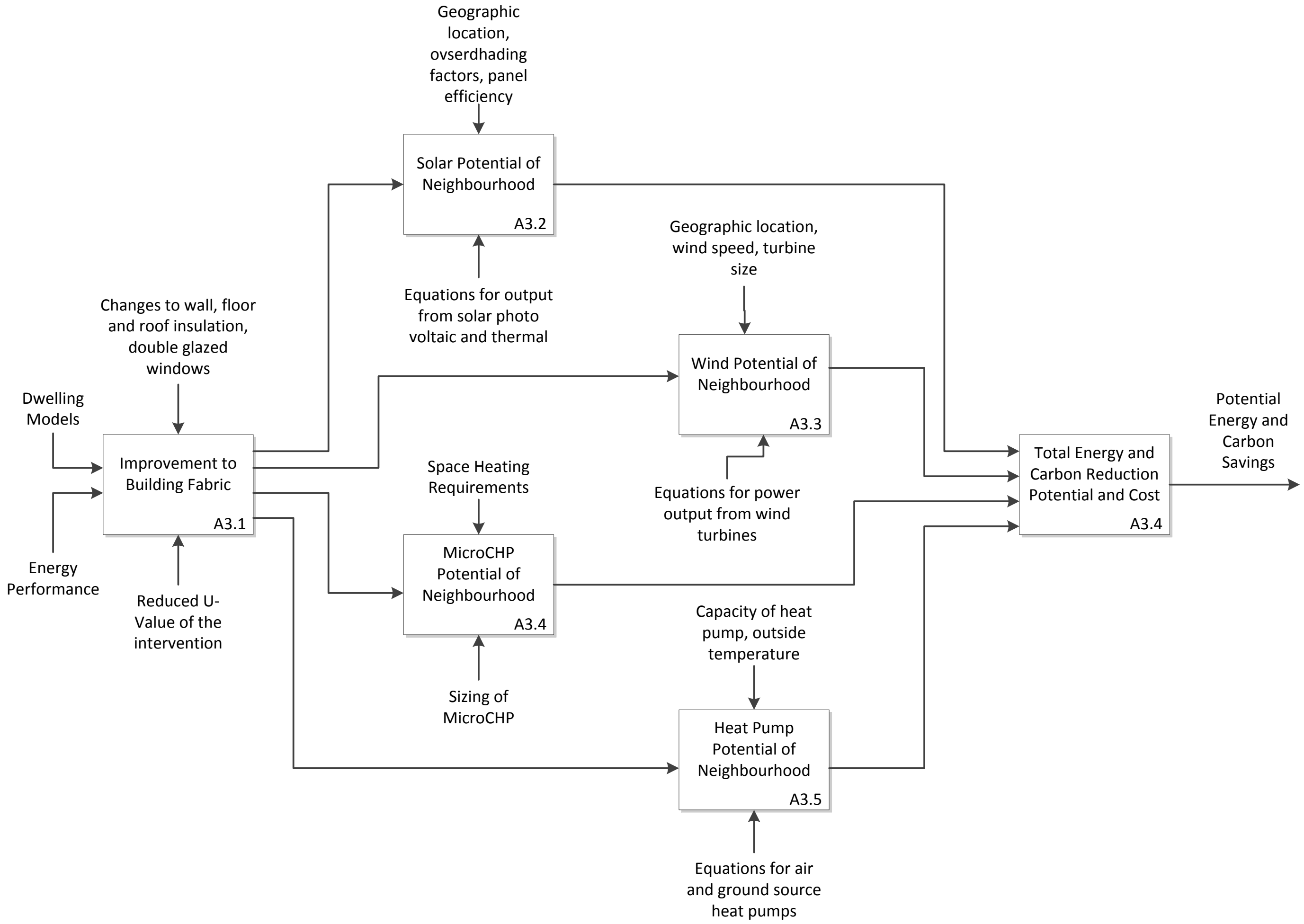

Figure 6-5: Quantification of Energy and Carbon Reduction Potential

- Installation of air source and ground source heat pumps to meet space heating demand.

The amount of energy saved, associated yearly or lifetime cost savings and the amount of CO_2 reduced annually are discussed in sections below.

6.6.1 Changes to Building Fabric

Changes to building fabric essentially involve decreasing the thermal conductivity (U value) of the existing fabric to reduce heat loss. With more heat retained within the dwelling, space heating demand is reduced. The effective U value after changes to the building fabric is known (Chapter 4), and hence all dwellings in a neighbourhood having U value higher than the effective U value of the particular element (roof, wall, floor and windows) are selected. The new heat loss value is estimated by using the geometry component developed earlier. The difference between the original heat loss and the new heat loss is the savings in energy demand leading.The amount of energy saved (kWh) is then multiplied by the cost per unit of fuel (£/kWh) to estimate the total savings (in £) for individual dwellings and aggregated to the neighbourhood. The amount of energy saved when multiplied by the CO_2 emission factor of the space heating fuel (kg CO_2/kWh) gives the amount of CO_2 saved annually (in kg).

6.6.2 Changes to Heating System

Apart from the electrical storage heaters, all other space heating systems will involve use of a boiler. Amount of fuel required (in kWh) to heat the dwelling to a certain standard depends on the heat demand of the dwelling and the efficiency of the boiler. Condensing boilers (regular or combination) typically have efficiency higher than most other boilers (BRE, 2011). Dwellings having boiler efficiency less than that of an A rated condensing boiler are selected for replacement option. Since the heat (space and hot water) demand (in kWh) is already available from baseline energy performance assessment, the new heat requirement (in kWh) is estimated by dividing the original heat demand with the efficiency of the condensing boiler. The difference in the new and baseline heat demand is the amount (in kWh) of energy saved. The amount of energy saved (in kWh) is then multiplied by the cost per unit of fuel (in £/kWh) to estimate the total savings (in £). The amount of energy saved when multiplied by the CO_2 emission factor of the space heating fuel (kg CO_2/kWh) gives the amount of CO_2 saved annually (in kg).

6.6.3 Solar Photovoltaic and Solar Thermal

The solar potential of a dwelling depends on the available roof area, the orientation of the roof and its angle of inclination. The available roof area determines the size of solar panel that can be installed. The orientation and angle of inclination of the roof determines the amount of solar radiation it receives. The area, orientation and angle of inclination information for each dwelling can be sourced through the geometry component. Solar thermal panels further require a cylinder for storage and distribution of hot water. This this option is usually only feasible for dwellings having storage cylinders, the information which can be sourced from the building physics component. The solar flux (in W/m^2) for any orientation and tilt is given by equations (Cronemberger, et al., 2012; Gastli & Charabi, 2010):

$$S_{(orient,p,m)} = S_{h,m} \times R_{h-inc(orient,p,m)}$$

$$R_{h-inc(orient,p,m)} = A \times cos^2(\emptyset - \partial) + B \times \cos(\emptyset - \partial) + C$$

Where,

$S_{h,m}$ is average horizontal flux (in W/m^2) at the concerned location for the particular month (available from PVGIS (Šúri, et al., 2005))

$R_{h-inc(orient,p,m)}$ is the factor for converting horizontal flux to flux on inclined surface

$orient$ is the direction where the solar panel is facing (North, North East, East, South East, South, South West, West or North West)

p is the inclination angle of the surface from horizontal (0^o is horizontal 90^o is vertical)

$\emptyset$ is the latitude of the location in degrees

∂ is the solar declination for the applicable month

$A, B\ and\ C$ are constants depending on the orientation on tilt (described in Appendix B)

The annual solar radiation in kWh/m^2 for any orientation and tilt is given by:

$$S = 0.024 \sum_{m=1}^{12} n_m \times S_{(orient,p,m)}$$

Where,

n_m is the number of days in a month

6.6.3.1 Solar PV

Solar panels are available in standard size of 1.6 m^2 and peak power generation capacity for each panel is 220 W. Depending on the available roof area, the number of solar panels is selected. Once the annual solar radiation on any surface is calculated, the amount of electricity typically generated (in kWh) annually by a solar photo-voltaic is given by:

$$E_{PV} = 0.8 \times kWp \times S \times Z_{PV}$$

Where,

kWp is the total installed peak power depending on number of panels

Z_{PV} is the over shading factor depending on percentage of sky blocked by obstacles

The electricity generated by the PV panels (in kWh) can be used to power lights and appliances thus saving the cost of buying electricity from the grid (in £/kWh). All the electricity generated by the PV is further eligible for feed-in-tariffs which at the time of writing stands at £0.1544/kWh. The feed-in-tariff will be paid for 20 years from the date of installation. Any excess electricity that is not used within the dwelling can be exported to the grid the rate of which currently stands at £0.045/kWh. In the absence of smart metering, the actual amount of electricity used within the dwelling and the amount exported cannot be measured for every installation. Hence for cost calculation purposes, the DECC recommends to assume that 50% of electricity generated is used within the dwelling where as 50% is exported to the grid.

The annual savings in electricity cost through installation of solar PV is evaluated by equation:

$$CS_{PV} = E_{PV} \times FIT_{SPV} + 0.5 \times ET_{PV} \times E_{PV} + 0.5 \times E_{PV} \times T_E$$

Where,

T_E is the tariff of the electricity (provided in SAP) from the grid that will be replaced by the electricity generated solar panel.

FIT_{SPV} is the feed-in-tariff for electricity generation from solar PV (currently £0.1544/kWh).

ET_{PV} is the export tariff for electricity generation from solar PV (currently £0.045/kWh)

The annual reduction in CO_2 emissions (in kg) due to installation of solar PV is evaluated by equation:

$$ER_{PV} = E_{PV} \times EF_E$$

Where,

EF_E is the CO_2 emission factor for electricity from grid (in kg CO_2/kWh) provided in SAP

6.6.3.2 Solar Thermal

Equations for contribution towards domestic hot water from solar thermal panels are provided in SAP. Solar thermal panels typically come in a size of 2.15 m^2 absorber surface area. The number of solar panels that can be installed on the roof is determined from the dwelling geometry model. The calculation of solar radiation for given orientation and tilt is discussed in Section 6.6.3. Based on the solar radiation and available surface absorption area, annual solar input Q_S(in kWh) is determined.

The heat generated by the solar thermal panel is expected to be eligible for 'renewable heat incentive'. While the tariff is still under consultation at the time of writing, the indicative value provided is £0.173/kWh. The payment for the total heat expected to be generated over the lifetime of the solar thermal panels will be paid in a span of seven years. The life time savings in fuel cost through installation of solar thermal panels is evaluated by equation:

$$CS_{LHW} = LT_{ST} \times (Q_S \times T_F + RHI_{HW} \times Q_S)$$

Where,

LT_{ST} is the lifetime of the solar thermal panel

T_F is the tariff of the fuel being used for hot water heating that solar thermal replaces

RHI_{HW} is the renewable heat incentive for solar thermal panels (currently £0.173/kWh)

The annual reduction in CO_2 emissions (in kg) due to installation of solar thermal panels is evaluated by equation:

$$ER_{ST} = Q_S \times EF_F$$

Where,

EF_F is the CO_2 emission factor for fuel being replaced (in kg CO_2/kWh) provided in SAP

6.6.4 Micro-Wind Turbines

Installation of micro-wind turbines is independent of buildings of the dwelling models. However, the Planning Permission requires any building mounted or standalone micro-wind turbines to be installed only on detached dwellings. There are further requirements with respect to height of the nearby dwellings. Thus detached dwellings satisfying these requirements are identified from the building geometry models. The amount of electricity generated depends on the average wind speed in the area and the peak power generation capacity of the turbine. The peak power generation capacity (kWp) of the micro-wind turbine depends on the turbine diameter. The average wind speed data for any UK OS grid reference is available from the DECC. Based on the wind speed and the size of the turbine, the amount of electrical energy generated E_{WT} is determined based on the equations provided in SAP.

Similar to solar PV, the electricity generated by micro-wind turbines (in kWh) contributes to replacing the electricity from the grid. All the electricity generated by the micro-wind turbines is further eligible for feed-in-tariffs which at the time of writing stands at £0.21/kWh. The feed-in-tariff will be paid for 20 years from the date of installation. Any excess electricity that is not used within the dwelling can be exported to the grid the rate of which currently stands at £0.045/kWh. In the absence of smart metering, the actual amount of electricity used within the dwelling and the amount exported cannot be measured for every installation. Hence for cost calculation purposes, the DECC recommends to assume that 50% of electricity generated is used within the dwelling where as 50% is exported to the grid.

The annual savings in electricity cost through installation of micro-wind turbine is evaluated by equation:

$$CS_{WT} = E_{WT} \times FIT_{WT} + 0.5 \times ET_{WT} \times E_{WT} + 0.5 \times E_{WT} \times T_E$$

Where,

T_E is the tariff of the electricity (provided in SAP) from the grid that will be replaced by the electricity generated from micro-wind turbine.

FIT_{SPV} is the feed-in-tariff for electricity generation from micro-wind turbine (currently £0.21/kWh).

ET_{WT} is the export tariff for electricity generation from wind turbines (currently £0.045/kWh).

The annual reduction in CO_2 emissions (in kg) due to installation of micro-wind turbine is evaluated by equation:

$$ER_{WT} = 0.5 \times E_{WT} \times EF_E$$

Where,

EF_E is the CO_2 emission factor for electricity from grid (in kg CO_2/kWh) provided in SAP

6.6.5 Micro-Combined Heat and Power Unit

The primary benefit of μ-CHP is that the fuel used to generate heat is also used to generate electricity at the point of use. The typical ratio of heat to electricity generation is about 6:1 in domestic units (Hayton & Young, 2008). The thermal and electrical efficiencies of the units typically are 76% for heat generation and 8% for electricity generation providing an overall efficiency of 84% (Gazis & Harrison, 2011). The net efficiency of the μ-CHP unit is thus less than that of an A rated condensing boiler (which is typically 90% or higher). Hence, μ-CHP units are suitable for dwellings having gas boilers rating B (84%) or lower and those heated using electricity (immersion or storage heaters) and have a possibility to be connected to gas network or can use biomass as fuel. The electricity generated by the μ-CHP unit is driven by the heat demand of the dwelling. The heat (space and hot water) demand of the dwelling is known from the baseline energy performance assessment. Thus the amount of fuel (in kWh) required by the μ-CHP unit is evaluated by:

$$Q_{CHP} = \frac{(Q_{Space}+Q_{Water})}{\eta_{SCHP}}$$

Where,

Q_{Space} is the space heating demand of the dwelling (calculated in baseline energy performance assessment)

Q_{Water} is the water heating demand of the dwelling (calculated in baseline energy performance assessment)

η_{SCHP} is the heat efficiency of the μ-CHP unit (typically 76%)

The amount of electricity generated (in kWh) by the μ-CHP unit is evaluated by:

$$E_{CHP} = Q_{CHP} \times \eta_{ECHP}$$

Where,

η_{ECHP} is the electrical efficiency of the μ-CHP unit (typically 8%)

Similar to Solar PV and micro-wind turbines, the electricity generated by μ-CHP is eligible for feed-in-tariff which currently stands at £0.125/kWh. Any excess electricity that is not used within the dwelling can be exported to the grid the rate of which currently stands at £0.045/kWh. In the absence of smart metering, the actual amount of electricity used within the dwelling and the amount exported cannot be measured for every installation. Hence for cost calculation purposes, the DECC recommends to assume that 50% of electricity generated is used within the dwelling where as 50% is exported to the grid. Taking this into consideration, the annual cost savings achieved due to installation of μ-CHP is evaluated by:

$$CS_{CHP} = E_{CHP} \times FIT_{CHP} + 0.5 \times ET_{CHP} \times E_{CHP} + 0.5 \times E_{CHP} \times T_E$$

Where,

T_E is the tariff of the electricity (provided in SAP) from the grid that will be replaced by the electricity generated from μ-CHP.

FIT_{CHP} is the feed-in-tariff for electricity generation from μ-CHP (currently £0.125/kWh).

ET_{CHP} is the export tariff for electricity generation from wind turbines (currently £0.045/kWh).

The annual reduction in CO_2 emissions (in kg) due to installation of μ-CHP is evaluated by:

$$ER_{CHP} = 0.5 \times E_{CHP} \times EF_E + (Q_{TF} \times EF_F - Q_{CHP} \times EF_{CHP})$$

Where,

EF_E is the CO_2 emission factor for electricity from grid (in kg CO_2/kWh) provided in SAP

Q_{TF} is the total fuel (for space and domestic water heating) calculated during baseline energy performance assessment

EF_{CHP} is the emissions factor of the fuel used by μ-CHP unit to generate heat and electricity (most likely gas but could be biomass)

6.6.6 Air and Ground Source Heat Pumps

The underlying principle of a heat pump’s operation is the reverse of a heat engine: using mechanical work to move heat against its natural gradient from a cold location to a hotter one, e.g. from outdoors into the home. This means the heat pumps extract ambient heat from the environment and increases its temperature to heat space or water. GSHP require heating coils to be laid in the ground. Thus only dwellings having sufficiently large and accessible back yards can be considered for GSHP. ASHP can be considered for dwellings where GSHP is not an option. Further, it is discussed in Chapter 4 that ASHP or GSHP are more applicable to dwellings which are not connected to the gas network and use other fuels for space and water heating. The dwelling criteria can be selected from the dwelling physics component for installation of heat pumps. Further based on the dimensions and the access of the available space around the dwelling identified from the geometry component, the dwellings suitable for GSHP or ASHP are selected.

It has been discussed earlier in Chapter 4 that heat pumps operate either on gas or electricity. The coefficient of performance (COP) (efficiency) varies significantly for both fuels. Further, the efficiency of the heat pump also varies significantly depending on the heat emitter type. Heat pumps having under-floor heating have much higher efficiency than those having radiators. The heat required for space and water, Q_{Space} and Q_{Water} respectively, is identified during baseline energy performance assessment. Based on the efficiency of heat pumps (η_{HP}), the annual fuel demand of the heat pump (in kWh) is given by:

$$Q_{HP} = \frac{(Q_{Space}+Q_{Water})}{\eta_{HP}}$$

The heat generated by the heat pumps is expected to be eligible for ‘renewable heat incentive’. While the tariff is still under consultation at the time of writing, the indicative values provided are £0.069/kWh for air source and £0.125/kWh for ground source heat pumps. The payment for the total heat expected to be generated over the lifetime of the heat pumps will be paid in a span of seven years. The life time savings in fuel cost through installation of heat pumps is evaluated by equation:

$$CS_{HP} = LT_{HP} \times ((Q_{HP} \times T_{HPF} - Q_S \times T_F) + RHI_{HW} \times Q_{HP})$$

Where,

LT_{HP} is the lifetime of the heat pump

T_{HPF} is the tariff of the fuel required by the heat pump

$T_F$is the tariff of the fuel being used for hot water heating that solar thermal replaces

RHI_{HP} is the renewable heat incentive for heat pumps (currently £0.069/kWh for air source and £0.125 for ground source heat pumps)

The annual reduction in CO_2 emissions (in kg) due to installation of heat pumps is evaluated by:

$$ER_{HP} = Q_{Space+}Q_{Water} \times EF_F - Q_{HP} \times EF_{HPF}$$

Where,

EF_F is the CO_2 emission factor for fuel currently used to supply space and water heating demand

Q_{Space} is the space heating demand of the dwelling (calculated in baseline energy performance assessment)

Q_{Water} is the water heating demand of the dwelling (calculated in baseline energy performance assessment)

EF_{HPF} is the emissions factor of the fuel used by the heat pump to generate heat

6.7 Decision Support System

Data on baseline energy performance of dwellings and the energy and carbon reduction potential of several interventions is a large amount of information. This information needs to be systematically analysed by the stakeholders involved so that informed decisions are made with regards to implementation of various energy related policies. Decision support techniques are extensively discussed in Chapter 5 and Analytical Hierarchy Process (AHP) is selected as a decision support mechanism for this research. Decisions with regards to selecting energy performance improvement alternatives discussed in Section 6.6 are based on criteria identified in Section 5.5 and listed below:

- Annual Reduction in CO_2 levels
- Initial Investment (Fixed Cost and Grants Received)
- Return on Investment (Annual running cost to user and savings made through feed-in-tariff)
- Social Acceptability
- Ease of implementation (access to resources and timeline)

The first step of AHP is to rank the criteria through pairwise comparison (as shown in Figure 7-9). While doing pairwise comparison a scale of 1-9 is used to assess the intensity with 1 indicating equal importance and 9 extremely high importance. Based on the intensities assigned, a matrix is created. An example of such a matrix is presented in Table 6-4. The matrix is then normalised and iterations of the normalised matrix are undertaken until eigen-values and eigen-vector are identified. For any non-negative $n \times n$ matrix A,

$$(A - \lambda I)v = 0$$

Where,

A is the normalised matrix developed based on initial weightages
I is the identity matrix
λ is the eigen-value
v is the eigen vector

Table 6-4: AHP Matrix to Rank the Criteria

	Annual Reduction in CO_2 levels	**Initial Investment**	**Return on Investment**	**Social Acceptability**	**Ease of implementation**
Annual Reduction in CO_2 levels	1	1/3	1/5	1	1
Initial Investment	3	1	3	5	3
Return on Investment	5	1/3	1	3	1
Social Acceptability	1	1/5	1/3	1	1/3
Ease of implementation	1	1/3	1	3	1

The eigen-vector thus obtained from evaluating the matrix through above equation is the weightage for the criteria. The higher the weightage, the higher is the priority. The resultant eigen-vectors for the example presented in Table 6-4 are presented in Table 6-5 and is displayed to user as shown in Figure 7-11. In the example shown below, initial investment is the criteria with the highest priority.

Table 6-5: Ranking of the Criteria

	Criteria	Weightage
1	Annual Reduction in CO_2 levels	11.66%
2	Initial Investment	44.84%
3	Return on Investment	19.98%
4	Social Acceptability	7.77%
5	Ease of implementation	15.74%

AHP allows for inconsistency because in making judgments people are more likely to be cardinally inconsistent than cardinally consistent (Saaty, 2003). In case of a totally consistent matrix (Saaty, 2003; Alonso & Lamata, 2006):

$$\lambda_{max} = n$$

Where,

λ_{max} is the maximum eigen value

n is the number of number of parameters involved (for e.g. there are 5 criteria involved in this research)

In order to find out the how consistent the pairwise rankings are, Saaty (2008) has developed a formula for Consistency Ratio. In an ideal world, the consistency ratio would be 0. However, stakeholders rarely assign weightage to reach a ‘perfect’ scenario. However, a matrix is termed consistent if and only if consistency ratio < 0.1. If the consistency ratio is higher, then the weightages have to be reassigned to arrive at a lower value. Consistency ratio is evaluated by first evaluating the consistency index given by (Saaty, 2008):

$$CI = \frac{(\lambda_{max} - \mathrm{n})}{n-1}$$

Based on consistency index the consistency ratio is then evaluated by (Saaty, 2008):

$$CR = \frac{CI}{RI}$$

Where,

RI is the Random Index value obtained by Saaty scale[20] depending on number of parameters.

For the hypothetical case presented in Table 6-4, the consistency ratio is 0.09. Thus the relative values assigned in pairwise comparison are consistent.

Subsequent to establishing the priorities for the criteria, similar pairwise comparison is undertaken for all the alternatives for all the criteria. Since in this study, we are considering 5 criteria, 5 matrices are prepared consisting of pairwise comparison for all interventions being considered. The eigen-vectors of all the 5 matrices are then added to get resultant eigen-vector. The value of the resultant eigen-vector of the alternatives multiplied by the weightages obtained from ranking the criteria finally gives the rankings of the alternatives.

6.8 Summary

In this chapter we have described the framework for the tool development based on the identified gaps and requirements of the stakeholders. The primary step is to create domestic dwelling models that can be then used for further energy performance assessment. This includes estimating the baseline performance and then the carbon reduction potential through various improvement measures. Finally a decision support system is presented which assists stakeholders to make informed decisions regarding the implementation of improvement measures. The next chapter discusses the development of a prototype tool based on the framework described.

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[20]

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Adapted from (Forman, 1990)

Chapter 7 Development of Prototype Tool

7.1 Introduction

The earlier chapter presented in detail the structural aspects for development of energy performance assessment and decision support tool. The framework addressed the part of ‘what’ needs to be undertaken. The next stage is to define ‘how’ these activities are put into real work practice to assess current and future energy performance of dwellings (Schnieders, et al., 2004). This chapter presents how the framework is being applied to develop a ‘proof-of-concept’ prototype and demonstrate the suggested approach. A prototype is a working model of a developed process, or framework in this case, and helps in establishing how realistic the developed framework is (Smith, 1991). Prototype is always in a ‘test-mode’ and allows developers to make several changes to it depending on technical and user requirements and hence make recommendations for tool that is robust and free of any errors (Lantz, 1986). A proof-of-concept prototype is typically developed to test various aspects of the proposed fully functional tool, but without attempting to simulate the exact visual appearance (Dutta, et al., 2010). The benefit of developing a prototype is that it can be tested by potential users and their valuable opinion can be taken into consideration before complete software tool development thus making it user friendly.

7.2 Methodology of System Architecture

The prototype is constructed to undertake the activities described in the framework. It is thus a precursor for building a prototype to understand how the various activities relate with each other. This involves developing system architecture that describes the operations and relationship behind these activities. In a systems based technique development such as this study, architecture typically describes handling of the tasks from the framework, i.e. energy models, in such a way that it supports reasoning of the structural properties of these tasks (Golden, 2010). The system architecture of the energy assessment and decision support tool describes the following:

- Operations of various energy models that contribute to determining the energy characteristics of the dwellings e.g. equations related to ventilation, space heating, etc.
- Parameters involved in these energy models and their attributes e.g. number of chimneys decide the quantity of ventilation.
- Relationship amongst the energy models i.e. which models precede or succeed which model e.g. the amount of ventilation decides the heat demand of the dwelling.
- Influence of individual attributes within the energy model on the attributes of the following energy models e.g. depending on the age of the dwelling, the U value of solid wall will vary.

In a study such as this, several activities are involved; however, they collaborate with each other to achieve a common goal. In systems or tool development, this is commonly termed as object-oriented analysis (Jacobson, et al., 1999; Priestly, 2000). It is of paramount importance in that the objects and their relationships involved in the analysis are correctly identified and recorded. This is typically undertaken using a modelling language (Barclay & Savage, 2004). Some of common methods of describing relationship are:

- RACI matrix table: RACI (Responsible Accountable Consulted and Informed) matrix is used to relate process activity with the roles (of people, departments, organisations, etc.). According to the RACI approach, for each activity a particular role is responsible for its success or failure (accountable), has to participate in the activity (consulted) and hold information of the activity assigned to them (Melton, 2007). The RACI matrices work well for simple structures, however for larger structures as this study, the RACI approach contorts the relationships which makes them complex to understand and are of little value (Holt, 2009).
- Business Process Modelling Notation (BPMN): BPMN provides notation that enables users visualise business execution language (BPMI, 2002). Although BPMN notations assist in defining the

association semantics, it is far too narrow concept that does not amalgamate with structural diagrams and fails consider requirements essential for process validation (Holt, 2009).

- Unified Modelling Language: In the late 1990's, (Booch, 1999; Rumbaugh, 1991) developed Unified Modelling Language (UML) as the means of capturing and recording object-oriented analysis and design. It is a visual technique where results are seen graphically. Or in other words, it is a language of diagrams containing symbols. UML enables defining the model objects, their attributes and their operations. UML has notations to describe relationships and directions of information flow and can display large amounts of complex information including analytics effectively. It can also depict objects' state and transition among these states (Saleh, 2009). UML is currently the most widely used language in the world to describe relationships between activities (Dennis, 2010). UML has become an ISO standard – ISO 19501 which gives it more credibility than just being an industry standard (ISO/IEC, 2005). The Object Management Group, an international, open membership, not-for-profit computer industry standards consortium, has granted UML an approval as a vendor-neutral standard (OMG Inc., 2012). This means that the systems architecture presented using UML can subsequently be used to develop software across various different platforms.

Considering the benefits UML is the preferred modelling language used to describe relationships. UML has thirteen types of diagrams serving different purposes, of which the class diagram is the one which allows relationships to be established and is used in this chapter (Holt, 2009). A class is a descriptor for a set of objects that share some attributes and/or operations. Classes and objects are a natural way of conceptualizing the world around us.

The graphical notations for the elements that make up a class diagram are shown in Figure 7-1. The entire box represents a class. The top part of the box describes the name of the activity (a mathematical model) that needs to be evaluated. The middle part of the box present the attributes required for the activity. These are essentially the input parameters required for the equations which the user needs to input using visual imagery or identified databases. The bottom part presents the operations that the attributes undertake.

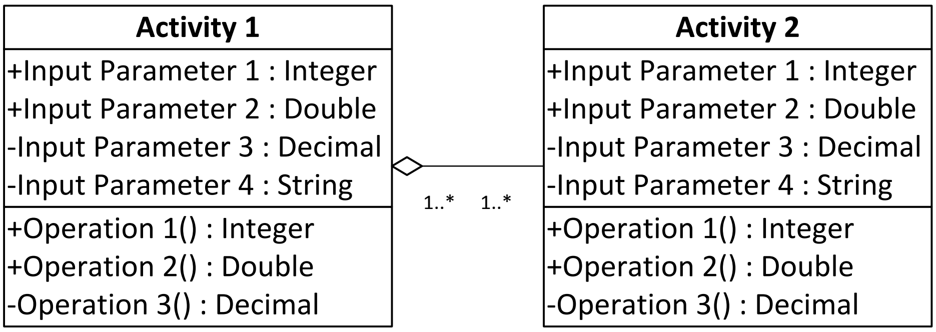

Figure 7-1: Description of Class Diagram

The line connecting the classes describes the relationship. The diamond at the end of the line describes the association between the two activities. In this example, Activity 1 ‘is made up of’ Activity 2, or in other words, the input parameter and/or the operations in Activity 1 depend on the input parameters and/or operations in Activity 2. The number below the relationship line denotes how many of Activity 1 are made up or how many of Activity 2. ‘1’ denotes activity for only 1 dwelling is being considered; ‘*’ denotes activity for multiple dwellings is being considered; and 1..* denotes one or many dwellings are considered. The plus (+) sign before an attribute denotes the input parameter required for the operation is visible to the user. The value is to be input by the user based on the identified database. The dash (-) sign before an attribute denotes that the input parameter required for the operation is not visible to the user and is derived/obtained through intermediary calculations. Similarly, the plus (+) sign before the operation denotes that the output of the operation is visible to the user and dash (-) denotes the output of operation is hidden from the user. The data type of the attribute and the output of the operation is described as integer, double, decimal, boolean or string[21].

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[21] Data types as defined in (MSDN, 2013)

The following sections describe the system architecture for evaluating baseline energy performance, assessing improvement scenarios and the decision making process.

7.3 System Architecture for Baseline Performance

It is established from the activities in the framework that estimating the dwelling energy performance involves calculation of heat losses due to ventilation and building fabric; heat gains from within the dwelling and solar radiation; energy required for domestic hot water; energy required for space heating depending on internal and external temperatures; and energy required for lights and appliances. A detailed description of the models which form a part of these calculations and their relationship is presented in Figure 7-2 and described in following sections.

7.3.1 Construction Period

Construction period has by far the largest impact on the characteristic of dwellings and is a widely used means of classifying dwellings in the UK (BRE, 2011). Dwelling stock from the 19th century is likely to consist of solid walls and single glazing (Everett, 2007). Building regulations were introduced in the 1965, when rules were made for minimum standard to be met by the buildings (HM Government, 2013). Though the standards then were not targeted towards influencing energy performance, based on the compliance requirements needed to be met, the thermal characteristics are determined. The construction periods identified from EHS and HEED are pre 1900; 1900-1929; 1930-1949; 1950-1966; 1967-1975; 1976-1982; 1983-1990; 1991-1995; 1996-2002; 2003-2006 and post 2007. The LandMap Building Blocks layer contains the age information which forms an input parameter and is available for most areas of UK (MIMAS, 2012). The dwelling age determines parameters such as wall thickness, window area and U value for walls, roofs and windows.

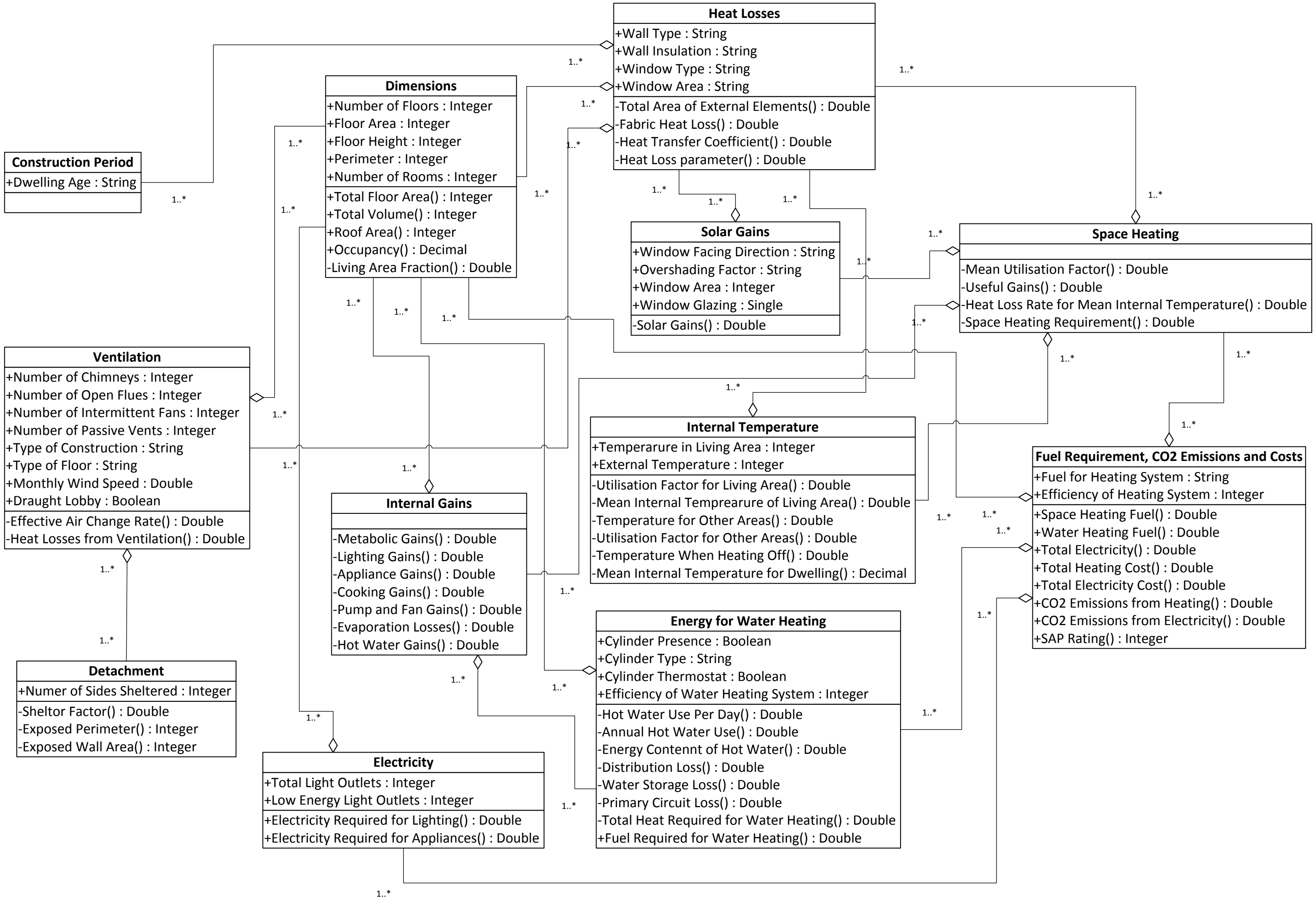


Figure 7-2: System Architecture for Baseline Energy Performance Assessment

7.3.2 Dimensions and Detachment

The attributes required to define the dwelling dimensions are number of floors, individual floor area, individual floor height, number of rooms and the perimeter of dwellings and thus form the input parameters. Dwellings scaled to actual footprint are one of the features in the OS MasterMap layer (vector map). This feature is uniquely referenced along with information such as area and perimeter (Ordnance Survey, 2010). Similarly, the Land Map Building Blocks layer (vector map) consists of Building heights information. Information from these attributes is used to calculate the total floor area and volume of the dwelling. The roof-area is equated to the area of the largest floor where there are multiple floors. The Neighbourhood Statistics database holds details on the number of dwellings with 1 to 9 or more rooms within Lower Layer Super Output Area (LLSOA) (Office of National Statistics, 2012). There are two methods to determine the occupancy of dwelling; the first one is using empirical equation based on the total area of the dwelling (BRE, 2011) and the second method is using the Neighbourhood Statistics information. For every LLSOA, the Neighbourhood Statistics provide details on number of dwellings with 1 to 8 and more people. It also provides information on occupancy rating of the dwelling which details if the rooms within a dwelling are over or under occupied (Office of National Statistics, 2012).

The dwelling detachment determines the number of sides of dwelling shared with other properties. This is essential to calculate the shelter factor which affects the ventilation of the dwelling and the exposed wall area which determines the heat loss from the dwelling.

7.3.3 Ventilation

The total infiltration due to ventilation affects the total heat loss of the dwellings and depends on its total air change rate (Blomsterberg, et al., 1999). The air change rate is the ratio of the volume of air replaced every hour to the total volume of the dwelling. The input parameters for calculation of ventilation are the number of chimneys or open flues, passive vents, intermittent fans; type of construction and the floor; presence of a draught lobby and the average wind speed in the area.

The presence of chimneys or flues and type of construction is detected using aerial imagery. Further, chimneys have been an integral part of UK dwellings until 1960’s due to presence of fireplaces (UWE, 2006). Dwellings post 1960’s are more likely to have only passive vents for the purpose of healthy indoor environment (Lowe, et al., 2000). Masonry and timber frame construction have been the most common construction types for dwellings of which masonry has dominated until the 1950’s (Roberts, 2008). The type of floor is selected based on the age of the dwelling. Until 1970’s suspended wooden floors was a common practice beyond which pre-cast concrete became a norm (Shorrock, et al., 2005). Depending on the type of construction and the floor that is selected, standard infiltration value is assigned during calculation. Draught lobby has not been traditionally associated with dwellings, however, by 2006, 88% of dwellings have had draught proofing measures in place (Utley & Shorrock, 2008). Where it is known that draught lobby exists, standard infiltration value is assigned during calculation. Total infiltration is calculated from these parameters. Adjustment to these values is made based on the wind factor and the shelter factor. The wind factor depends on the local wind speed, the data for which is available from the DECC.

7.3.4 Heat Losses

The heat loss of dwelling depends on its construction period, dimensions and ventilation losses. The heat losses occur from exposed surfaces of dwelling such as walls, windows and roof and the floor next to ground. The areas of walls, roof and floor are available from the dimensions and detachment model described earlier. Empirical equations are available for calculating typical window area depending on the age of the dwelling (BRE, 2011). The equations allow for factors if the window area is above or below the typical for that particular age. The type of walls, windows and roof are the input parameters and determined using terrestrial imagery from Google Street View. A database of U values is prepared based on type and age of walls, windows and roof. Based on the selected type and age, relevant U values are returned for calculation of heat losses. The U value of floor is determined by the ratio of floor area and perimeter and the type of floor available from the dimensions model. The total area of external surface elements and their respective U values calculate the fabric heat loss. The ventilation losses and fabric heat loss provide the heat transfer coefficient, which is then normalised by area to determine the heat loss parameter. The output from heat loss is used to calculate the internal temperature and space heating requirements.

7.3.5 Water Heating Demand

The amount of energy required for water heating depends on the number of occupants, efficiency of heating system, presence and type of storage cylinders, and thermostatic controls if any (BRE, 2011). All parameters other than the number of occupants are input parameters as occupancy is derived from the dimensions model. All types of water heating system other than combination gas boilers require a storage cylinder. HEED and ONS hold information on the type of heating system that determines the presence storage cylinder and its efficiency. HEED also contains information on installation measures undertaken under CERT and CESP which determine the presence of thermostatic controls (Energy Saving Trust, 2013). Based on occupancy total amount of hot water required and energy required to heat it to a particular temperature is determined. If there is storage, losses from storage and distribution are calculated. There are primary circuit losses irrespective of storage. All these outputs calculate total energy required to maintain the hot water at desired levels.

7.3.6 Heat Gains

Heat gains within dwelling comprise of internal gains and external gains. The internal heat gains in a dwelling occur from the metabolism of occupants, heat generated during cooking, heat generated by lights, appliances and water circulation pumps and heat gained from hot water. No input parameters from user perspective are involved in this model as all individual equations rely on the floor area and number of occupants of the dwelling

(BRE, 2011). This is obtained from the dimensions model described earlier. A proportion of heat lost from hot water, calculated earlier, contributes to the heat gain by the dwelling.

The external heat gains occur from the solar radiation entering the dwelling through wall and roof windows. The intensity of solar radiation is different in different directions (Padovan & Del Col, 2010). Hence the impact of the solar radiation depends input parameters like orientation of the windows, the area of the windows and the glazing type of windows. The area of the windows is estimated earlier in heat loss model. The orientation of the windows is determined from the OS vector maps and Google Street View. The glazing type of the windows determines its U Value. This information is obtained from the Google Street View and HEED which consists of information on installation measures undertaken as part of CERT and CESP. Typical U values are assigned for types of windows selected, particular U value is selected from database for the calculations.

The internal and external heat gains within the dwelling affect the internal temperature of the dwelling which further affects the space heating requirements.

7.3.7 Mean Internal Temperature

The mean internal temperature of the dwelling is the function of the demand temperature of the living area, the fraction of living area to total area of the dwelling, heating patterns and the external temperature (BRE, 2011). The fraction of the living area is available from the dimensions model hence the only input parameters here are the living room demand temperature and the external temperature. While there is no regulatory requirement for minimum temperature settings in a dwelling, the Decent Homes Standard recommends a temperature of 21^{o}C (Communities and Local Government, 2006). The data on external temperature is maintained for stations across the UK from the Met Office (2012). Cheng & Steemers (2011) in their study have identified the heating patterns depending one the type of occupancy of the dwelling. The type of occupancy is determined from the Neighbourhood

Statistics which define the heating patterns. The temperature demand of the rest of the dwelling is calculated using the heat loss parameter determined in the heat loss model. Utilisation factor is calculated respectively for living room and the rest of the dwelling based on temperature demand, external temperatures, total heat gains and heat loss parameter. While the dwelling is not heated, the temperature of the dwelling will fall down. The heating patterns determine the number of hours the heating will be off and this temperature is calculated based on heat loss of dwelling. The demand temperature and temperature when heating is off determine the mean internal temperature of dwelling.

7.3.8 Space Heating Demand

Energy required for space heating forms the largest share of total energy use within dwelling and depends on the mean internal temperature, external temperature, total gains and heat loss (BRE, 2011). All these parameters are calculated in earlier models hence no separate user input parameters are required from a user perspective. Using the mean internal temperature identified from earlier model, the mean utilisation factor for gains is calculated. This gives a figure for the proportion of heat gains that contribute towards space heating. The heat loss parameter and the difference between mean internal and external tempreatures give the total heat loss. The difference between the total heat loss and the usegful gains is the space heating energy requirement. The total space heating energy demand of the dwelling affects the fuel requirements and thus the costs.

7.3.9 Electricity Demand

The electricity demand of the dwelling comprises the electricity required for lighting and appliances. Electricity demans is a function of the total floor area of the dwelling and the number of occupants. Adjustment is made to the calculation based on the proportion of lighting supplied by low energy bulbs. The total floor area and the number of occupants is available from the dimensions model. The total number of lighting outlets is determined from the number of rooms within the dwelling, which is available from dimensions model. The number of dwellings with low enegy lighting is the only input parameter required which is obtained from HEED which consists of information on installation measures undertaken as part of CERT and CESP (Energy Saving Trust, 2013). The total electricity demand of dwelling affects the total fuel costs.

7.3.10 Fuel Requirements, CO_2 Emissions and Costs

The total fuel requirement, CO_2 emissions and costs depend on the heating and electricity demand. All electricity demand for lights and appliances is met by sourcing the electricity from the grid, hence no fuel is being converted into energy at the point of use. For heating purposes however, some fuel needs to be converted into heat at the point of use. Thus the amount of fuel required for hotwater and space heating depends on the efficiency of the meachanism that is being used to convert fuel into useful energy. The CO_2 emissions depend on the type and quantity of fuel used. Standard emission factors for different fuel types are available in the Digest of UK Energy Statistics (Department of Energy and Climate Change, 2009). The type of fuel and efficiency of heating mechanism hence are the two inpurt parameters for this model.

In 2007, 87% of dwellings in UK had hot water and space heat supplied through dedicated central heating (Communities and Local Government, 2009). This means only one boiler is used to meet both heat demands and hence only one efficiency value is required. Of all dwellings having central heating, 86% are fuelled by natural gas boilers, the remaining being oil and solid fuel fired boilers (Communities and Local Government, 2009). For the remaining 13% dwellings however had separate mechanisms for hot water and space heating and hence separate efficiency values are needed. HEED consists of details on type of space and water heating systems from which the type of fuel and efficiency information is obtained. The per unit cost of fuel and its CO_2 emissions factors are sourced for calculations from the type of fuel selected which evaluate the total cost and CO_2 emissions from all the energy demand of the dwelling. The total cost of energy demand (for heating and lighting) of dwelling when normalised by the area of dwelling derives the SAP rating of the dwelling.

7.4 System Architecture for Improvement Scenarios

The characteristics and variables of dwelling identified in the baseline energy performance define the improvements that can be undertaken and hence the potential for energy consumption and carbon emission reduction scenarios. The relationship between the models developed for interventions described in Section 6.6 is presented in Figure 7-3 and described in following sections.

7.4.1 Fabric Change

The energy performance improvement from fabric change is the function of the lowered U value of walls, roof, floor and windows (refer Section 6.6.1). The input parameters to evaluate impact from fabric change include selecting the type of improvement for walls, roof, floor and window. The type of improvement options presented depends on the existing characteristics and is sourced from the ventilation and the heat loss model.

Wall insulation includes internal and external wall insulation option for solid walls and cavity insulation for cavity walls (Section 4.2.1). The roof insulation consists of option to increase the thickness from none (or existing) to 270 mm (Section 4.2.3). Window installation includes replacing to low-e double glazed windows (Section 4.2.4) and floor insulation includes sealing option for suspended floors (Section 4.2.2). Each type of intervention is linked to database with respective U values, fixed costs, CO_2 emissions factors and expected lifetime in years. The database provides values for calculating new energy consumption values. These values along with the output from fuel requirement, CO_2 emissions and cost model determine annual savings in energy consumption and CO_2 emissions and annual and lifetime cost savings. The annual cost savings made in fuel costs provides an indicative increase in SAP rating of the dwelling.

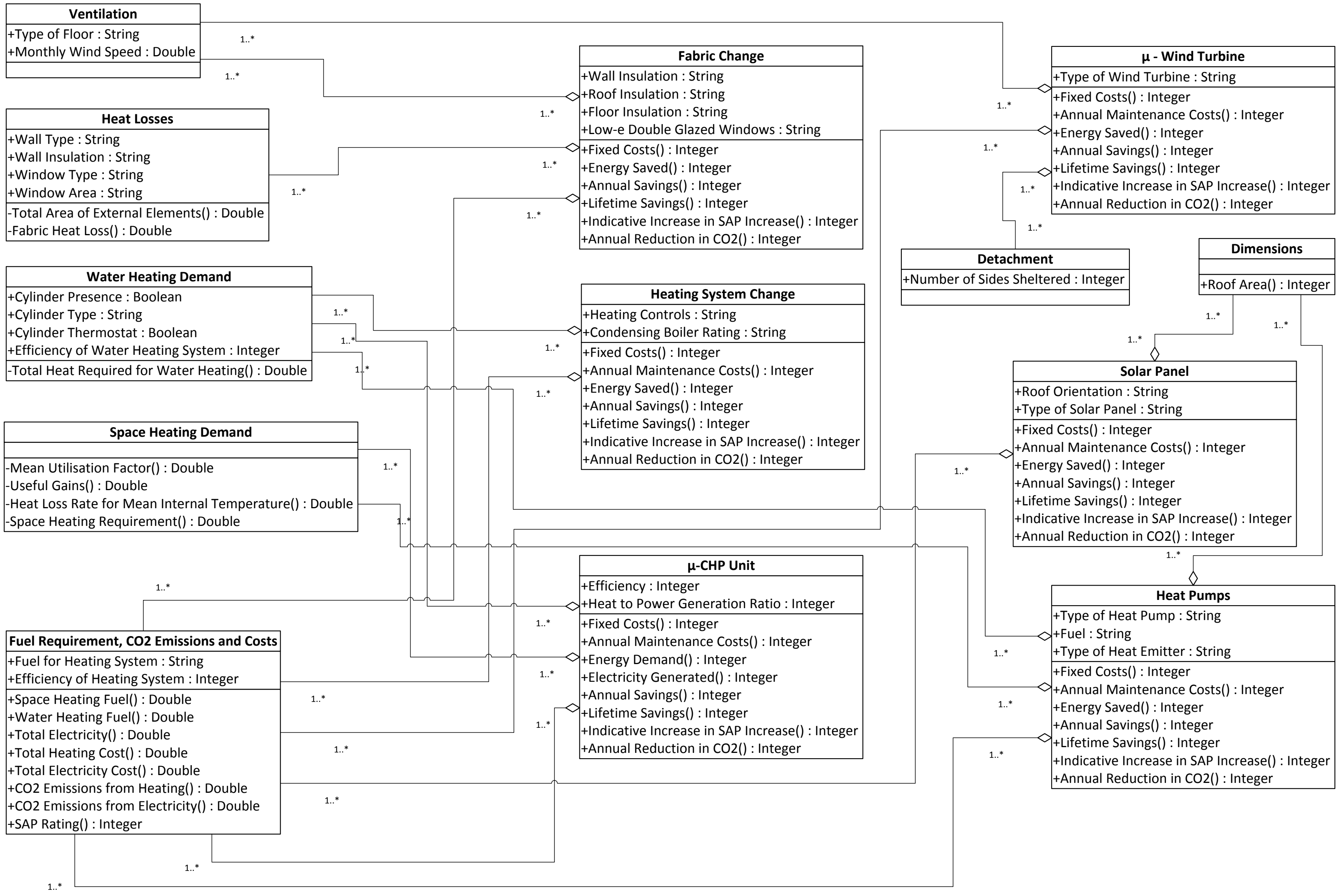


Figure 7-3: System Architecture for Improvement Scenarios

7.4.2 Heating System

The improvement in energy performance from changes to heating system is the function of improving efficiency of the heating system and is achieved through installing heating controls and condensing boilers (refer Section 6.6.2).

The input parameters for this model include selecting the type of heating controls and the rating of the condensing boiler. The type of heating control includes options such as room thermostats and thermostatic regulator valves. The options for condensing boiler include replacing the existing system with A or B rated condensing boiler. Each intervention type is linked with database providing respective values for efficiency, fixed cost, additional annual maintenance cost and expected lifetime. The new energy consumption values calculated are based on the water heating and space heating models. These values along with the output from fuel requirement, CO_2 emissions and cost model determine annual savings in energy consumption and CO_2 emissions and annual and lifetime cost savings. The annual cost savings made in fuel costs provide an indicative increase in SAP rating.

7.4.3 Solar Panels

Solar panels include installation of solar PV for electricity generation or solar thermal for hot water generation. Energy generated from solar panels is a function of available roof area and the orientation of the roof (refer Section 6.6.3). The roof area is available from the dimensions model. The orientation of roof and type of solar panel (PV or thermal) are the needed input parameters. The roof orientation is determined from vector map and aerial imagery. The type of solar panel is the choice of the user; however, installation of solar thermal is limited to dwellings having storage cylinder which is known from water heating model. The details on fixed costs, annual maintenance cost, feed-in-tariff or renewable heat incentive per unit of energy generated and lifetime are linked to a database for respective panel types. These details are accessed by equations for solar PV and solar thermal (presented in Section 6.6.3) to determine total electricity or hot water generated, annual and lifetime savings and annual CO_2 savings. The values generated are then compared with the output of the fuel requirements, CO_2 emissions and costs model to determine annual cost savings made through generation of electricity or hot water and provide indicative increase in SAP rating.

7.4.4 Micro-Wind Turbine

The energy generated from a micro-wind turbine is influenced by the average wind speed in the area and the diameter of the turbine blades (refer Section 6.6.4). The wind speed is available from the ventilation model. The planning requirements currently permit installation of micro-wind turbines only on detached properties. Dwelling detachment is available from the detachment model. The micro-wind turbines are either roof mounted or pole mounted and both of them come with standard blade diameters. Hence, the only input parameter is type of turbine.

Each type of wind turbine is linked to a database consisting information on the diameter of the blades, fixed costs, annual maintenance costs, feed-in-tariff per unit of electricity generated and lifetime. This information is sourced by equations for wind turbine (presented in Section 6.6.4) to calculate total electricity generated, income from feed-in-tariff and annual CO_2 savings from amount of electricity from grid replaced. The values generated from this model are compared with output of the fuel requirements, CO_2 emissions and costs model to determine annual and lifetime cost savings. The annual cost savings made provide indicative increase in SAP rating.

7.4.5 Micro-Combined Heat and Power Unit

The working of µ-CHP unit is influenced by the total heat demand of the dwelling, the efficiency of the unit and the heat to power generation ratio (refer Section 6.6.5). The total heat demand of the dwelling is available from the water heating and space heating demand models. The input parameters required are efficiency and power generation ratio and depends on the model under consideration. Manufacturers provide this information for every model typically as a part of product specifications.

Based on the efficiency of the model, the energy demand and amount of electricity generated from the μ-CHP unit is calculated. The details on fixed costs, annual maintenance cost, feed-in-tariff per unit of electricity generated, CO_2 emission factor and lifetime are linked to database. These details are accessed by equations for μ-CHP unit (presented in Section 6.6.5) to determine energy demand of μ-CHP unit, total electricity generated, income from feed-in-tariff and annual CO_2 savings. The values generated from this model are compared with output of the fuel requirements, CO_2 emissions and costs model to determine annual and lifetime savings and indicative increase in SAP rating.

7.4.6 Heat Pumps

This model includes options for installing either air source or ground source heat pumps to provide hot water and space heating demand of dwelling. The energy generated from either of the heat pumps is the function of the total heat demand of the dwelling and the efficiency of the heat pump (refer Section 6.6.6). The total head demand is available from water heating and space heading demand models. The efficiency of the heat pump is further influenced by the type of fuel used by the heat pump and the type of heat emitter. The type of heat pump, fuel used and emitter type are the input parameters and is linked to database with efficiencies, fixed costs, annual maintenance costs, lifetime and renewable heat incentive per unit of energy generated for each of these combinations. The choice between ground source and air source heat pump is made from the available installation area around the house the information for which is available from the dimensions model. The fuel type and the emitter type are the preferences of the user. Based on this input, total amount of heat generated, income from renewable heat incentive and annual savings in CO_2 emissions are calculated. The values generated from this model are compared with output of the fuel requirements, CO_2 emissions and costs model to determine annual and lifetime savings and indicative increase in SAP rating.

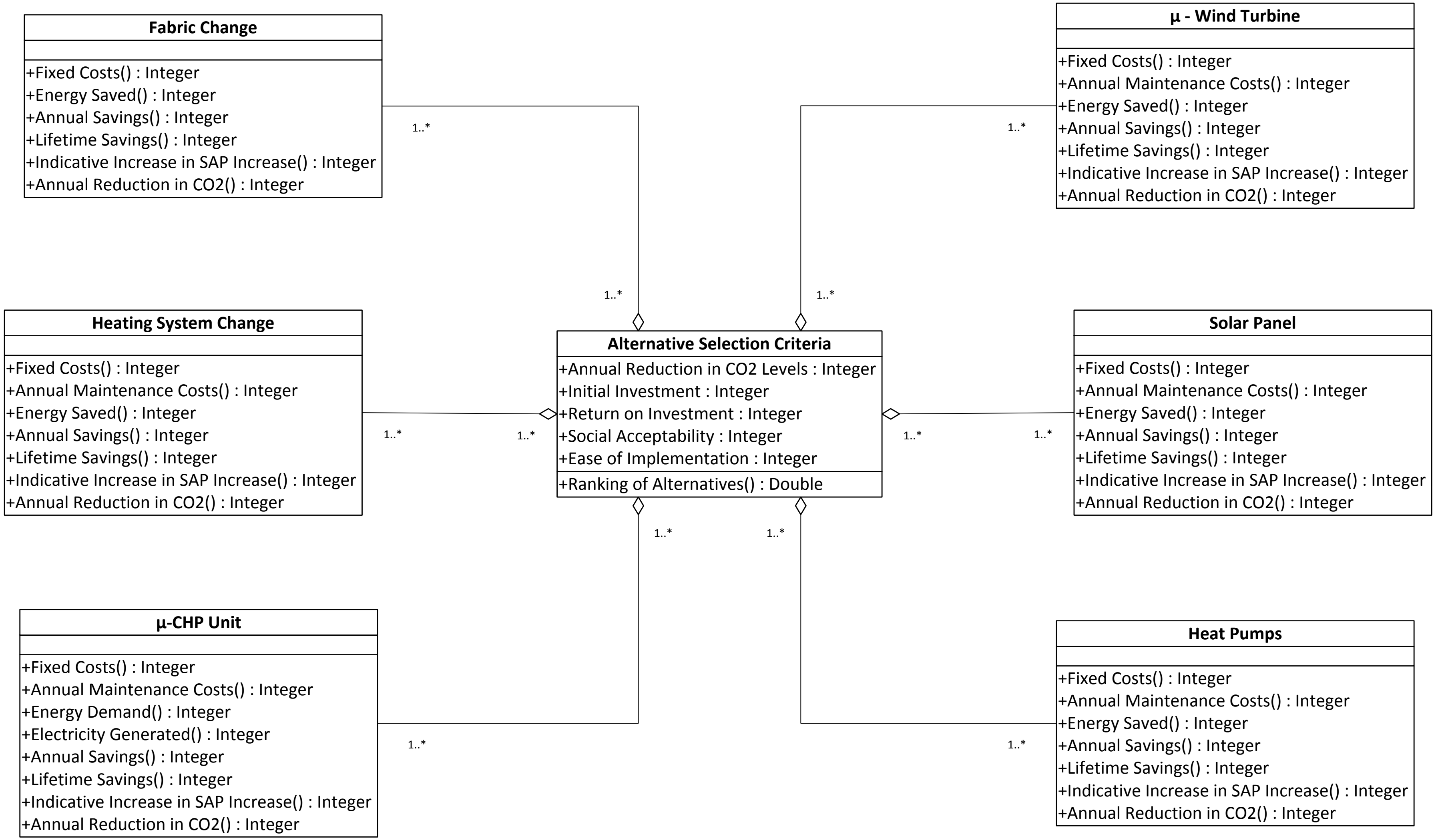


Figure 7-4: System Architecture for Decision Support Process

7.5 System Architecture for Decision Support Process

The decision support relies on ranking the criteria according to their importance and then evaluating the alternatives with each of those criteria. A detailed description of the models involved and their relationship is presented in Figure 7-4.

The input parameters are the intensities for annual reduction in CO_2 level, initial investment, return on investment, social acceptability and ease of implementation. The intensity values for tangible parameters such as annual reduction in CO_2 level, initial investment and return on investment are obtained after analysing the output of the models for each interventions described in Section 7.4. The initial investment is the fixed costs less any grants available towards installing the alternative. The fixed cost is available from models for each alternative and the grants available are condition specific determined by the user. The return on investment depends on the annual savings from using less energy, income from feed-in-tariff or renewable heat incentive and any additional maintenance costs. Social acceptability and the ease of implementation are intangible parameters and their intensities are influenced by the perspective of the stakeholders using this technique.

7.6 User Interface Design

The vector maps and aerial imagery is added in ArcGIS Explorer, which is a freely available tool from Environmental Services Research Institute. ArcGIS supports all types of maps, imagery and databases from Ordnance Survey, LandMap and Office of National Statistics described in earlier sections. All user interfaces and calculation models in this research are developed in MS-Excel as it supports complex programming models. MS-Excel is widely used and available in most organisations hence it comes as a significant advantage with testing the prototypes with stakeholders, particularly in development stages. MS-Excel allows databases to be built-in and linked with various input parameters. A menu toolbar consisting of three button controls is created as shown in Figure 7-5 below.

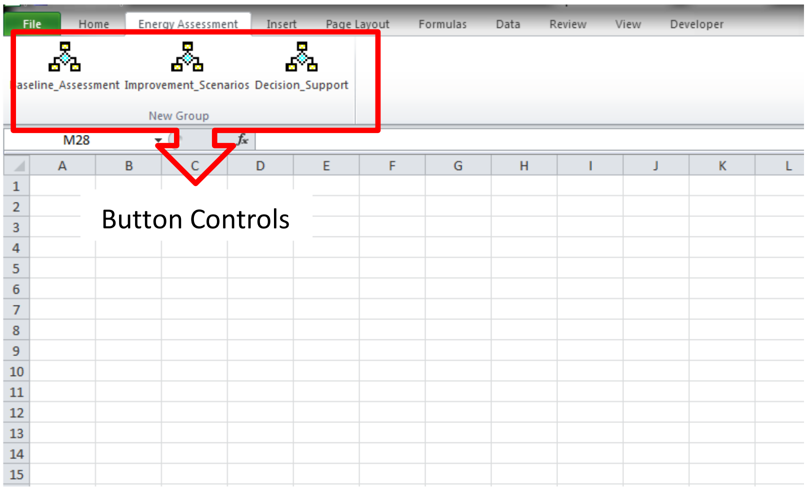


Figure 7-5: Menu Toolbar of the Prototype Tool

The three button controls represent the three main tasks that need to be undertaken with a function to open respective user-forms. Clicking on the ‘Baseline Assessment’ button control brings up the user-form shown in Figure 7-6 below.

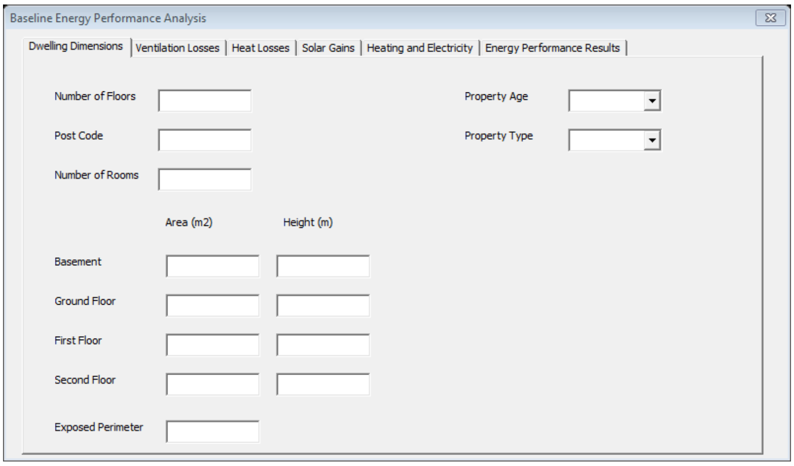


Figure 7-6: User-form for Baseline Energy Performance

The user-form consists of various tabs that correspond to the models described in Section 7.3 and also enable easy viewing for the user of the tool. Each tab on the user-form allows user to enter the ‘input parameters’ for respective models. The final tab as shown in Figure 7-7 displays the energy performance output from the calculations undertaken.

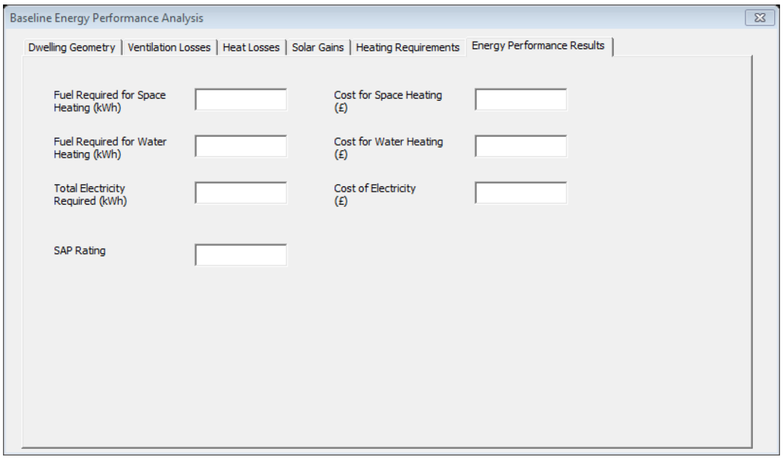


Figure 7-7: User-form Display of Energy Performance

The next button control is ‘Improvement Scenarios’, clicking on which brings the user-form shown in Figure 7-8 which allows the user to analyse the impact of various improvement measures.

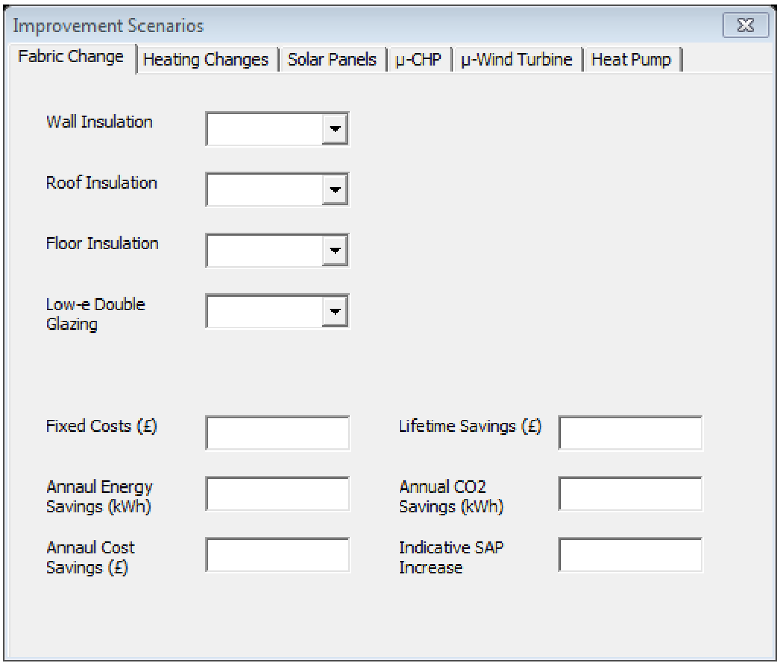
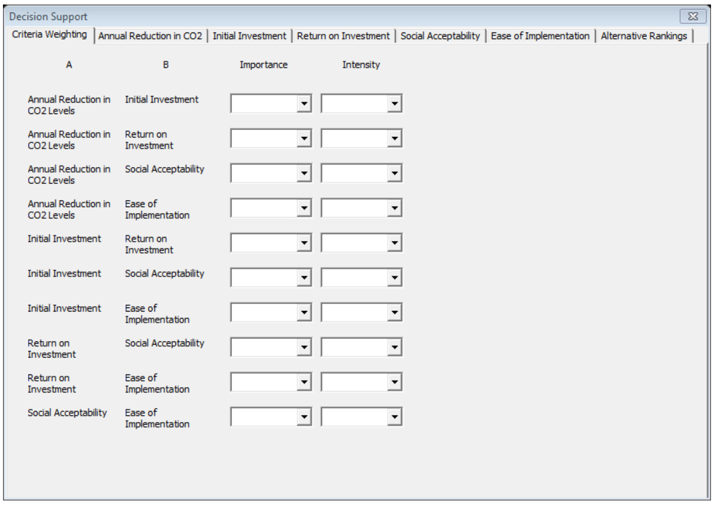


Figure 7-8: User-form for Improvement Scenarios

Similar to the earlier user form, this user-form also consists of separate tabs for energy performance improvement interventions. Each tab on the user-form allows user to enter the ‘input parameters’ for respective models identified in Section 7.4. The output from the analyses for each intervention is shown on the same tab.

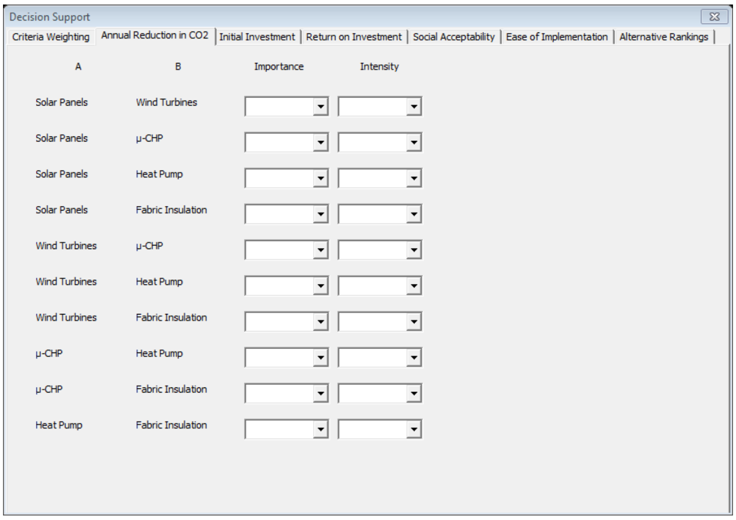
The final button control is ‘Decision Support’, clicking on which brings the user-form shown in Figure 7-9 which allows user to rank the energy performance alternatives based on tangible and intangible criteria as described in Section 6.7.



A	B	Importance	Intensity
Annual Reduction in CO2 Levels	Initial Investment		
Annual Reduction in CO2 Levels	Return on Investment		
Annual Reduction in CO2 Levels	Social Acceptability		
Annual Reduction in CO2 Levels	Ease of Implementation		
Initial Investment	Return on Investment		
Initial Investment	Social Acceptability		
Initial Investment	Ease of Implementation		
Return on Investment	Social Acceptability		
Return on Investment	Ease of Implementation		
Social Acceptability	Ease of Implementation		

Figure 7-9: User-form for Decision Support

The first tab on the user-form presents a screen where the user can provide weightage to the selection criteria through pairwise comparison. In the importance drop-down box allows user to select the column of the criteria which they think is important (A or B) and the intensity allows them to select the intensity of their importance (1 to 9). The subsequent tabs allow user to weigh the alternatives with respect to each of the criteria, an example of which is shown in Figure 7-10.



A	B	Importance	Intensity
Solar Panels	Wind Turbines		
Solar Panels	µ-CHP		
Solar Panels	Heat Pump		
Solar Panels	Fabric Insulation		
Wind Turbines	µ-CHP		
Wind Turbines	Heat Pump		
Wind Turbines	Fabric Insulation		
µ-CHP	Heat Pump		
µ-CHP	Fabric Insulation		
Heat Pump	Fabric Insulation		

Figure 7-10: Tab Showing Pairwise Comparison of Alternatives

Similar to the earlier tab, the screen allows for pairwise comparison for each alternative. The pairwise comparison of energy performance improvement alternatives is undertaken for each criterion in separate tab. The importance and the intensities are assigned in the manner described earlier.

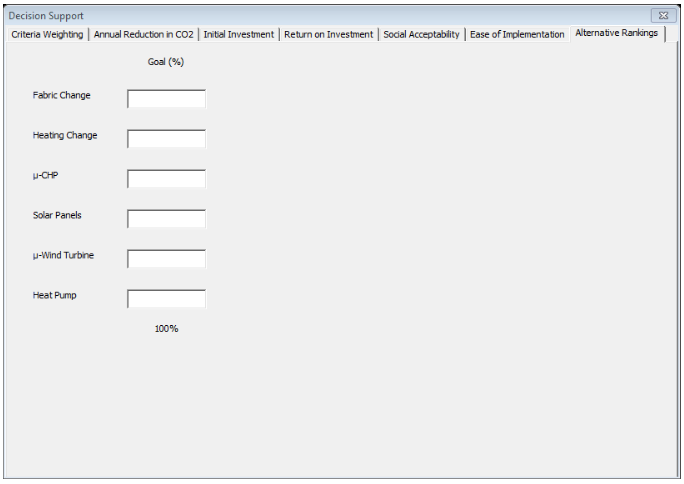


Figure 7-11: Tab Showing the Rankings of the Alternatives

The final tab, shown in Figure 7-11, displays the result of the matrix calculation described in Section 6.7. The screen displays the rankings as a percentage for each of the energy performance improvement alternative.

7.7 Summary

This chapter described the development of the prototype based on the framework described in the earlier chapter. The system architecture makes use of UML diagrams to present the relationship between various models. The input parameters required, their connections to database, the output from the models and the inter-dependencies of the models is described in detail. A prototype is developed on ArcGIS and MS Excel platform to undertake energy assessments and support decision making. The user interface is presented to describe how the user sees the input screen and the output from calculations of these models. The next chapter describes the calibration and validation of the framework and the prototype and demonstrates the practicality of the tool through case studies.

Chapter 8 Calibration, Validation and Demonstration

8.1 Introduction

In the previous chapters we have described the framework for tool development and then developed a prototype based on the framework and the system architecture. This chapter focuses on calibration and empirical validation of the developed prototype tool. Calibration is the process of checking instrument (tools) and making sure that values generated from measurements are similar to that of a given reference. It is the process of verifying that the tools work and perform within a given set of specifications (Oxford University, 1993). The calibrated and validated prototype is then used to undertake case studies to identify baseline energy performance and quantify the energy emissions and CO_2 reduction potential for various LLSOA's. The results of the baseline energy performance and the quantification of reduction potential are then presented to stakeholders to identify their preferences for the decision support tool.

8.2 Calibration

Calibration process essentially involves measurements between two values. The tool which is being calibrated is used to measure a particular instance. The results are noted. Another tool which is considered as 'standard' and whose results are certified as authentic is used to measure the same instance. The two results are then compared. If the results are similar, the tool under scrutiny is considered to give reliable results and hence is accurate. If the results do not match then troubleshooting is undertaken to identify the reasons for the mismatch and make corrections until the results obtained are similar (Taylor & Opperman, 1986).

Calibration is undertaken for the prototype tool developed in this research to ensure for similar input values entered into the prototype and the standard tool, similar outputs are obtained. For this purpose, the NHER Plan Assessor is used as the standard tool. NHER Plan Assessor is Government-authorised software for assessing the energy efficiency of dwellings. BRE has approved that the NHER Plan Assessor complies with SAP requirements and can be used to issue Energy Performance Certificates. NHER Plan Assessor is also the preferred tool for energy assessment amongst stakeholders as noted in Section 3.3.

A sample of fifteen dwellings was randomly chosen across Middlesbrough and Newcastle-upon-Tyne. Key characteristics of the dwellings which also form a part of the input parameters are presented in Table 8-1. The detailed list of input parameters for these dwellings and the output is presented in Appendix C.

Table 8-1: Sample Dwellings for Calibration of Prototype

Location		Property Type	Construction Period	Number of Floors	Total Area (m^2)
House No.	Post Code				
2	TS1 5LN	Mid Terrace	1976-1982	2	88
23	TS1 5ND	Mid Terrace	1900-1929	2	80
75	TS1 4PA	Mid Terrace	1930-1939	2	90
124	TS1 4NB	Mid Terrace	1900-1929	2	88
11	TS4 2LH	Semi-Detached	1930-1949	2	118
11	TS5 5QJ	Semi-Detached	1900-1929	3	254
24	TS5 6RY	Semi-Detached	1976-1982	2	115
42	TS5 7QB	Semi-Detached	1967-1975	2	112
27	TS7 0GB	Detached	2003-2006	2	210
5	NE4 6XB	Semi-Detached	1930-1949	2	208
36	NE28 0HG	Semi-Detached	1950-1966	2	90
90	NE4 6PS	Terraced Flat (Ground)	1900-1929	1	84

Location		**Property Type**	**Construction Period**	**Number of Floors**	**Total Area (m^2)**
House No.	**Post Code**				
21	NE8 4QQ	Terraced Flat (First Floor)	1900-1929	1	75
7	NE31 1QA	Bungalow	1930-1949	1	40
78	NE31 1YH	Detached	2003-2006	2	110

As seen from Table 8-1, the dwellings consisted of various types such as mid-terraced, semi-detached, detached, flats amongst terraced houses and bungalow. The construction period of the properties ranged from 1900 to 2006 thus all age types. The dwellings also varied in terms of their wall types, window glazing types and orientation and heating and control systems. Dwellings with all these different characteristics ensured that all parameter specific equations developed within the model are tested. This is necessary as errors may occur when several equations are programmed during prototype development, which need to be identified and rectified. The results obtained subsequent to debugging for rectification of errors are presented in Table 8-2.

The results indicate that the final values obtained for space heating, water heating and electricity for lighting from the prototype match with that obtained from the NHER Plan Assessor. Minor variations were observed in values for space and water heating, however, the maximum variation was 0.008% and can be attributed to number of decimal points considered in intermediate calculations by the prototype and NHER Plan Assessor. The prototype is thus considered to give accurate output to the given input data and hence calibrated.

Table 8-2: Calibration Results

Location		Space Heating (kWh)		Water Heating (kWh)		Electricity for Lighting (kWh)		SAP Rating	
House No.	**Post Code**	**Prototype**	**NHER**	**Prototype**	**NHER**	**Prototype**	**NHER**	**Prototype**	**NHER**
2	TS1 5LN	12008	12009	2553	2553	1123	1123	70	70
23	TS1 5ND	19986	19987	2474	2474	1029	1029	55	55
75	TS1 4PA	21951	21952	2623	2624	1129	1129	55	55
124	TS1 4NB	18997	18997	2484	2484	1504	1505	59	59
11	TS4 2LH	32091	32093	2675	2676	1299	1299	50	50
11	TS5 5QJ	77440	77446	2772	2772	1955	1956	42	42
24	TS5 6RY	19365	19365	2678	2678	1284	1284	65	65
42	TS5 7QB	28541	28542	2664	2664	1263	1263	53	53
27	TS7 0GB	25178	25178	4451	4452	1799	1800	72	72

Location		Space Heating (kWh)		Water Heating (kWh)		Electricity for Lighting (kWh)		SAP Rating	
House No.	**Post Code**	**Prototype**	**NHER**	**Prototype**	**NHER**	**Prototype**	**NHER**	**Prototype**	**NHER**
5	NE4 6XB	51431	51434	5227	5229	1766	1767	50	50
36	NE28 0HG	22533	22533	2563	2563	1099	1099	55	55
90	NE4 6PS	20087	20087	2628	2629	1077	1077	56	56
21	NE8 4QQ	10665	10665	6080	6082	983	983	63	63
7	NE31 1QA	12705	12705	1866	1866	1183	1183	53	53
78	NE31 1YH	13312	13312	4373	4374	1296	1296	70	70

8.3 Validation of the Prototype

Validation is a process which ensures that a newly developed tool/system/process functions in a manner in which it was designed for (Scott, 1997). Irving (1988) and Richards (1992) in their studies have identified that validation process is often overlooked and lack of proper methodology and data are found as some of the reasons. Validation of tool such as the one developed in this research can be attempted by analytical or empirical validation (Irving, 1988).

In analytical validation the tool is tested and compared to an exact situation from previous works or studies. The method has an advantage of being inexpensive in terms of cost and time as data may be readily available. It however has a limitations as it may not necessarily reflect the reality of the existing situation. The data available may be for limited cases thus limiting the scope of validation. In some cases the data may not cover the entire range the tool has to offer and hence only some parts of the tool may be validated (Judkoff, et al., 1983).

In empirical validation, the tool is tested and compared with real or existing situations. This method has a disadvantage over the analytical validation as obtaining precise data for existing situations can be an expensive and time consuming process. However, it offers several advantages as well. Data can be obtained for exact situations as the tool is developed for those particular situations. The entire range of data available means all parts of the tool can be validated. The validation can be undertaken on various levels of complexity and thus provides a rigorous test of performance (Judkoff, et al., 1983).

The above arguments suggest that empirical validation is clearly more suited for this study. Reliance on standard archetypes has clearly been identified as one of the limitations of previous research discussed in Section 3.4. By employing the empirical validation method, this limitation is overcome. Empirical validation of the prototype was undertaken in this research through energy performance assessment of over 100 dwellings for two social housing providers: Erimus Housing and Your Homes Newcastle.

It is mentioned earlier that Erimus Housing, was included as one of the stakeholders and they manage 15,000 properties across Middlesbrough. Your Homes Newcastle (YHN) is an Arm’s Length Management Organisation[22] responsible for managing council homes on behalf of Newcastle City Council and currently manages over 30,500 dwellings.

The Housing Act 2004 introduced the Home Information Packs which made it mandatory for an Energy Performance Certificate (EPC) to be issued for every dwelling that is being rented or sold subsequent to 1st August 2007 (Act of Parliamnent, 2004). Social housing providers and local authorities own and manage up to 20% of UK properties. Erimus Housing and YHN social housing providers have to maintain up-to-date EPCs for the dwellings that they rent out. Both these organisations kindly agreed to share the data for some of their properties for the validation purpose.

The organisations were asked to provide only the address of the dwellings for which they had undertaken energy assessments. Based on the address energy performance assessment was undertaken using the developed framework and prototype. Subsequent to the assessment the results from the prototype were compared with the energy assessment results provided by the housing providers. The housing providers had undertaken their energy assessment in the traditional method, i.e. through detail site survey. The validation will help to establish if the framework and the approach developed in this research gives results similar to that if they were undertaken using detailed site survey.

8.3.1 Validation with Erimus Housing Data

Erimus Housing provided address of 35 properties in Middlesbrough. Energy assessment of these dwellings was undertaken using the developed approach and the prototype. Table 8-3 shows a summary of two output

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[22] An arm's length management organisation is a not-for-profit company that provides housing services on behalf of a local authority (NFA, 2012).

parameters: the primary energy consumption[23] and SAP rating, estimated by the prototype and those provided by Erimus Housing, and the percentage difference between these values.

Table 8-3: Validation Results (Erimus Housing)

Location		Primary Energy (kWh/m²)			SAP Rating		
No.	**Post Code**	**Prototype**	**Erimus**	**% Diff.**	**Prototype**	**Erimus**	**% Diff.**
16	TS1 4DB	303.00	298.78	1.41	60	64	-6.32
8	TS1 5LJ	187.00	191.62	-2.41	73	79	-7.18
36	TS1 5LJ	186.00	187.52	-0.81	74	82	-9.25
29	TS1 4DA	241.00	242.86	-0.77	66	70	-5.64
5	TS5 4DZ	382.00	381.69	0.08	55	56	-1.57
3	TS1 5LL	182.88	175.00	4.51	73	79	-7.20
21	TS1 5LL	177.18	176.65	0.30	74	79	-5.97
4	TS1 5NB	194.00	190.08	2.06	72	75	-3.76
22	TS1 5NB	171.82	163.53	5.07	74	81	-8.33
3	TS1 4BS	282.75	283.26	-0.18	61	67	-9.52
43	TS1 4BU	388.23	380.96	1.91	55	52	4.96
5	TS1 5NH	249.04	249.14	-0.04	69	75	-8.56
40	TS1 5NH	272.42	286.21	-4.82	59	63	-6.01
5	TS1 4SE	233.04	221.90	5.02	67	74	-9.13
125	TS1 4SA	359.91	361.75	-0.51	56	57	-2.42
36	TS1 4BZ	278.90	272.40	2.39	59	65	-9.73

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[23] Primary energy consumption data is the total fuel requirement for heating (space and water) and lighting normalised by the area of the dwelling (BRE, 2011).

Location		Primary Energy (kWh/m^2)			SAP Rating		
No.	**Post Code**	**Prototype**	**Erimus**	**% Diff.**	**Prototype**	**Erimus**	**% Diff.**
24	TS1 4BP	275.58	267.38	3.07	66	69	-4.35
9	TS1 4JX	279.75	265.72	5.28	66	70	-6.35
2	TS1 5LN	166.07	167.63	-0.93	72	77	-6.73
7	TS1 5LN	166.07	166.18	-0.07	72	78	-7.99
26	TS1 5LN	147.35	147.86	-0.35	78	84	-6.65
33	TS1 5LF	166.53	165.00	0.93	74	78	-5.12
4	TS1 5LW	205.09	215.88	-5.00	72	73	-1.37
6	TS1 5NF	196.54	189.83	3.54	70	73	-3.52
2	TS1 5LP	164.43	163.56	0.53	76	79	-4.22
7	TS1 5LR	156.36	162.73	-3.91	76	83	-8.35
14	TS1 5LR	180.00	198.88	-9.49	75	81	-7.01
26	TS1 5LR	228.00	217.26	4.94	70	73	-4.53
96	TS1 4SL	236.97	243.08	-2.52	65	65	-0.14
4	TS1 4RR	237.70	258.95	-8.21	66	67	-0.77
12	TS1 4RS	271.63	260.57	4.24	63	68	-7.87
80	TS1 4JS	317.00	304.29	4.18	61	62	-1.96
21	TS1 5LE	222.87	212.30	4.98	74	70	5.01
22	TS1 4DE	341.60	362.59	-5.79	57	62	-8.25

The positive difference value indicates that the value calculated by the prototype is higher than that provided by Erimus Housing. A negative value indicates that the value calculated by the prototype is lower than that provided by Erimus Housing. A statistical analysis of the above values is presented in Table 8-4 and described below.

Table 8-4: Statistical Analysis of Validation Results (Erimus Housing)

	Primary Energy	SAP Rating
Mean (Average of Diff.)	0.25%	-5.17%
Standard Deviation	±3.85%	±3.70%
Standard Error	0.66	0.63
Confidence Level (95%)	±1.34%	±1.29%

The above analysis indicates that the primary energy value estimated by the prototype is on average only 0.25% higher than the actual value measured by Erimus Housing. SAP rating estimated by prototype is on average 5.17% lower than that estimated by Erimus housing. A mean value of the differences does not reflect how widely the results are distributed. Hence the standard deviation is calculated, which is approximately ±4% of the average for both the parameters. This indicates that the values are not widely distributed and close to the mean. The standard error depends on the sample mean and the sample size and provides an indication on the accuracy of the mean (Altman, 2005). A low value of 0.66 and 0.63 indicates that the accuracy level of the mean is high and the uncertainties are very low. Finally it can be said with 95% confidence level that the primary energy and SAP rating values obtained using this prototype are accurate in order of -3% to -6% each respectively of those estimated by traditional means using site survey.

8.3.2 Validation with YHN Data

A similar validation process was undertaken for 65 dwellings managed by YHN. Similar validation method was adopted wherein only the address of these properties was obtained initially and analysis undertaken with the developed prototype. The detailed results for the 65 properties (similar to the results for 35 properties presented in Table 8-3) are presented in Appendix D. Statistical analyses of the results are presented in Table 8-5 and discussed below.

Table 8-5: Statistical Analysis of Validation Results (YHN)

	Primary Energy	**SAP Rating**
Mean (Average of Diff.)	0.39%	1.40%
Standard Deviation	±5.18%	±7.02%
Standard Error	0.65	0.88
Confidence Level (95%)	±1.30%	±1.76%

The above analysis indicates that the primary energy value estimated by the prototype is on average only 0.39% higher than the actual value measured by YHN. SAP rating estimated by prototype is on average 1.4% higher than that estimated by YHN. The standard deviation is just over ±5% of average value for primary energy and ±7% of average value for SAP rating. This indicates that the validation results of YHN are spread across wider scale than the validation results presented for Erimus Housing. The standard error however is close to zero indicating the accuracy and consistency of the results. It can be said with 95% confidence level that the primary energy and SAP rating values obtained using this prototype are accurate in order of ±2% and 0% to 3% respectively of those estimated by traditional means using site survey

8.3.3 Significant Outcomes of Validation Process

The results from the two validation studies undertaken indicate that the primary energy (space heating, water heating and the electricity consumption) values estimated by the prototype have on an average less than 0.5% error with majority of values in the order of ±5%. The SAP rating was observed to have higher error compared to the primary energy in case of Erimus Housing. This can be attributed to the fact that energy assessments for Erimus Housing properties were undertaken prior to 2011, when energy prices were low. As SAP is sensitive to energy prices (lower the money spent on fuel, higher is the SAP rating), the higher SAP rating achieved by the prototype reflects reality. The energy assessment for most YHN properties was undertaken post 2011 and hence the average error is low. The confidence level margin suggests that the results are close to reality. Based on these validation results, the developed framework and the prototype are considered to provide trustworthy and reliable results.

This is a significant achievement over the limitation of earlier models (discussed in Chapter 3) in addition to the elimination of the need for site visits for energy assessments. The tool can therefore be applied for energy performance assessment of dwellings in a neighbourhood and explore their potential in reducing energy consumption and carbon emissions.

8.4 Demonstration through Case Studies

Subsequent to the calibration and validation process it is now established that the developed framework and the prototype using innovative methods, provides quick and reliable means of assessing energy performance of dwellings. To demonstrate how this can be applied in practical situations, two case studies are undertaken.

For the case studies, two neighbourhoods were selected: one neighbourhood in Middlesbrough and the other in Newcastle-upon-Tyne. Each of these neighbourhoods consisted of dwellings of various types, sizes and construction periods. Dwelling models were first created using the method described in Section 6.4. Subsequent to creation of dwelling models the prototype was then used to undertake assessment of baseline energy, quantification of energy consumption and CO_2 emission reduction potential. The improvement measures chosen for these case studies meet the best practice recommendations by the Energy Savings Trust (BRE/EST, 2007; 2005). To demonstrate the decision support tool, the results from the energy performance assessment were then shown to 32 participants in two separate focussed groups. Each focussed group consisted of 16 participants. Table

8-6 presents the participants involved from local authorities, planners, architects, building engineers, energy assessors and energy efficiency interventions suppliers.

Table 8-6: Participants Involved in Demonstration Case Studies

	Designation/Role	Organisation
1	Lead for Energy & Carbon Management	Northamptonshire County Council
2	Climate Change Manager	Leicester City Council
3	Head of Energy Services	Leicester City Council
4	Lead for Sustainability	Leicester City Council
5	Housing Asset Manager	East Midlands Housing Association
6	Energy Officer	Efficiency East Midlands
7	Housing Asset Manager	Seven Locks Housing Association
8	Managing Director	Deep Green Sustainable Solutions
9	Manager and Operations Consultant	Vanguard Homes
10	Project Manager	Parity Projects
11	Managing Director	Parity Projects
12	Sustainability Charity Director	Change Agents UK
13	Energy Officer	Change Agents UK
14	City Partnership Manager	E.ON Energy
15	Sustainable Market Harborough	Rural Community Council
16	Director / Project Officer	Saffron Community Association

17	Professor of Sustainable Architecture	Sheffield University
18	Architect	Sheffield University
19	Research / Project Officer	Action for Market Towns
20	Planner & Sustainability Consultant	Turley Associates
21	Investment Manager	North Northants Development Company / Infrastructure SPV
22	Technical Retrofits Projects Officer	Parity Projects
23	Low Carbon and Energy Consultant	Sustain 3D
24	Project Architect	Baumann Lyons Architects
25	Asset Management Officer	Middlesbrough Council
26	Conservation Planner / Urban Designer	Leeds City Council
27	Environment Officer	Bradford City Council
28	Climate Change Officer	Middlesbrough Council
29	Regional Partnerships Director	E.ON Sustainable Cities
30	Energy Management Officer	Bradford City Council
31	Reader in Building Engineering Physics	DE Montfort University
32	Professor of Intelligent Energy Systems	DE Montfort University

The participants were from the stakeholders who would be typically involved in making energy policy implementation decisions. The number of participants and their backgrounds ensured that there is no bias in the decision making process (Mishra, 2008; Bourdieu, 2001). This way the requirements of the LDF are also met.

The participants were asked to rank the energy performance improvement alternatives based on the selection criteria using the decision support tool. The findings from these case studies are presented in following sections.

8.4.1 Middlesbrough Case Study

For the case study in Middlesbrough a random LLSOA[24] consisting of properties of various type, construction period, size and tenure was chosen as shown in Figure 8-1. To create the dwelling models, the vector maps and aerial imagery was obtained and imported in GIS software.

Figure 8-1: LLSOA for Middlesbrough Case Study

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[24] LLSOA's are census areas in the UK. The information contained within the databases described in Section 6.4 is stored according to LLSOA (Office of National Statistics, 2012).

Figure 8-1 shows the aerial image obtained from Landmap as a base map. The construction period vector map sourced from Landmap is overlaid on the aerial imagery. The construction period vector map also holds data on the height of the dwellings. The dwelling address, dwelling foot-print vector maps are obtained from OS and are also overlaid on the aerial imagery. From the foot-print and height the dwelling geometry model is created and from the age and dwelling address maps, the building physics and the building usage models are created as described in Sections 6.4 and 7.3.

As all these maps are geo-referenced, the terrestrial imagery (Google Street View) of the location is also seen by clicking on any location of the map in the GIS. This is shown in Figure 8-2. The information contained within the dwelling model forms an input to the prototype.

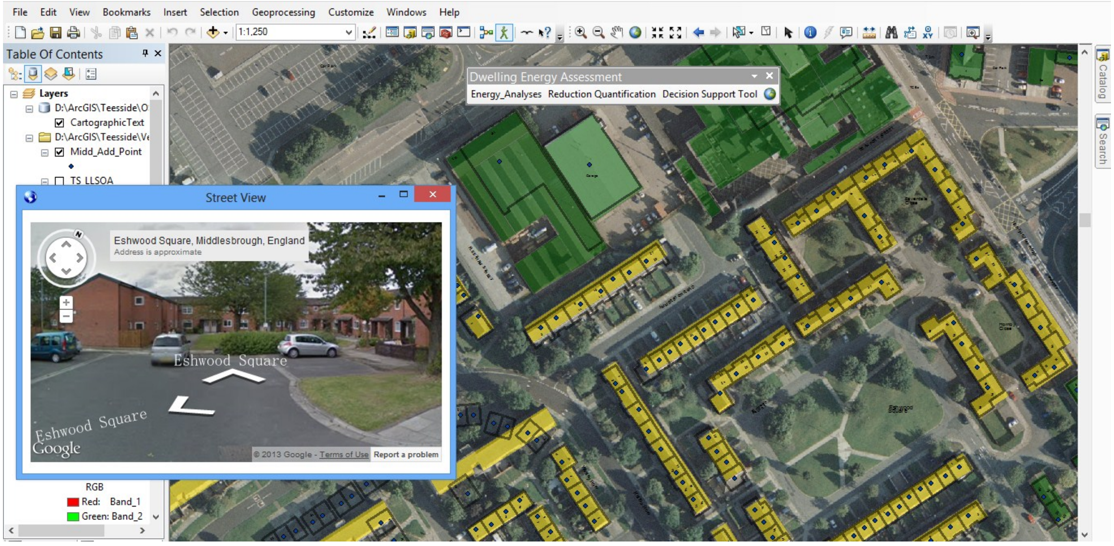

Figure 8-2: Aerial and Terrestrial Imagery in GIS

The LLSOA selected for Middlesbrough case study consisted of 765 dwellings. The dwelling model for each of these dwellings consists of information required to undertake energy assessment. This information was imported in the prototype for energy performance assessment.

Table 8-7 presents a summary of the energy required for space heating, hot water and electricity consumption for different types of dwellings. The results indicate that the total energy consumption of the 765 dwellings within the LLSOA of case study is just over 16.7 GWh per annum. This averages approximately to 21.8 MWh per annum per dwelling. The national average energy consumption estimated for domestic dwellings is 19.8 MWh per annum (OFGEM, 2011). The observed results are only slightly higher than the national average, and can be considered as consistent as most of the properties within this LLSOA are pre-war properties with low levels of thermal insulation (Energy Saving Trust, 2013).

Table 8-7: Annual Energy Consumption for Middlesbrough LLSOA

Dwelling Type	Number	Space Heating (kWh)	Hot Water (kWh)	Electricity Consumption (kWh)	SAP Rating (Avg.)
Terraced	719	11,478,600	2,952,100	1,099,964	60
Semi-Detached	23	539,882	76,126	40,953	58
Detached	14	303,548	60,039	25,223	56
Flats	9	109,456	21,465	12,737	63
Total	765	12,431,486	3,109,730	1,178,877	
Total CO_2 (Tons)		**2,461**	**616**	**609**	

Based on the characteristics of these properties and the identified baseline energy consumption information, the prototype is then used to estimate the potential for installation of energy performance improvement interventions. The prototype is developed to identify the potential for all interventions described in Chapter 4, however, µ-wind turbines and ground source heat pumps are not considered. The average wind speed in this LLSOA is less than 5 m/s. As this is below the minimum speed required for functioning of the wind turbines, they are considered unsuitable. Most dwellings in this LLSOA are terraced dwellings and it is observed from Figure 8-1 and Figure 8-2 that these dwellings do not have space for installation of ground source heat pumps. The potential for reductions in energy consumption and CO_2 emissions is presented in Table 8-8.

Table 8-8: Analyses of Interventions for Middlesbrough LLSOA

Intervention	**Fixed Cost (Million)**	**Energy Saved (MWh/ Year)**	**CO_2 Saved (Tons/ Year)**	**Annual Cost Savings**	**Lifetime Cost Savings (Million)**	**SAP Diff.**[25]
Fabric Change	£5.86	8,796	1,742	£272,600	£8.18	10
Solar Panels	£3.33	945	489	£221,400	£5.53	8
µ-CHP	£2.10	1,217	377	£117,500	£2.35	7
Heating System	£1.54	1,127	223	£35,000	£0.70	3
ASHP (Under-floor)	£3.00	2,047	405	£63,486	£1.90	8
ASHP (Radiator)	£2.40	-527	-104	-£16,400	-£0.38	-2

The results indicate that for the LLSOA under consideration, changes to building fabric offer the most potential for energy savings which also reflects in the amount of CO_2 saved. An investment of about £6 million for measures such as solid/cavity wall insulation, double glazing of windows, roof and floor insulation can result in lifetime savings of about £8 million. Changing the building fabric reduces the total space heating requirement by 70% and increases SAP rating by an average of 10.

ASHPs with under-floor heating are the next best intervention in terms of energy savings, however, they fail to offer returns on investment. An investment of £3 million returns only £1.9 million during its entire lifetime. Radiator based ASHPs have efficiencies lower than the existing boilers and

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[25] SAP Diff. indicated is the average increase/decrease observed per dwelling within the LLSOA.

hence increase the energy consumption leading to huge losses on investment.

Solar Panels are an attractive measure as they not only provide good savings in energy consumption but also offer attractive return on investment. An investment of just over £3 million returns over £5.5 million in its lifetime. Installing solar panels contributes to over 80% of the LLSOA’s electricity demand and increase the SAP rating by 8.

Installations of µ-CHP are only marginally effective in this LLSOA. This is because compared to the existing boilers µ-CHPs have only slightly higher efficiencies. Further, electricity from µ-CHP is heat driven. Given the smaller dwelling sizes, the heat demand generates only enough electricity to provide some return on investment through feed-in-tariffs.

The changes to heating systems involved installing condensing boiler and heating controls. These installations fail to achieve even break-even return on investment. Though the dwellings in this LLSOA are old, they have fairly modern boilers with an average efficiency over 80%. This leads to only marginal increase in efficiency and hence low energy savings.

To demonstrate the decision support system, the results from Table 8-8 were shown to 16 participants from various stakeholder organisations listed in Table 8-6. The group was asked to rank the interventions based on the criteria using the decision support system developed. A pairwise comparison was undertaken to first rank the criteria and then pairwise comparison was undertaken to rank the alternatives for each of these criteria. Detailed pairwise comparisons for the criteria and the alternatives for this case study are presented in Appendix E. Based on the intensities assigned during for pairwise comparison the prototype evaluates the weightage for each criterion which is summarised in Table 8-9 below.

Table 8-9: Ranking of the Criteria

Criteria	Weightage
Initial Investment	44.84%
Return on Investment	19.98%
Ease of Implementation	15.74%
Annual Reduction in CO_2 Levels	11.66%
Social Acceptability	7.77%

The weightage (eigen vector) allocated to each of these criteria after pairwise comparison indicates that initial investment is the most important criteria for the selection of any improvement measure. This is followed by the return on investment and only then is the annual reduction in CO_2 is ranked. Amongst all the criteria social acceptability has the least weightage. This indicates that stakeholders are willing to implement most energy performance improvement measures.

Subsequent to ranking the criteria, the participants were asked to undertake pairwise comparison for each of the interventions for each of the criteria. ASHP with radiator heating is not considered during this evaluation as it does not provide any energy savings or return on investment. The prototype evaluates the weights (eigen vector) for each intervention for each criteria. Based on these weights and those obtained from Table 8-9 (the next hierarchy), the final weights for the alternatives are evaluated by the prototype. A summary of the final weightage and hence the ranking of the interventions for this case study is presented in Table 8-10.

The results indicate that based on the criteria for selection, fabric change achieves the highest rank and hence is the most preferred choice of the stakeholders involved. This is followed by preference for solar panels and μ-CHP.

Table 8-10: Ranking of the Alternatives

Interventions	Weightage
Fabric Change	31.33%
Solar Panels	28.75%
µ-CHP	21.01%
Heating Systems	12.85%
ASHP (Under-floor Heating)	6.06%

ASHP is the least preferred choice amongst all the alternatives. This means that for the LLSOA under consideration, the stakeholders can focus on improving the building fabric as a priority. It is mentioned earlier that this LLSOA has majority of dwellings built prior to 1950s and hence the building fabric loose significant amount of heat. With regards to installation of renewable or low carbon energy generation technology, the stakeholders can opt for solar panels as they are more preferable over ASHP. If consideration is being given to changes to the existing boiler or replacing electrical heating, more priority can be given to µ-CHP over condensing boiler as µ-CHP also generate electricity.

8.4.2 Newcastle Case Study

For the case study in Newcastle a random LLSOA consisting of properties of various type, construction period, size and tenure was chosen. Figure 8-3 shows the aerial image and the related vector maps imported in GIS software to create dwelling models for the chosen LLSOA. Process similar to that described for the earlier case study is repeated to create dwelling models. These dwelling models consist of information that forms input to the prototype for energy performance assessment.

Figure 8-3: LLSOA for Newcastle Case Study

The LLSOA selected for Newcastle case study consisted of 570 dwellings. Based on the information within the dwelling models, baseline energy performance is first undertaken. Table 8-11 presents a summary of the energy required for space heating, hot water and electricity consumption for all the dwellings in the LLSOA.

The results indicate that the total energy consumption of the 570 dwellings within the LLSOA of case study is just over 14 GWh per annum. This averages approximately to 25.1 MWh per annum per dwelling. The national average energy consumption estimated for domestic dwellings is (OFGEM, 2011). The observed results are higher than the national average of 19.8 MWh as more than three quarters of the dwellings are semi-detached or detached houses and hence have a large surface area for heat loss. Further, most of the dwellings are pre 1965 properties when thermal insulation standards were not yet introduced.

Table 8-11: Annual Energy Consumption for Newcastle LLSOA

Dwelling Type	Number	Space Heating (kWh)	Hot Water (kWh)	Electricity Consumption (kWh)	SAP Rating (Avg.)
Terraced	166	2,356,578	968,942	270,716	59
Semi-Detached	304	6,149,565	1,515,592	581,578	56
Detached	55	1,401,120	262,295	109,193	57
Flats	45	404,450	196,575	67,671	65
Total	570	10,311,713	2,943,404	1,029,158	
Total CO_2 (Tons)		**2,041**	**582**	**532**	

Based on the characteristics of the dwellings and the identified baseline energy consumption, the prototype is then used to estimate the potential for installation of energy performance improvement interventions. Similar to the earlier case study, µ-wind turbines are not considered as the average wind speed in this LLSOA is less than 5 m/s. Contrary to the earlier case study, most dwellings in this LLSOA are semi-detached or detached dwellings and it is observed from Figure 8-3 that these dwellings have space for installation of ground source heat pumps. As only one heat pump technology is feasible at a time, ASHP is not considered for this scenario. The potential for reductions in energy consumption and CO_2 emissions from this LLSOA is presented in Table 8-12.

The results indicate that fabric insulation once again offers the most energy savings. This is due to the fact that most dwellings in this LLSOA have more exposed wall areas. Thus just over £3 million investment yields a return of over £8 million during the expected lifetime. This LLSOA also has more dwellings with south-facing roof and also has larger average roof area per dwelling. This means that more solar panel modules can be fitted on each roof tops leading to more energy generation and hence better return on investment than the earlier case study.

Table 8-12: Analyses of Interventions for Newcastle LLSOA

Intervention	Fixed Cost (Million)	Energy Saved (MWh/ Year)	CO_2 Saved (Tons/ Year)	Annual Cost Savings	Lifetime Cost Savings	SAP Diff.
Fabric Change	£3.02	8,975	1,795	£281,090	£8,432,708	11
Solar Panels	£1.79	672	347	£157,288	£3,932,193	9
μ-CHP	£0.95	669	214	£135,702	£2,714,040	8
Heating System	£0.70	978	196	£30,320	£606,409	3
GSHP (Under-floor)	£2.70	3411	682	£106,808	£3,204,240	8
GSHP (Radiator)	£2.40	9	2	£21,552	£646,600	2

Heating systems again fail to provide return on investment during the lifetime of the product as the increase in efficiency of the condensing boilers is only marginal over the existing. This is however not the case with μ-CHP systems and they continue to offer good return on investment. GSHP with under-floor heating are also an attractive option as they offer higher energy savings due to their higher coefficient of performance. Though initial cost of installation per dwelling is higher, they offer comparable return on investment during their lifetime. GSHP with radiator heating offer very low energy savings compared to the costs involved. This leads to very low savings and hence no return on investment during their lifetime. The results confirm that only by improving the building fabric and installation of solar panels about 70% reduction in CO_2 emissions can be achieved.

The results from Table 8-12 were shown to 16 participants from various stakeholder organisations listed in Table 8-6. Similar to the earlier case study, the group was asked to rank the interventions based on the criteria using the decision support system developed. Detailed pairwise comparisons for the criteria and the alternatives for this case study are presented in Appendix F. Based on the intensities assigned during for pairwise comparison the prototype evaluates the weightage for each criterion which is summarised in Table 8-13 below.

Table 8-13: Ranking of the Criteria

Criteria	Weightage
Annual Reduction in CO_2 Levels	49.68%
Initial Investment	21.57%
Return on Investment	13.23%
Social Acceptability	7.00%
Ease of Implementation	8.52%

The weightage (eigen vector) allocated to each of these criteria after pairwise comparison indicates that for the stakeholders in this case study, annual reduction in CO_2 levels is the most important criteria for the selection of any improvement measure. This is followed by the initial investment required and then the return on investment. The rankings are unsurprising as we have seen that the average energy consumption per dwelling in this LLSOA is much higher than the national average. Amongst all the criteria social acceptability again has the least weightage. This indicates that stakeholders are willing to implement energy performance improvement measures.

Subsequent to ranking the criteria, the participants were asked to undertake pairwise comparison for each of the interventions for each of the criteria. GSHP with radiator heating is not considered during this evaluation as it does not provide any return on investment. The prototype evaluates the weights (eigen vector) for each intervention for each criteria. Based on these weights and those obtained from Table 8-13 (the next hierarchy), the final weights for the alternatives are evaluated by the prototype. A summary of the final weightage and hence the ranking of the interventions for this case study is presented in Table 8-14.

Table 8-14: Ranking of the Alternatives

Interventions	Weightage
Fabric Change	41.97%
Solar Panels	23.37%
μ-CHP	15.90%
GSHP (Under-floor Heating)	12.60%
Heating Systems	6.16%

The results indicate that based on the criteria for selection, fabric change again achieves the highest rank and hence is the most preferred choice of the stakeholders involved. This is followed by preference for solar panels and μ-CHP, similar to that observed in earlier case study. GSHP though expensive to install is preferred over changes to heating system (installing condensing boilers) as offer better energy savings and return on investment.

This means that for the LLSOA under consideration, the stakeholders can focus on improving the building fabric as a priority. Though most of the dwellings in this LLSOA are built between 1930s and 1970s and have cavity walls, further energy savings can be achieved by filling these cavities and further adding external or internal insulation. This LLSOA has an added advantage of installing solar panels and GSHP as renewable and low carbon energy generation techniques. This makes it possible to install GSHPs with compressors that can be run on electricity provided by solar panels and make the system more sustainable.

8.4.3 Significant Outcomes of Demonstration Process

The demonstration process has presented the practical applicability of the tool and its effectiveness in making decisions amongst stakeholders. Both the case studies have demonstrated a potential for approximately 70% reduction in CO_2 emissions from the LLSOAs albeit with different intervention implementations. Both the case studies confirmed that fabric change can reduce the space heating demand by 80% and solar panels can contribute to over 80% of dwellings electricity demand. The variations in the results indicate that as the characteristics of the dwellings change, the baseline energy consumption and the potential for reduction in energy consumption and CO_2 emissions change. The previous energy models discussed in Section 3.2 used standard archetypes which did not reflect the actual characteristics within a particular area. However, with the developed framework and prototype, the user can now create archetypes that are realistic of the area under consideration. It is to be noted that in both case studies, the best practice guidelines from Building Regulations were used. If interventions of higher performance are chosen, even more energy consumption and carbon emission savings can be achieved.

The results from the case studies also indicate that interventions that are good in one particular area may not be as effective in another area. As the prototype informs these results, informed judgement can be made for implementation. Only one scenario has been undertaken for each case study for demonstration purpose, however, in practical situations, several scenarios can be undertaken for each area under consideration depending on the emission targets that the stakeholders need to achieve or the investment budgets available. For e.g. for a limited budget available, fabric insulation levels can be increased beyond the best practice guidance levels in short term over installation of more expensive solar thermal panels.

The results from the prototype can be transferred to GIS for making thematic maps on various geographical levels. Figure 8-4 shows the average space heating values of dwellings on various LLSOAs. Several such thematic maps can be prepared such as a map showing the existing wall insulation levels in a particular area. Maps of several combinations can also be prepared by sourcing other data. For e.g. maps of dwellings with poor energy performance can be overlaid on a map showing fuel poor areas, so as to target these dwellings for improvement measures as a priority over other dwellings.

Figure 8-4: Average Space Heating Values in Different LLSOA's

8.5 Summary

The framework and the prototype developed to meet the gaps identified in the research is calibrated and validated in this chapter. The results from the calibration indicate that for similar inputs, the results from the prototype match that of the BRE approved energy assessment software. The validation process undertaken for two social housing providers helped to establish the confidence level of the results provided by the prototype. The results from the prototype are within ±5% of the empirical observation levels. Output parameters such as space heating, hot water, electricity and SAP rating, are the key parameters for domestic energy assessments which all fall within this range. The results from the prototype are thus reliable and trustworthy.

Finally, two case studies are undertaken to demonstrate the effectiveness of the tool in practical situations. The results from both the studies indicate that fabric insulation and installation of solar panels contribute to 80% reduction in The case studies indicate the dwelling characteristics vary widely across the regions and hence it also affects the energy consumption levels. This has an impact on type of energy performance improvement interventions applicable for the area and their costs. The decision support tool finally helps to establish the ranks of the interventions based on various criteria and help stakeholders in making informed choice regarding their implementation. Energy performance assessment of several hundred dwellings can be undertaken by employing this framework and prototype in a day as opposed to several days or months required by the traditional drive-by or site visit methods. The next chapter discusses the major outcomes of this research and concludes describing further research opportunities.

Chapter 9 Discussions, Conclusion and Future Work

9.1 Introduction

This chapter concludes the research by presenting a recap of the objectives along with a description on how they have been met. The first chapter set the tone for the research through establishing the aims and objectives. The subsequent chapters helped in achieving these objectives and meeting the aims of the research. The previous chapter presented the calibration and validation the framework and prototype and demonstrated its application through case studies. Major findings during the process of meeting these objectives are discussed here. The chapter finally states how this research can form a basis of future applications and research.

9.2 Recap of Aims of this Research

Kyoto Protocol places a need on the industrialised nations to reduce their CO_2 emissions through increased use of renewable energy sources and reducing energy demand. The UK's commitment is for a reduction in greenhouse gas emissions of 20% by 2020 and by 80% by 2050 from 1990 levels. The UK housing stock is one of the oldest and the least efficient in Europe and contributes to more than a quarter of the total emissions. The reduction of CO_2 emissions from the existing dwellings is thus a key component of meeting the overall CO_2 emissions reduction target. UK has developed several energy policies to compliment the reduction targets. The research thus aimed to assess energy performance of dwellings using innovative techniques and develop decision support tool for selection of energy performance improvement interventions. This would enable the stakeholders to implement the energy policies and meet their energy emissions and CO_2 reduction targets in an informed manner.

9.3 Discussions on Findings

This section reiterates the objectives set out earlier and describes key findings during the course of achieving these objectives towards meeting the aim of the research.

9.3.1 Obj. 1: Review of Existing Energy Assessment Techniques

This objective is achieved through literature review presented in Chapter 2. The techniques to model energy consumption in residential sector can be broadly classified into ‘top-down’ and ‘bottom-up’ approaches. The approaches have a vast diversity in terms of their level of detail, their complexity, the data input required by the user, the time periods covered and their geographical coverage. The major finding of this objective is that, bottom-up models have an advantage over top down models in estimating energy consumption of dwellings and also identifying the impact of technology on energy demand. Building physics based bottom-up method was chosen to undertake energy performance assessment for this research.

9.3.2 Obj. 2 & 3: Review of Performance Characteristics & Data Sources

These objectives are achieved through review of building physics based bottom-up methods developed for the UK housing stock and discussions with stakeholders. Notable models such as BREHOMES, Johnston Model, UKDCM, DECarb, DECoRuM, EEP and CDEM were reviewed. The review and discussions with stakeholder also helped to identify how the existing models and tools are currently being used by the stakeholders.

The finding of the review of these models is that the energy consumption of the dwelling is assessed by the energy balance i.e. heat lost to atmosphere and heat generated to maintain minimum levels of comfort. Heat is lost through built fabric (types of wall, roof, floor and windows). Type, efficiency and usage of heating systems within the dwelling define the total energy demand of the dwelling. The electricity demand of the dwelling depends on its size and number of occupants. Literature review in Chapter 3 also identified the sources where data on these characteristics and variable can be obtained, the third objective of this research. The finding of achieving this objective is that dwellings built during particular periods have certain construction characteristics that define the characteristics and variable required for energy performance.

The most significant outcome of achieving these two objectives was that they established the gaps in the existing tools and methods and helped to understand the requirements of the stakeholders. This is a step towards making key contributions to knowledge. The transparency of models in terms of data sources and model structures was recognised as a crucial issue. All these models rely on standard archetype models of dwellings which are limited in number or drive-by surveys to determine dwelling characteristics. These models assist in informing policy development, but none of them assist stakeholders involved in implementing these policies. All the models fail to consider the requirement of LDF of taking into consideration stakeholder requirements during energy related urban planning. Discussions with stakeholders revealed that none of the reviewed models and tools were currently being used. Complexity regarding their use, amount of data required and the time required for data gathering and input were cited as major concerns. The discussions also revealed that currently there is no formal method for choosing between energy performance improvement interventions. The participants mentioned that they currently lack a tool that allows them to construct scenarios for energy performance improvements for practical cases. The characteristics, variables, data sources limitations of the existing models, the gaps identified and the requirements of the stakeholders helped to establish the concept of the framework and the prototype.

9.3.3 Obj. 4: Review of Energy Performance Improvement Interventions

The major finding of achieving this objective is that changes to building fabric (wall, roof and floor insulation and low-e windows), changes to heating systems (condensing boilers and heating controls), solar panels (PV and thermal), µ-CHP, µ-wind turbines and heat pumps can significantly contribute to improvement in energy performance. There are several types available within each option and they improve the characteristics and variables of energy performance at various levels. The interventions discussed are identified by stakeholders as most commonly implemented measures. The measures also meet the requirements of micro-generation technologies and can be implemented on individual dwelling level. The renewable and low carbon energy generation technologies discussed are eligible for feed-in-tariffs or renewable heat incentives. These findings are used to quantify the energy consumption and CO_2 reduction scenarios.

9.3.4 Obj. 5: Review of Decision Support Systems

Lack of decision support in selection of interventions is one of the key gaps identified from literature review and stakeholder engagement. Thus selecting a method that allows stakeholders to choose between various interventions was the next objective. Review multi-criteria decision analyses techniques such as TOPSIS, PROMETHEE, SMART, ELECTRE, Fuzzy-MCDA and AHP was undertaken. A critical analysis of these techniques revealed that AHP is the most suitable method for this research as it can efficiently handle tangible and intangible parameters. It can break the problem in hierarchy and allows ranking of the alternatives through pairwise comparison.

The major outcome of achieving this objective was that it helped to establish the criteria for selecting the alternatives. Technological, environmental, economic and social criteria are identified as the most important in decision making. Most common factors amongst these criteria were selected and discussed with the stakeholders. Taking into consideration their opinion a final list of criteria is drawn which forms input to the framework and prototype.

9.3.5 Obj. 6: Development of Framework

The major findings of achieving this objective are that the developed framework overcomes several limitations and gaps of the models previously described. It also meets the requirements of the stakeholders identified earlier. Achieving this objective makes key contributions to knowledge.

The IDEF0 diagrams presented in this chapter describe the activities that need to be undertaken to estimate baseline energy performance, quantification of energy consumption and CO_2 emission reduction potential and the decision support. The activities consist of various energy calculation models that contribute to determining the energy balance. Several energy and cost savings models were developed that also included the feed-in-tariff and renewable heat incentives. This is one of the key contributions of this research. The framework allows user to develop archetypes of dwellings rather than using standard archetypes for energy assessment, overcoming a major limitation of earlier models. The framework makes innovative use of digital maps, aerial and terrestrial imagery and national databases thus eliminating the need for drive-by surveys. The framework integrates decision support system thus addressing a gap in the previous models and meeting the requirements of LDF and the stakeholders.

9.3.6 Obj. 7: Development of Prototype

Similar to the earlier objective, achieving this objective has overcome several limitations and gaps of the models previously described. It meets the requirements of the stakeholders and makes key contributions to knowledge.

The system architecture presented in this chapter using UML diagrams clearly describe how the activities and models from the framework relate with each other. It explains the input and output parameters and their inter-dependencies. This makes the developed framework and prototype transparent, overcoming another limitation of previous models. The framework and the system architecture inform the development of prototype which enables the energy performance evaluations to be undertaken. The framework feeds most of the information to the prototype thus reducing amount of data input for end user. Yet the user has access to these parameters to make changes if required. This meets another requirement of the stakeholders. The prototype allows user to undertake several scenarios for energy performance improvement at various geographical levels and estimate the energy consumption and CO_2 reduction potential. It also generates values such as installation costs and annual and lifetime cost savings. The prototype finally allows ranking of the alternatives based on criteria. This addresses another gap amongst previous models and the requirements of the stakeholders.

9.3.7 Obj. 8: Calibration, Validation and Case Study

Calibration was undertaken by performing energy assessment of 15 dwellings representing various construction periods, types and sizes. Same data was input into the newly developed prototype and BRE approved NHER Plan Assessor. The results from both the tool match accurately. The major finding of the calibration process is that there are no errors in the tool.

Subsequently, validation was undertaken with empirical data available for 100 dwellings from two social housing providers. Baseline energy assessment was undertaken for these dwellings based on the developed framework using the prototype. The results from this assessment were then compared with the empirical data available for these dwellings. The major findings of the validation process is that the assessment results obtained from the prototype are within a range of ±5% of those obtained by traditional method with a 95% confidence level. Thus the results are very close to reality and hence the framework and the prototype provide reliable and trustworthy results.

The practical applicability of the tool was demonstrated by undertaking two case studies with involvement of stakeholders. The framework and the prototype were applied to two LLSOA's. The LLSOA in Middlesbrough consisted on 765 dwellings and the LLSOA in Newcastle consisted of 570 dwellings. Both the LLSOA's consisted of dwellings of various construction period, type, size and tenure. The prototype evaluated average dwelling energy consumption of 20 MWh/Annum for Middlesbrough LLSOA and 25 MWh/Annum for Newcastle LLSOA. The prototype further confirmed that just fabric change and installation of solar panels have a potential to reduce about 70% CO_2 emissions in each case study. The savings in energy consumption and cost of fuel can increase the average SAP rating by 18. The performance assessment results were then shown to participants in two separate focussed groups to rank the improvement measures based on selection criteria. In both case studies fabric change and solar panels were the most preferred interventions with at least 31% and 23% weightage respectively.

The demonstration process not only proved the practical application of the framework and prototype but also the vast range of scenarios that can be processed and analysed. The implementation of energy performance improvement interventions though this informed decision support system can significantly contribute towards the UK target of 80% reduction in greenhouse gas emissions by 2050.

The case studies have also revealed that best option for improvement of energy performance can be different for different dwellings. Installation of heat pumps may not be ideal in some cases as it may return only losses. For some interventions, the amount of energy saved or the return on investment may indicate that the installation of that intervention is not justified. This is one of the unique outcomes of this research that can be greatly exploited in future work.

9.4 Conclusion

The research was initiated with an intention to contribute to reducing the carbon emissions and help in meeting UK’s international and national commitments. Niche area of energy consumption within the dwellings was selected as it is a significant factor and aims and objectives were correspondingly set. The literature review undertaken in this research has identified several gaps in the models developed to assess energy performance of dwellings in the last three decades. Key gaps identified are in relation to implementation of various energy policies developed in UK to meet energy consumption and carbon emission reduction targets. The findings of this literature review were supplemented through initial discussions with the stakeholders. A comprehensive review of the energy performance improvement measures and the existing decision support systems was undertaken in an attempt to address the identified gaps and requirements of energy policies and the stakeholders. These reviews enabled development of a framework to for estimating energy performance and decision support in implementation of energy performance improvement measures. Based on the framework, a prototype was developed which was calibrated and validated to ensure reliability. Case studies were undertaken using the developed framework and the prototype to demonstrate its applicability and capabilities. The case studies confirm that 80% reduction in energy consumption is a possibility through effective implementation of energy performance improvement measures. The findings from this research and the development of the framework and prototype form a significant contribution to knowledge. The outcomes of this research are not only expected to help in meeting the carbon reduction targets but also pave a way for future work.

9.5 Recommendations for Future Work

9.5.1 Commercial Application

The tool developed in this research, though useful, is only a prototype. Switching between the GIS software and the MS-Excel is still a limitation of this prototype. Though a vast amount of database is created, it is in MS-Excel. The research has now confirmed that the tool of this capacity has a good potential for practical use. The prototype can be further developed to make it commercially more attractive and viable. One such option is to integrate the prototype within commercially available software such as ArcGIS.

GIS is a promising branch of Information Technology (IT) and has achieved considerable success in recent years. This area of IT has concentrated on the construction of computer-based information systems that enable capture, modelling, storage, retrieval, sharing, manipulation, analysis, and presentation of geographically referenced data (Worboys & Duckham, 2004). ArcGIS is currently the most widely used commercial GIS platforms (Teng, et al., 2008).

ArcGIS is built on a technology framework known as ArcObjects. ArcObjects is a set of platform-independent software components, written in C++, which provides services to support GIS applications on the desktop in the form of thick and thin clients and on the server. ArcObjects makes use of the Microsoft Component Object Model (COM) (ESRI, 2004). COM is a standard that enhances software interoperability. Interoperability is the ability of two or more software components to directly cooperate/communicate despite of their differences in programming language, interface, and execution platform (Finkelstein, 1998). ArcObjects is a development environment used to customise and extend capabilities of ArcGIS using the embedded Visual Basic for Applications (VBA). Developers can create add-ons suited to their needs using VBA which comes along with ArcGIS as a part of the Software Development Kit (SDK). There are three levels of customisation provided in ArcGIS (ESRI, 2004):

1. Develop process models – The process models access the attributes from the input data to undertake defined mathematical evaluations.
2. Creation of user interface – The user interface allows users to input data required to create dwelling models and store the input information as attributes in a database.
3. Use an external development environment to create a standalone COM component to create executable add-on files.

Stage 1 and Stage 2 of the above levels has already been undertaken in this research. Hence it is about implementing Stage 3 especially with the use of IDEF0 and UML diagrams.

9.5.2 Research Application

The framework and the prototype developed in this research help in generating a vast array of information on existing and predicted energy performance of the dwellings. The demonstration has considered only one improvement scenario, however, the framework and the prototype can be used to undertake several scenarios. The generated information can be analysed to better understand the impact of implementation of technologies to dwellings of various characteristics. The cost models developed in this research can be further investigated and improved to include factors such as rate of interests, inflation, etc. Including these factors may also make it possible to inform energy pricing policies at a national level.

This research has already informed some parts of a project co-funded by the European Commission within the 7th Framework Programme. The project deals with development of Semantic Tools for Carbon Reduction in Urban Planning[26](SEMANCO). The framework and the prototype developed within this research are being adopted in the SEMANCO project for building extraction, classification, energy simulation and trade-off.

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[26] Project ICT 287534; Start Date: 1st Sep 2011; Duration: 36 months; http://semanco-project.eu/

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Appendix A Stakeholder Semi-Structured Interview[27]

Name of the Participant:

Role of the Participant:

Brief Profile of the Participant:

Questions:

1. What domestic energy modelling tools do you currently use?

2. How do you obtain the data required to undertake the energy modelling?

3. Is all required data usually available or any assumptions made? If yes, what is the basis of those assumptions?

4. What are the perceptions and constrains of the tools currently being used?

5. What is the stage at which the decisions related to energy consumption of dwellings is made?

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[27] Source (Hague & Hague, 2004)

6. What is the current process of making decisions regarding the improvement of energy efficiency of the dwellings?
7. Do you currently use any tools to support your decision making?
8. What are the alternatives of energy efficiency or renewable energy interventions that you typically consider?
9. What are the criteria based on which decisions on energy efficiency or renewable energy interventions are made?
10. What are the typical obstacles to implementation of energy efficiency and renewable energy interventions?
11. What are the stages at which these obstacles are observed? i.e. discussions with the householders, etc.

Appendix B Solar Radiation Constants[28]

For Vertical Surfaces:

$$A = k_1 + k_2 + k_3$$

$$B = k_4 + k_5 + k_6$$

$$C = k_7 + k_8 + k_9 + 1$$

For Inclined Surfaces:

$$A = k_1 \times sin^3 p \times k_2 \times sin^2 p + k_3 \times \sin p$$

$$B = k_4 \times sin^3 p \times k_5 \times sin^2 p + k_6 \times \sin p$$

$$C = k_7 \times sin^3 p \times k_8 \times sin^2 p + k_9 \times \sin p + 1$$

Constants K1 to K9 Shown in Following Table:

	North	**NE/NW**	**East/West**	**SE/SW**	**South**
k_1	0.056	-2.85	-0.241	0.839	2.35
k_2	-5.79	2.89	-0.024	-0.604	-2.97
k_3	6.23	0.298	0.351	0.989	2.4
k_4	3.32	4.52	0.604	-0.554	-3.04
k_5	-0.159	-6.28	-0.494	0.251	3.88
k_6	-3.74	1.47	-0.502	-2.49	-4.97
k_7	-2.7	-2.58	-1.79	-2.0	-1.31
k_8	3.45	3.96	2.06	2.28	1.27
k_9	-1.21	-1.88	-0.405	0.807	1.83

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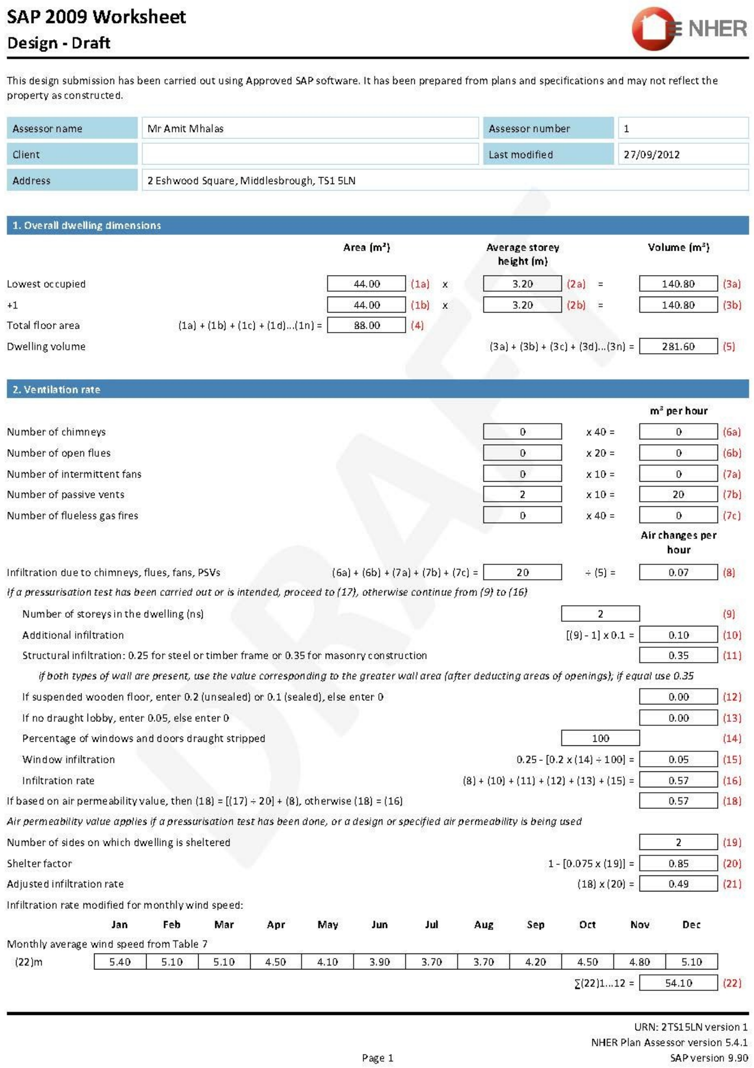
[28] Source (Šúri, et al., 2005)

Appendix C Calibration Data



SAP 2009 Worksheet

Design - Draft

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	27/09/2012
Address	2 Eshwood Square, Middlesbrough, TS1 5LN		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		44.00	(1a)	x	3.20	(2a)	=	140.80	(3a)
+1		44.00	(1b)	x	3.20	(2b)	=	140.80	(3b)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	88.00	(4)						
Dwelling volume							(3a) + (3b) + (3c) + (3d)...(3n) =	281.60	(5)

2. Ventilation rate

			m³ per hour	
Number of chimneys	0	x 40 =	0	(6a)
Number of open flues	0	x 20 =	0	(6b)
Number of intermittent fans	0	x 10 =	0	(7a)
Number of passive vents	2	x 10 =	20	(7b)
Number of flueless gas fires	0	x 40 =	0	(7c)

				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	20	÷ (5) =	0.07	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		2		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.10	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.00	(12)
If no draught lobby, enter 0.05, else enter 0			0.00	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.57	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.57	(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		2	(19)
Shelter factor	1 - [0.075 x (19)] =	0.85	(20)
Adjusted infiltration rate	(18) x (20) =	0.49	(21)

Infiltration rate modified for monthly wind speed:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average wind speed from Table 7												
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)

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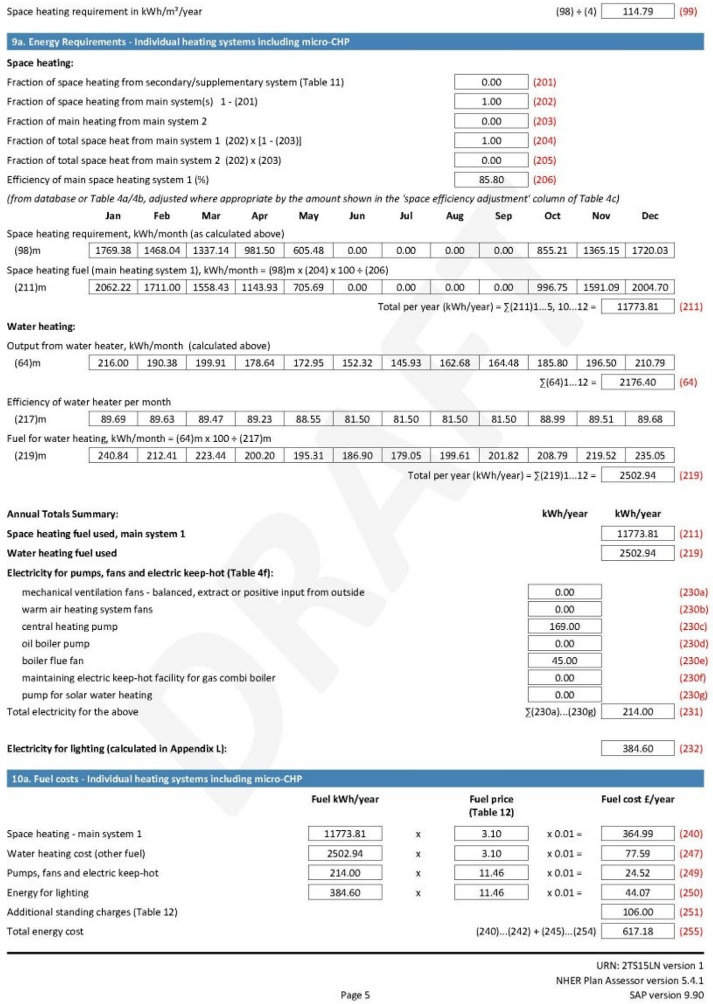

Space heating requirement in kWh/m²/year	(98) ÷ (4)	114.79	(99)

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	85.80	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space heating requirement, kWh/month (as calculated above)												
(98)m	1769.38	1468.04	1337.14	981.50	605.48	0.00	0.00	0.00	0.00	855.21	1365.15	1720.03
Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)												
(211)m	2062.22	1711.00	1558.43	1143.93	705.69	0.00	0.00	0.00	0.00	996.75	1591.09	2004.70

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 11773.81 (211)

Water heating:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Output from water heater, kWh/month (calculated above)												
(64)m	216.00	190.38	199.91	178.64	172.95	152.32	145.93	162.68	164.48	185.80	196.50	210.79

∑(64)1...12 = 2176.40 (64)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Efficiency of water heater per month												
(217)m	89.69	89.63	89.47	89.23	88.55	81.50	81.50	81.50	81.50	88.99	89.51	89.68
Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m												
(219)m	240.84	212.41	223.44	200.20	195.31	186.90	179.05	199.61	201.82	208.79	219.52	235.05

Total per year (kWh/year) = ∑(219)1...12 = 2502.94 (219)

Annual Totals Summary:		kWh/year	kWh/year	
Space heating fuel used, main system 1			11773.81	(211)
Water heating fuel used			2502.94	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):				
mechanical ventilation fans - balanced, extract or positive input from outside		0.00		(230a)
warm air heating system fans		0.00		(230b)
central heating pump		169.00		(230c)
oil boiler pump		0.00		(230d)
boiler flue fan		45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler		0.00		(230f)
pump for solar water heating		0.00		(230g)
Total electricity for the above		∑(230a)...(230g)	214.00	(231)
Electricity for lighting (calculated in Appendix L):			384.60	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	11773.81	x	3.10	x 0.01 =	364.99	(240)
Water heating cost (other fuel)	2502.94	x	3.10	x 0.01 =	77.59	(247)
Pumps, fans and electric keep-hot	214.00	x	11.46	x 0.01 =	24.52	(249)
Energy for lighting	384.60	x	11.46	x 0.01 =	44.07	(250)
Additional standing charges (Table 12)					106.00	(251)
Total energy cost				(240)...(242) + (245)...(254)	617.18	(255)

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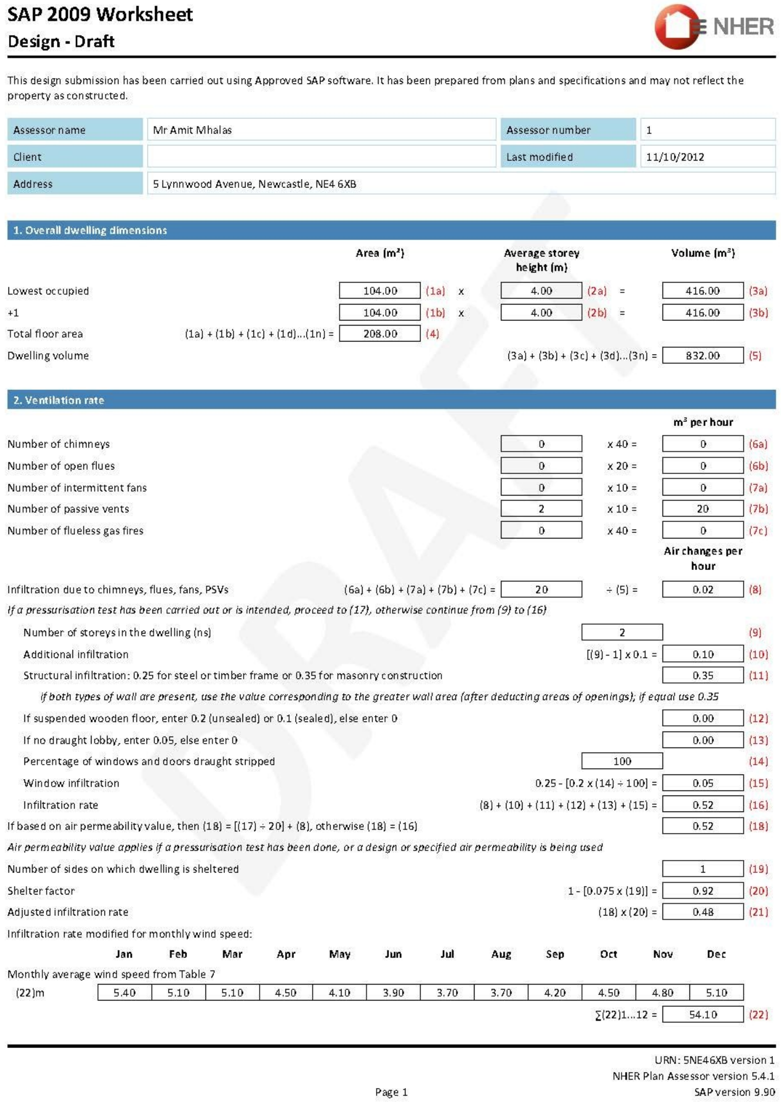

SAP 2009 Worksheet

Design - Draft

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	11/10/2012
Address	5 Lynnwood Avenue, Newcastle, NE4 6XB		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		104.00	(1a)	x	4.00	(2a)	=	416.00	(3a)
+1		104.00	(1b)	x	4.00	(2b)	=	416.00	(3b)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	208.00	(4)						
Dwelling volume							(3a) + (3b) + (3c) + (3d)...(3n) =	832.00	(5)

2. Ventilation rate

			m³ per hour	
Number of chimneys	0	x 40 =	0	(6a)
Number of open flues	0	x 20 =	0	(6b)
Number of intermittent fans	0	x 10 =	0	(7a)
Number of passive vents	2	x 10 =	20	(7b)
Number of flueless gas fires	0	x 40 =	0	(7c)

Air changes per hour

Infiltration due to chimneys, flues, fans, PSVs (6a) + (6b) + (7a) + (7b) + (7c) = 20 ÷ (5) = 0.02 (8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns) 2 (9)

Additional infiltration [(9) - 1] x 0.1 = 0.10 (10)

Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction 0.35 (11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0 0.00 (12)

If no draught lobby, enter 0.05, else enter 0 0.00 (13)

Percentage of windows and doors draught stripped 100 (14)

Window infiltration 0.25 - [0.2 x (14) ÷ 100] = 0.05 (15)

Infiltration rate (8) + (10) + (11) + (12) + (13) + (15) = 0.52 (16)

If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16) 0.52 (18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered 1 (19)

Shelter factor 1 - [0.075 x (19)] = 0.92 (20)

Adjusted infiltration rate (18) x (20) = 0.48 (21)

Infiltration rate modified for monthly wind speed:

Monthly average wind speed from Table 7

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)

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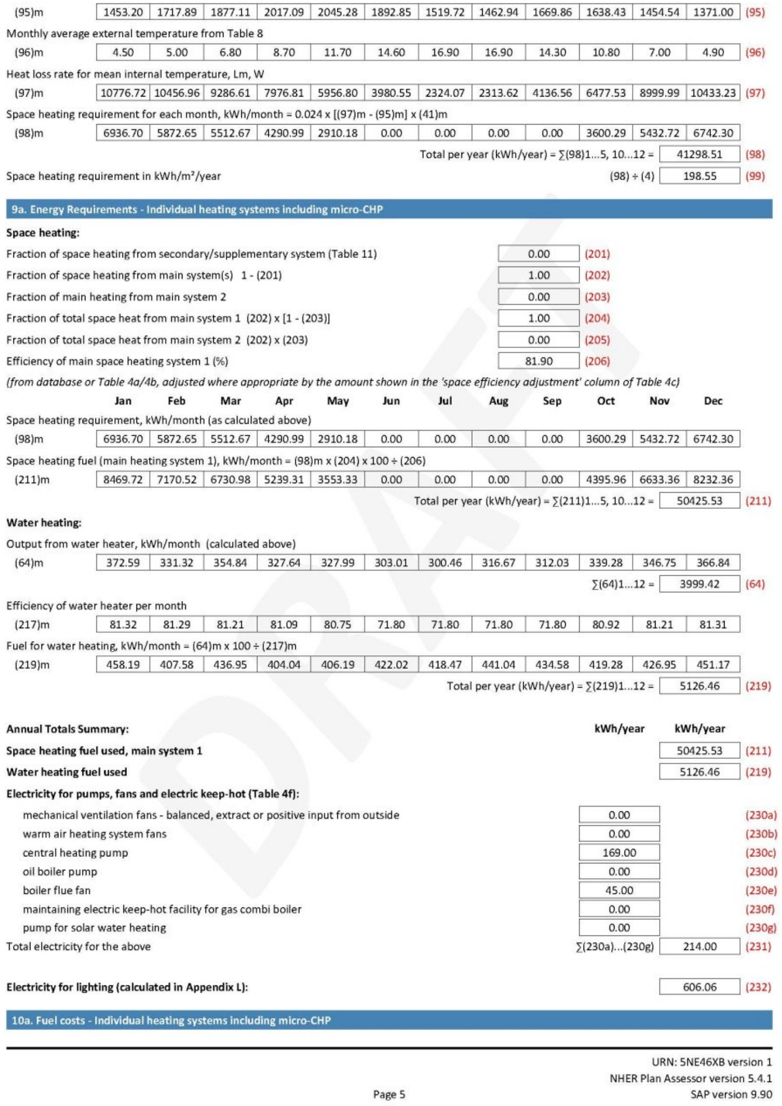

(95)m	1453.20	1717.89	1877.11	2017.09	2045.28	1892.85	1519.72	1462.94	1669.86	1638.43	1454.54	1371.00	(95)

Monthly average external temperature from Table 8

(96)m	4.50	5.00	6.80	8.70	11.70	14.60	16.90	16.90	14.30	10.80	7.00	4.90	(96)

Heat loss rate for mean internal temperature, Lm, W

(97)m	10776.72	10456.96	9286.61	7976.81	5956.80	3980.55	2324.07	2313.62	4136.56	6477.53	8999.99	10433.23	(97)

Space heating requirement for each month, kWh/month = 0.024 x [(97)m - (95)m] x (41)m

(98)m	6936.70	5872.65	5512.67	4290.99	2910.18	0.00	0.00	0.00	0.00	3600.29	5432.72	6742.30

Total per year (kWh/year) = ∑(98)1...5, 10...12 = 41298.51 (98)

Space heating requirement in kWh/m²/year (98) ÷ (4) 198.55 (99)

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	81.90	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

Space heating requirement, kWh/month (as calculated above)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(98)m	6936.70	5872.65	5512.67	4290.99	2910.18	0.00	0.00	0.00	0.00	3600.29	5432.72	6742.30

Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)

(211)m	8469.72	7170.52	6730.98	5239.31	3553.33	0.00	0.00	0.00	0.00	4395.96	6633.36	8232.36

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 50425.53 (211)

Water heating:

Output from water heater, kWh/month (calculated above)

(64)m	372.59	331.32	354.84	327.64	327.99	303.01	300.46	316.67	312.03	339.28	346.75	366.84

∑(64)1...12 = 3999.42 (64)

Efficiency of water heater per month

(217)m	81.32	81.29	81.21	81.09	80.75	71.80	71.80	71.80	71.80	80.92	81.21	81.31

Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m

(219)m	458.19	407.58	436.95	404.04	406.19	422.02	418.47	441.04	434.58	419.28	426.95	451.17

Total per year (kWh/year) = ∑(219)1...12 = 5126.46 (219)

Annual Totals Summary:	kWh/year	kWh/year	
Space heating fuel used, main system 1		50425.53	(211)
Water heating fuel used		5126.46	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):			
mechanical ventilation fans - balanced, extract or positive input from outside	0.00		(230a)
warm air heating system fans	0.00		(230b)
central heating pump	169.00		(230c)
oil boiler pump	0.00		(230d)
boiler flue fan	45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler	0.00		(230f)
pump for solar water heating	0.00		(230g)
Total electricity for the above	∑(230a)...(230g)	214.00	(231)
Electricity for lighting (calculated in Appendix L):		606.06	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

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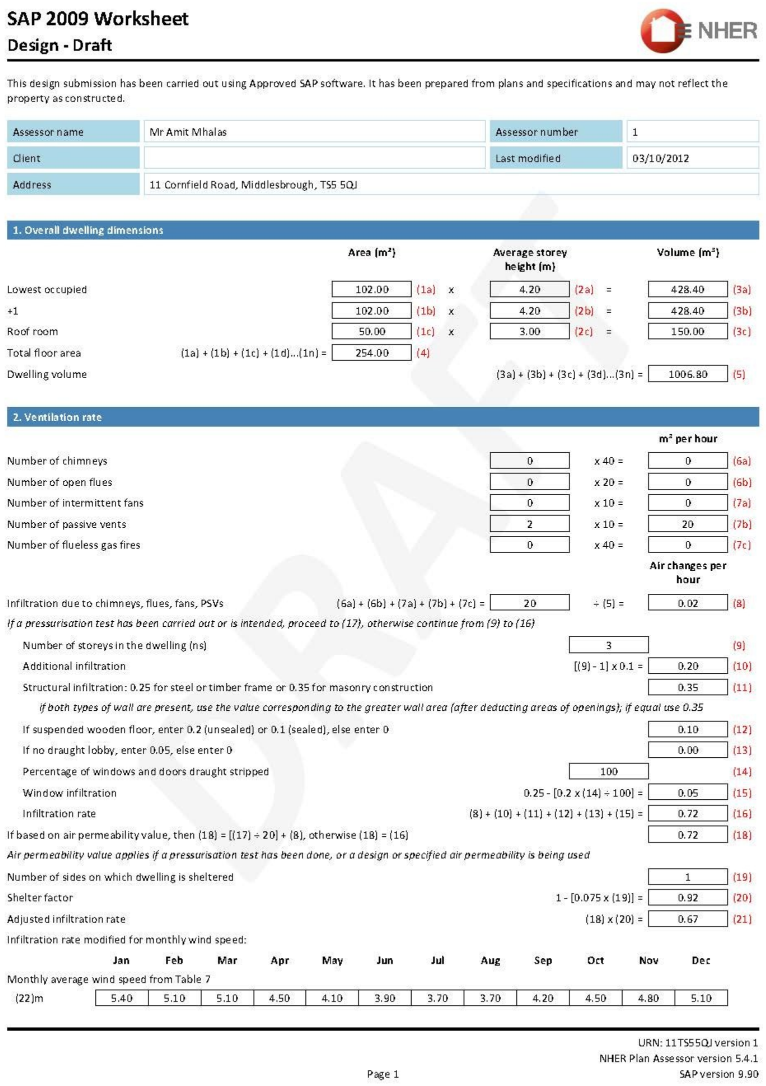

SAP 2009 Worksheet

Design - Draft

NHER

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	03/10/2012
Address	11 Cornfield Road, Middlesbrough, TS5 5QJ		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		102.00	(1a)	x	4.20	(2a)	=	428.40	(3a)
+1		102.00	(1b)	x	4.20	(2b)	=	428.40	(3b)
Roof room		50.00	(1c)	x	3.00	(2c)	=	150.00	(3c)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	254.00	(4)						
Dwelling volume							(3a) + (3b) + (3c) + (3d)...(3n) =	1006.80	(5)

2. Ventilation rate

				m³ per hour	
Number of chimneys		0	x 40 =	0	(6a)
Number of open flues		0	x 20 =	0	(6b)
Number of intermittent fans		0	x 10 =	0	(7a)
Number of passive vents		2	x 10 =	20	(7b)
Number of flueless gas fires		0	x 40 =	0	(7c)
				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	20	÷ (5) =	0.02	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		3		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.20	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.10	(12)
If no draught lobby, enter 0.05, else enter 0			0.00	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.72	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.72	(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		1	(19)
Shelter factor	1 - [0.075 x (19)] =	0.92	(20)
Adjusted infiltration rate	(18) x (20) =	0.67	(21)

Infiltration rate modified for monthly wind speed:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average wind speed from Table 7												
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

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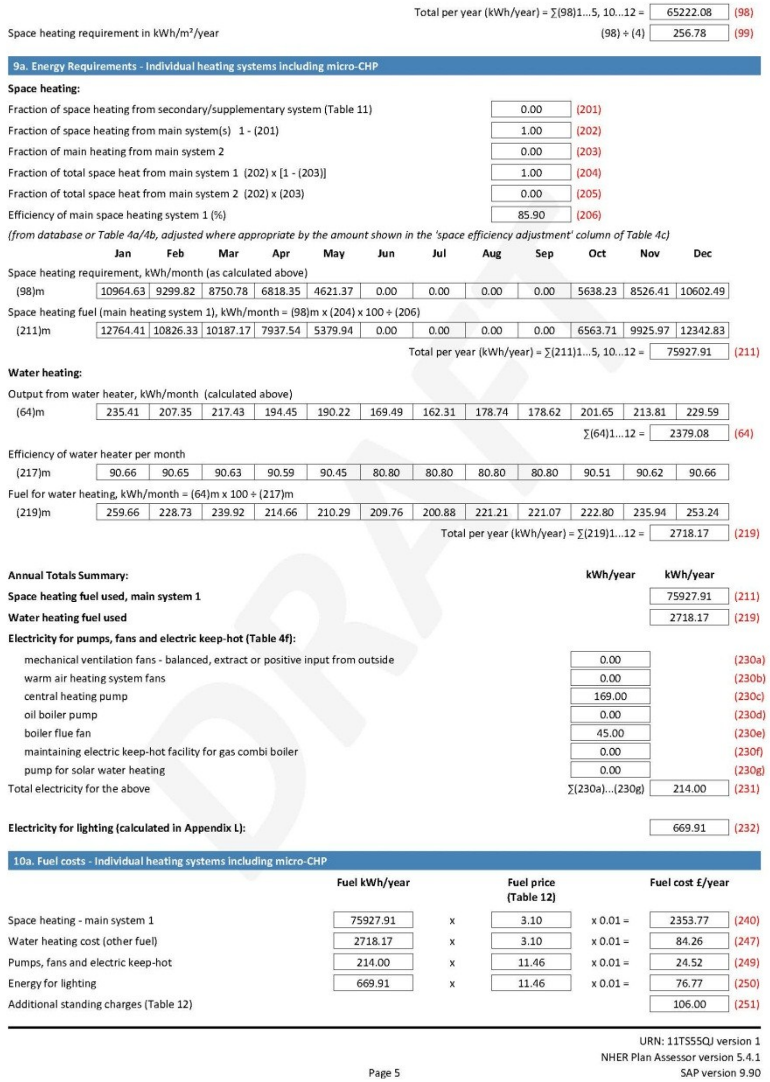

	Total per year (kWh/year) = ∑(98)1...5, 10...12 =	65222.08	(98)
Space heating requirement in kWh/m²/year	(98) ÷ (4)	256.78	(99)

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	85.90	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space heating requirement, kWh/month (as calculated above)												
(98)m	10964.63	9299.82	8750.78	6818.35	4621.37	0.00	0.00	0.00	0.00	5638.23	8526.41	10602.49
Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)												
(211)m	12764.41	10826.33	10187.17	7937.54	5379.94	0.00	0.00	0.00	0.00	6563.71	9925.97	12342.83

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 75927.91 (211)

Water heating:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Output from water heater, kWh/month (calculated above)												
(64)m	235.41	207.35	217.43	194.45	190.22	169.49	162.31	178.74	178.62	201.65	213.81	229.59

∑(64)1...12 = 2379.08 (64)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Efficiency of water heater per month												
(217)m	90.66	90.65	90.63	90.59	90.45	80.80	80.80	80.80	80.80	90.51	90.62	90.66
Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m												
(219)m	259.66	228.73	239.92	214.66	210.29	209.76	200.88	221.21	221.07	222.80	235.94	253.24

Total per year (kWh/year) = ∑(219)1...12 = 2718.17 (219)

Annual Totals Summary:		kWh/year	kWh/year	
Space heating fuel used, main system 1			75927.91	(211)
Water heating fuel used			2718.17	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):				
mechanical ventilation fans - balanced, extract or positive input from outside		0.00		(230a)
warm air heating system fans		0.00		(230b)
central heating pump		169.00		(230c)
oil boiler pump		0.00		(230d)
boiler flue fan		45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler		0.00		(230f)
pump for solar water heating		0.00		(230g)
Total electricity for the above	∑(230a)...(230g)		214.00	(231)
Electricity for lighting (calculated in Appendix L):			669.91	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	75927.91	x	3.10	x 0.01 =	2353.77	(240)
Water heating cost (other fuel)	2718.17	x	3.10	x 0.01 =	84.26	(247)
Pumps, fans and electric keep-hot	214.00	x	11.46	x 0.01 =	24.52	(249)
Energy for lighting	669.91	x	11.46	x 0.01 =	76.77	(250)
Additional standing charges (Table 12)					106.00	(251)

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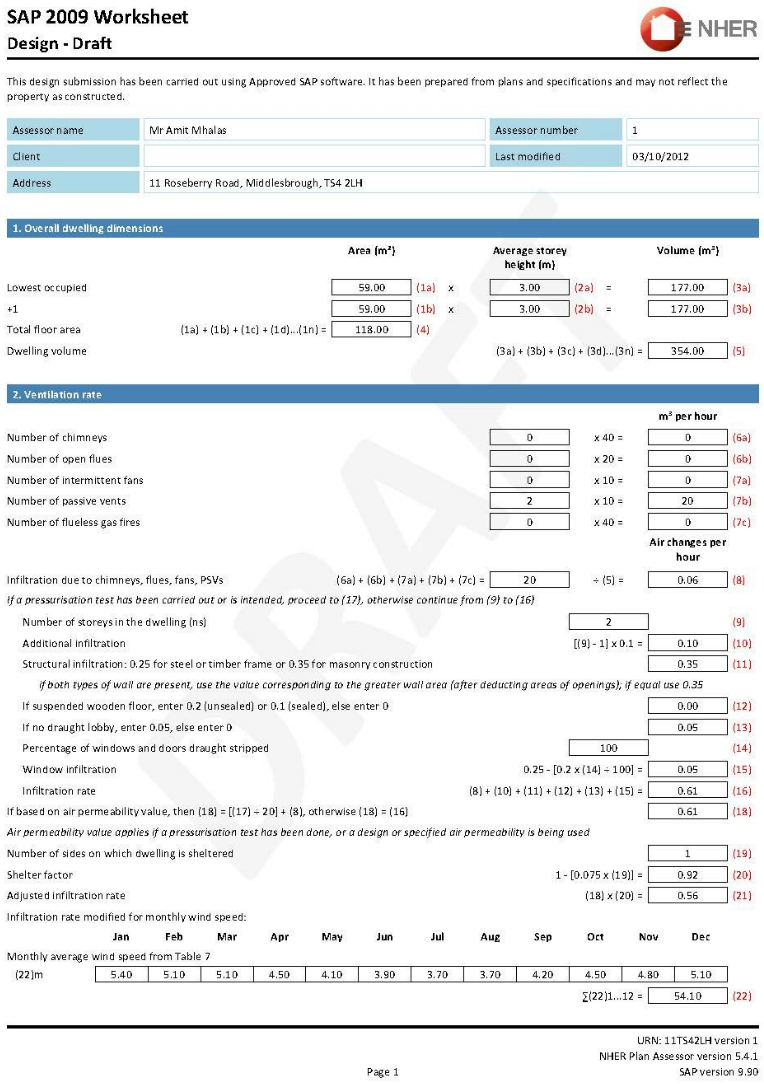

SAP 2009 Worksheet

Design - Draft

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	03/10/2012
Address	11 Roseberry Road, Middlesbrough, TS4 2LH		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		59.00	(1a)	x	3.00	(2a)	=	177.00	(3a)
+1		59.00	(1b)	x	3.00	(2b)	=	177.00	(3b)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	118.00	(4)						
Dwelling volume							(3a) + (3b) + (3c) + (3d)...(3n) =	354.00	(5)

2. Ventilation rate

			m³ per hour	
Number of chimneys	0	x 40 =	0	(6a)
Number of open flues	0	x 20 =	0	(6b)
Number of intermittent fans	0	x 10 =	0	(7a)
Number of passive vents	2	x 10 =	20	(7b)
Number of flueless gas fires	0	x 40 =	0	(7c)

				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	20	÷ (5) =	0.06	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		2		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.10	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.00	(12)
If no draught lobby, enter 0.05, else enter 0			0.05	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.61	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.61	(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		1	(19)
Shelter factor	1 - [0.075 x (19)] =	0.92	(20)
Adjusted infiltration rate	(18) x (20) =	0.56	(21)

Infiltration rate modified for monthly wind speed:

Monthly average wind speed from Table 7

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)

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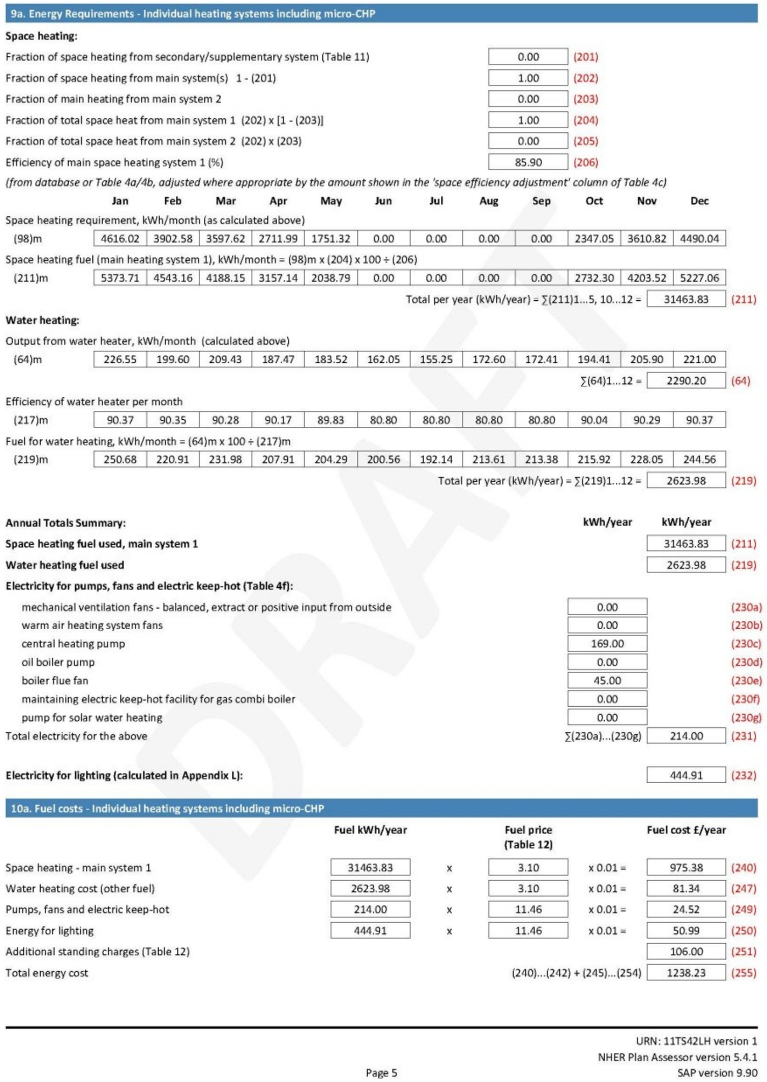

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	85.90	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space heating requirement, kWh/month (as calculated above)												
(98)m	4616.02	3902.58	3597.62	2711.99	1751.32	0.00	0.00	0.00	0.00	2347.05	3610.82	4490.04
Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)												
(211)m	5373.71	4543.16	4188.15	3157.14	2038.79	0.00	0.00	0.00	0.00	2732.30	4203.52	5227.06

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 31463.83 (211)

Water heating:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Output from water heater, kWh/month (calculated above)												
(64)m	226.55	199.60	209.43	187.47	183.52	162.05	155.25	172.60	172.41	194.41	205.90	221.00

∑(64)1...12 = 2290.20 (64)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Efficiency of water heater per month												
(217)m	90.37	90.35	90.28	90.17	89.83	80.80	80.80	80.80	80.80	90.04	90.29	90.37
Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m												
(219)m	250.68	220.91	231.98	207.91	204.29	200.56	192.14	213.61	213.38	215.92	228.05	244.56

Total per year (kWh/year) = ∑(219)1...12 = 2623.98 (219)

Annual Totals Summary:		kWh/year	kWh/year	
Space heating fuel used, main system 1			31463.83	(211)
Water heating fuel used			2623.98	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):				
mechanical ventilation fans - balanced, extract or positive input from outside		0.00		(230a)
warm air heating system fans		0.00		(230b)
central heating pump		169.00		(230c)
oil boiler pump		0.00		(230d)
boiler flue fan		45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler		0.00		(230f)
pump for solar water heating		0.00		(230g)
Total electricity for the above	∑(230a)...(230g)		214.00	(231)
Electricity for lighting (calculated in Appendix L):			444.91	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	31463.83	x	3.10	x 0.01 =	975.38	(240)
Water heating cost (other fuel)	2623.98	x	3.10	x 0.01 =	81.34	(247)
Pumps, fans and electric keep-hot	214.00	x	11.46	x 0.01 =	24.52	(249)
Energy for lighting	444.91	x	11.46	x 0.01 =	50.99	(250)
Additional standing charges (Table 12)					106.00	(251)
Total energy cost				(240)...(242) + (245)...(254)	1238.23	(255)

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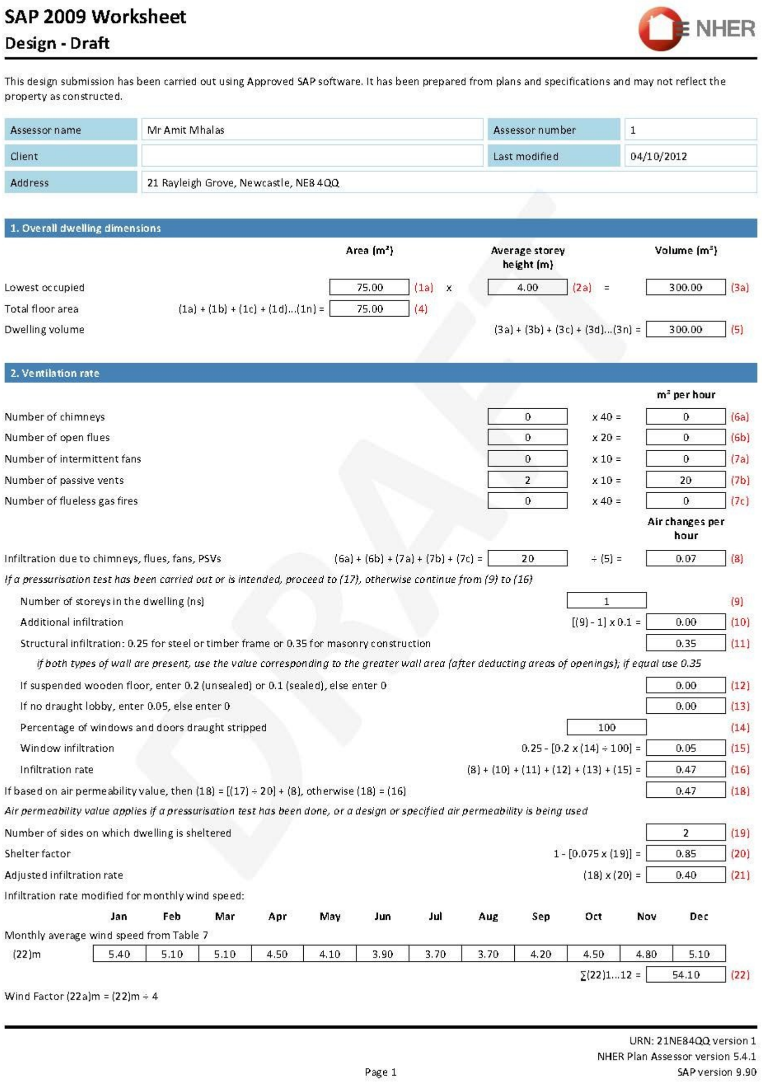

SAP 2009 Worksheet

Design - Draft

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	04/10/2012
Address	21 Rayleigh Grove, Newcastle, NE8 4QQ		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		75.00	(1a)	x	4.00	(2a)	=	300.00	(3a)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	75.00	(4)						
Dwelling volume							(3a) + (3b) + (3c) + (3d)...(3n) =	300.00	(5)

2. Ventilation rate

				m³ per hour	
Number of chimneys		0	x 40 =	0	(6a)
Number of open flues		0	x 20 =	0	(6b)
Number of intermittent fans		0	x 10 =	0	(7a)
Number of passive vents		2	x 10 =	20	(7b)
Number of flueless gas fires		0	x 40 =	0	(7c)
				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	20	÷ (5) =	0.07	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		1		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.00	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.00	(12)
If no draught lobby, enter 0.05, else enter 0			0.00	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.47	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.47	(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		2	(19)
Shelter factor	1 - [0.075 x (19)] =	0.85	(20)
Adjusted infiltration rate	(18) x (20) =	0.40	(21)

Infiltration rate modified for monthly wind speed:

Monthly average wind speed from Table 7

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)

Wind Factor (22a)m = (22)m ÷ 4

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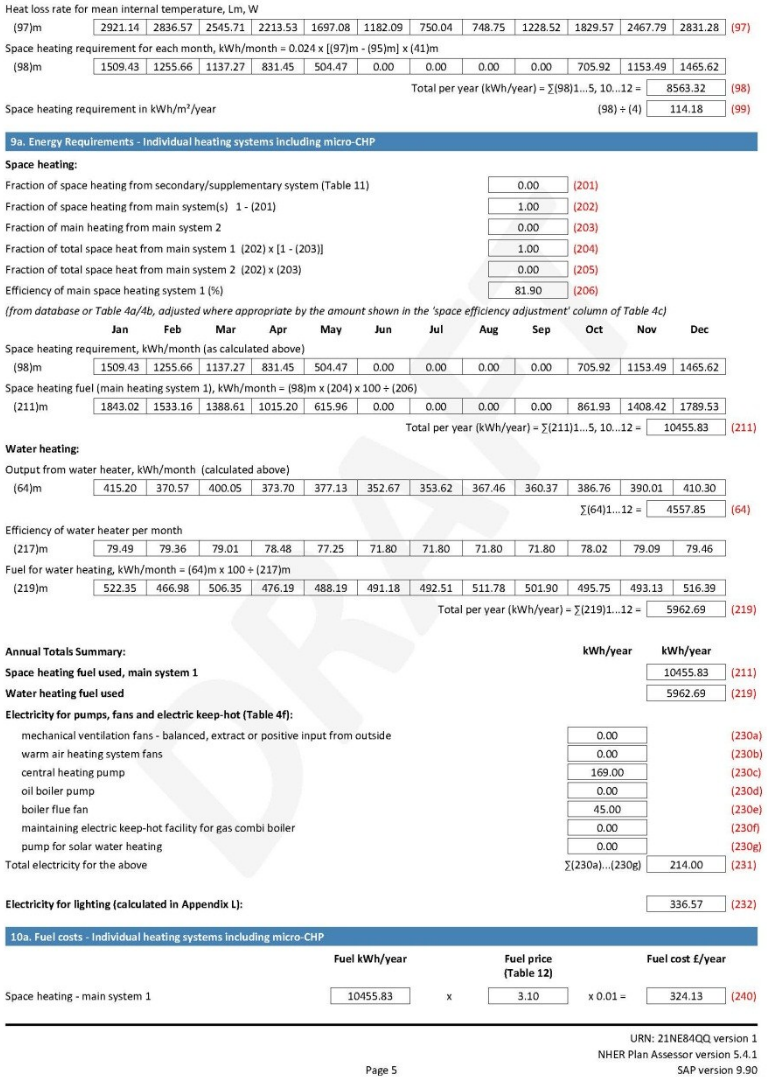

Heat loss rate for mean internal temperature, Lm, W

Space heating requirement for each month, kWh/month = 0.024 x [(97)m - (95)m] x (41)m

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
(97)m	2921.14	2836.57	2545.71	2213.53	1697.08	1182.09	750.04	748.75	1228.52	1829.57	2467.79	2831.28	(97)
(98)m	1509.43	1255.66	1137.27	831.45	504.47	0.00	0.00	0.00	0.00	705.92	1153.49	1465.62	

Total per year (kWh/year) = ∑(98)1...5, 10...12 = 8563.32 (98)

Space heating requirement in kWh/m²/year (98) ÷ (4) 114.18 (99)

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	81.90	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

Space heating requirement, kWh/month (as calculated above)

Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(98)m	1509.43	1255.66	1137.27	831.45	504.47	0.00	0.00	0.00	0.00	705.92	1153.49	1465.62
(211)m	1843.02	1533.16	1388.61	1015.20	615.96	0.00	0.00	0.00	0.00	861.93	1408.42	1789.53

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 10455.83 (211)

Water heating:

Output from water heater, kWh/month (calculated above)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(64)m	415.20	370.57	400.05	373.70	377.13	352.67	353.62	367.46	360.37	386.76	390.01	410.30

∑(64)1...12 = 4557.85 (64)

Efficiency of water heater per month

Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(217)m	79.49	79.36	79.01	78.48	77.25	71.80	71.80	71.80	71.80	78.02	79.09	79.46
(219)m	522.35	466.98	506.35	476.19	488.19	491.18	492.51	511.78	501.90	495.75	493.13	516.39

Total per year (kWh/year) = ∑(219)1...12 = 5962.69 (219)

Annual Totals Summary:		**kWh/year**	**kWh/year**	
Space heating fuel used, main system 1			10455.83	(211)
Water heating fuel used			5962.69	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):				
mechanical ventilation fans - balanced, extract or positive input from outside		0.00		(230a)
warm air heating system fans		0.00		(230b)
central heating pump		169.00		(230c)
oil boiler pump		0.00		(230d)
boiler flue fan		45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler		0.00		(230f)
pump for solar water heating		0.00		(230g)
Total electricity for the above	∑(230a)...(230g)		214.00	(231)
Electricity for lighting (calculated in Appendix L):			336.57	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	10455.83	x	3.10	x 0.01 =	324.13	(240)

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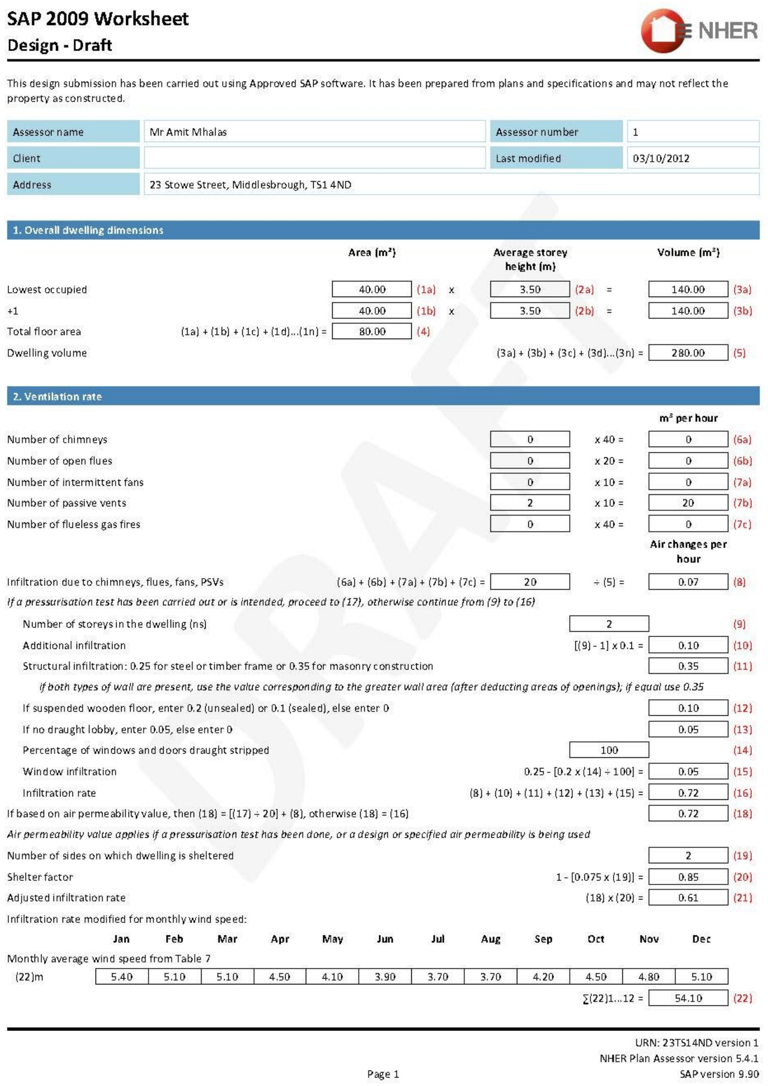


SAP 2009 Worksheet

Design - Draft

NHER

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	03/10/2012
Address	23 Stowe Street, Middlesbrough, TS1 4ND		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		40.00	(1a)	x	3.50	(2a)	=	140.00	(3a)
+1		40.00	(1b)	x	3.50	(2b)	=	140.00	(3b)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	80.00	(4)						
Dwelling volume							(3a) + (3b) + (3c) + (3d)...(3n) =	280.00	(5)

2. Ventilation rate

				m³ per hour	
Number of chimneys		0	x 40 =	0	(6a)
Number of open flues		0	x 20 =	0	(6b)
Number of intermittent fans		0	x 10 =	0	(7a)
Number of passive vents		2	x 10 =	20	(7b)
Number of flueless gas fires		0	x 40 =	0	(7c)
				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	20	÷ (5) =	0.07	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		2		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.10	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.10	(12)
If no draught lobby, enter 0.05, else enter 0			0.05	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.72	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.72	(18)

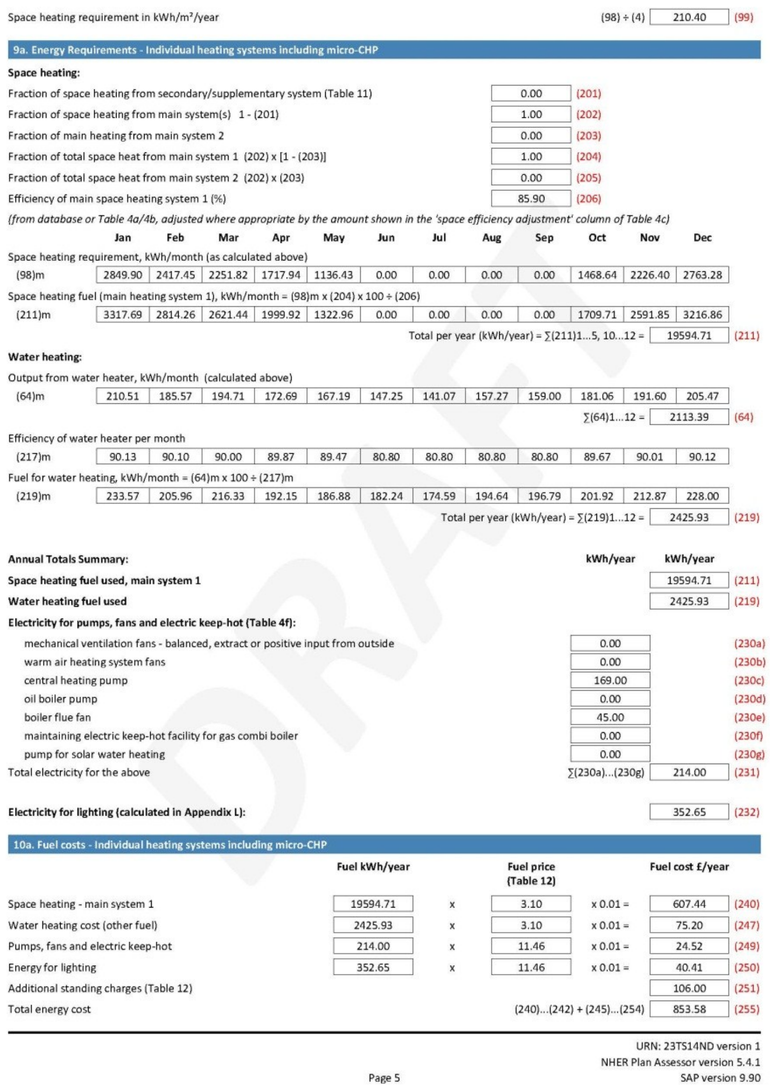
Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		2	(19)
Shelter factor	1 - [0.075 x (19)] =	0.85	(20)
Adjusted infiltration rate	(18) x (20) =	0.61	(21)

Infiltration rate modified for monthly wind speed:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average wind speed from Table 7 (22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)



Space heating requirement in kWh/m²/year	(98) ÷ (4)	210.40	(99)

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	85.90	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space heating requirement, kWh/month (as calculated above) (98)m	2849.90	2417.45	2251.82	1717.94	1136.43	0.00	0.00	0.00	0.00	1468.64	2226.40	2763.28
Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206) (211)m	3317.69	2814.26	2621.44	1999.92	1322.96	0.00	0.00	0.00	0.00	1709.71	2591.85	3216.86

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 19594.71 (211)

Water heating:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Output from water heater, kWh/month (calculated above) (64)m	210.51	185.57	194.71	172.69	167.19	147.25	141.07	157.27	159.00	181.06	191.60	205.47

∑(64)1...12 = 2113.39 (64)

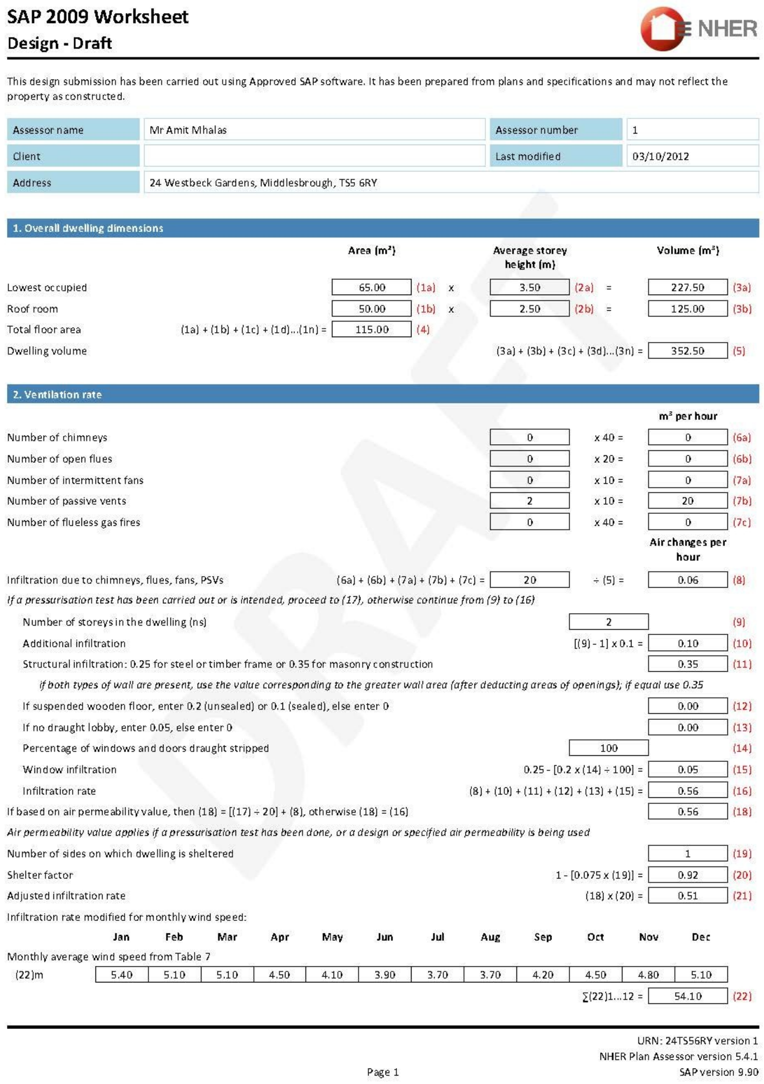
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Efficiency of water heater per month (217)m	90.13	90.10	90.00	89.87	89.47	80.80	80.80	80.80	80.80	89.67	90.01	90.12
Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m (219)m	233.57	205.96	216.33	192.15	186.88	182.24	174.59	194.64	196.79	201.92	212.87	228.00

Total per year (kWh/year) = ∑(219)1...12 = 2425.93 (219)

Annual Totals Summary:		kWh/year	kWh/year	
Space heating fuel used, main system 1			19594.71	(211)
Water heating fuel used			2425.93	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):				
mechanical ventilation fans - balanced, extract or positive input from outside		0.00		(230a)
warm air heating system fans		0.00		(230b)
central heating pump		169.00		(230c)
oil boiler pump		0.00		(230d)
boiler flue fan		45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler		0.00		(230f)
pump for solar water heating		0.00		(230g)
Total electricity for the above	∑(230a)...(230g)		214.00	(231)
Electricity for lighting (calculated in Appendix L):			352.65	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	19594.71	x	3.10	x 0.01 =	607.44	(240)
Water heating cost (other fuel)	2425.93	x	3.10	x 0.01 =	75.20	(247)
Pumps, fans and electric keep-hot	214.00	x	11.46	x 0.01 =	24.52	(249)
Energy for lighting	352.65	x	11.46	x 0.01 =	40.41	(250)
Additional standing charges (Table 12)					106.00	(251)
Total energy cost				(240)...(242) + (245)...(254)	853.58	(255)



SAP 2009 Worksheet

Design - Draft

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	03/10/2012
Address	24 Westbeck Gardens, Middlesbrough, TS5 6RY		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		65.00	(1a)	x	3.50	(2a)	=	227.50	(3a)
Roof room		50.00	(1b)	x	2.50	(2b)	=	125.00	(3b)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	115.00	(4)						
Dwelling volume							(3a) + (3b) + (3c) + (3d)...(3n) =	352.50	(5)

2. Ventilation rate

				m³ per hour	
Number of chimneys		0	x 40 =	0	(6a)
Number of open flues		0	x 20 =	0	(6b)
Number of intermittent fans		0	x 10 =	0	(7a)
Number of passive vents		2	x 10 =	20	(7b)
Number of flueless gas fires		0	x 40 =	0	(7c)

				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	20	÷ (5) =	0.06	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		2		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.10	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.00	(12)
If no draught lobby, enter 0.05, else enter 0			0.00	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.56	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.56	(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		1	(19)
Shelter factor	1 - [0.075 x (19)] =	0.92	(20)
Adjusted infiltration rate	(18) x (20) =	0.51	(21)

Infiltration rate modified for monthly wind speed:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average wind speed from Table 7												
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)

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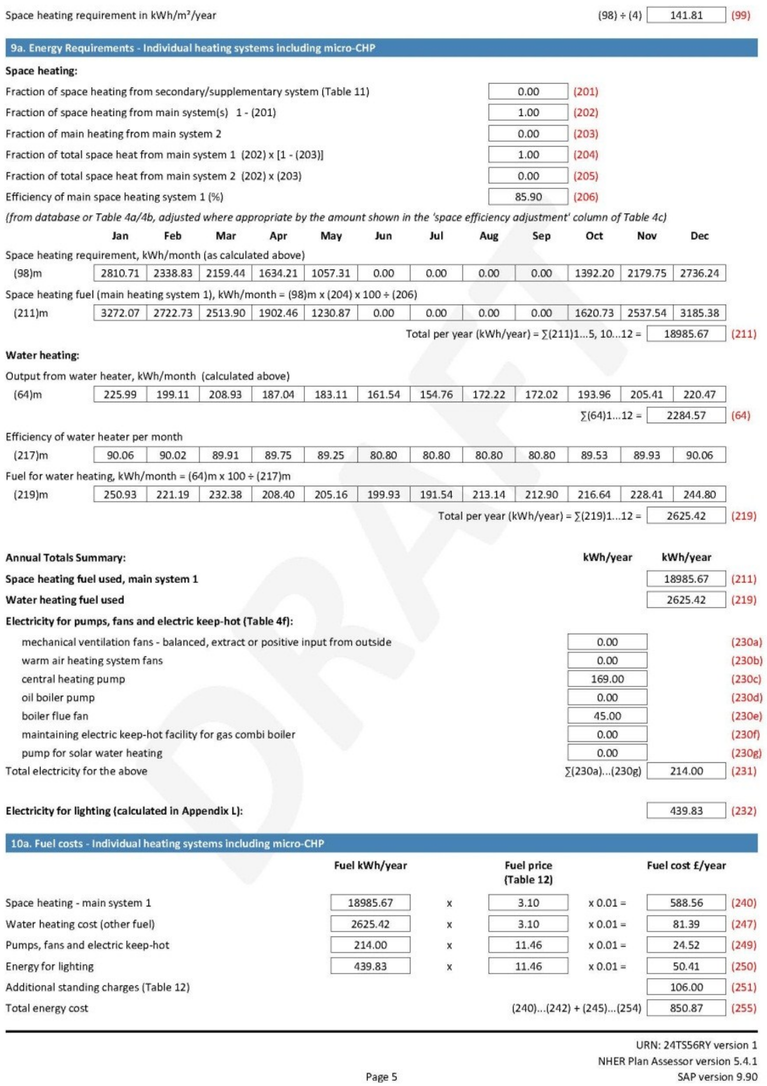

Space heating requirement in kWh/m²/year	(98) ÷ (4)	141.81	(99)

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	85.90	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space heating requirement, kWh/month (as calculated above)												
(98)m	2810.71	2338.83	2159.44	1634.21	1057.31	0.00	0.00	0.00	0.00	1392.20	2179.75	2736.24
Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)												
(211)m	3272.07	2722.73	2513.90	1902.46	1230.87	0.00	0.00	0.00	0.00	1620.73	2537.54	3185.38

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 18985.67 (211)

Water heating:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Output from water heater, kWh/month (calculated above)												
(64)m	225.99	199.11	208.93	187.04	183.11	161.54	154.76	172.22	172.02	193.96	205.41	220.47

∑(64)1...12 = 2284.57 (64)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Efficiency of water heater per month												
(217)m	90.06	90.02	89.91	89.75	89.25	80.80	80.80	80.80	80.80	89.53	89.93	90.06
Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m												
(219)m	250.93	221.19	232.38	208.40	205.16	199.93	191.54	213.14	212.90	216.64	228.41	244.80

Total per year (kWh/year) = ∑(219)1...12 = 2625.42 (219)

Annual Totals Summary:		kWh/year	kWh/year	
Space heating fuel used, main system 1			18985.67	(211)
Water heating fuel used			2625.42	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):				
mechanical ventilation fans - balanced, extract or positive input from outside		0.00		(230a)
warm air heating system fans		0.00		(230b)
central heating pump		169.00		(230c)
oil boiler pump		0.00		(230d)
boiler flue fan		45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler		0.00		(230f)
pump for solar water heating		0.00		(230g)
Total electricity for the above	∑(230a)...(230g)		214.00	(231)
Electricity for lighting (calculated in Appendix L):			439.83	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	18985.67	x	3.10	x 0.01 =	588.56	(240)
Water heating cost (other fuel)	2625.42	x	3.10	x 0.01 =	81.39	(247)
Pumps, fans and electric keep-hot	214.00	x	11.46	x 0.01 =	24.52	(249)
Energy for lighting	439.83	x	11.46	x 0.01 =	50.41	(250)
Additional standing charges (Table 12)					106.00	(251)
Total energy cost				(240)...(242) + (245)...(254)	850.87	(255)

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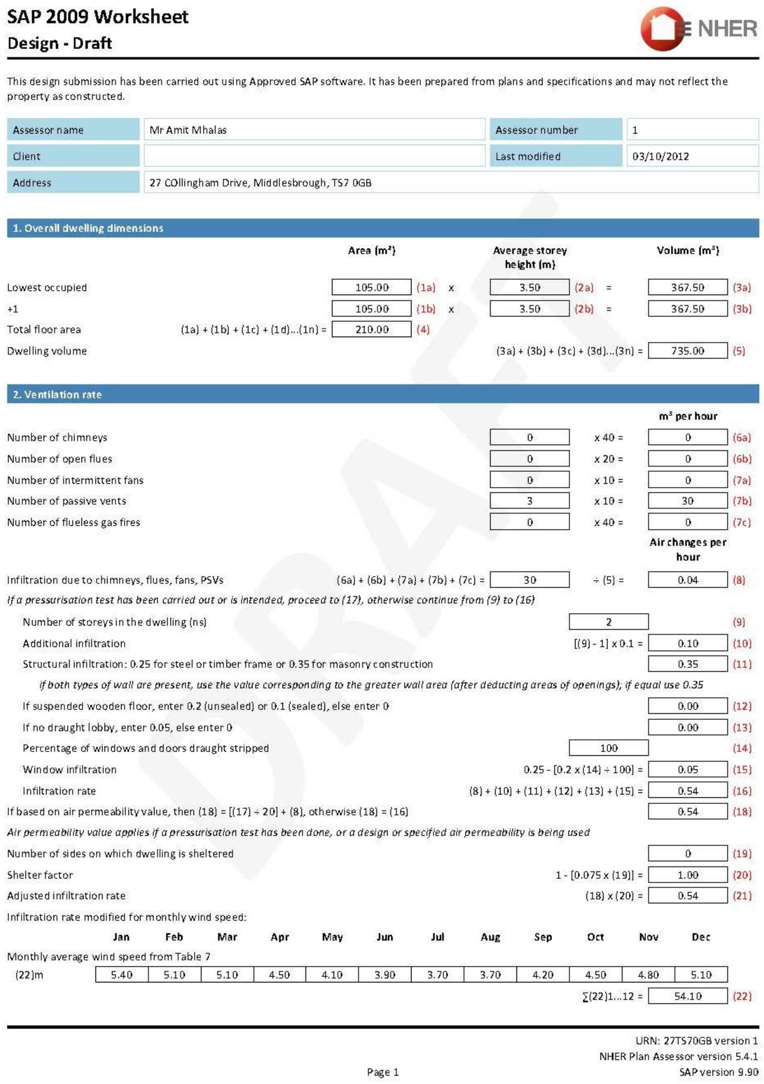

SAP 2009 Worksheet

Design - Draft

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	03/10/2012
Address	27 COllingham Drive, Middlesbrough, TS7 0GB		

1. Overall dwelling dimensions

		Area (m^2)			Average storey height (m)			Volume (m^3)	
Lowest occupied		105.00	(1a)	x	3.50	(2a)	=	367.50	(3a)
+1		105.00	(1b)	x	3.50	(2b)	=	367.50	(3b)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	210.00	(4)						
Dwelling volume					(3a) + (3b) + (3c) + (3d)...(3n) =			735.00	(5)

2. Ventilation rate

				m^3 per hour	
Number of chimneys		0	x 40 =	0	(6a)
Number of open flues		0	x 20 =	0	(6b)
Number of intermittent fans		0	x 10 =	0	(7a)
Number of passive vents		3	x 10 =	30	(7b)
Number of flueless gas fires		0	x 40 =	0	(7c)
				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	30	÷ (5) =	0.04	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		2		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.10	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.00	(12)
If no draught lobby, enter 0.05, else enter 0			0.00	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.54	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.54	(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		0	(19)
Shelter factor	1 - [0.075 x (19)] =	1.00	(20)
Adjusted infiltration rate	(18) x (20) =	0.54	(21)

Infiltration rate modified for monthly wind speed:

Monthly average wind speed from Table 7

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)

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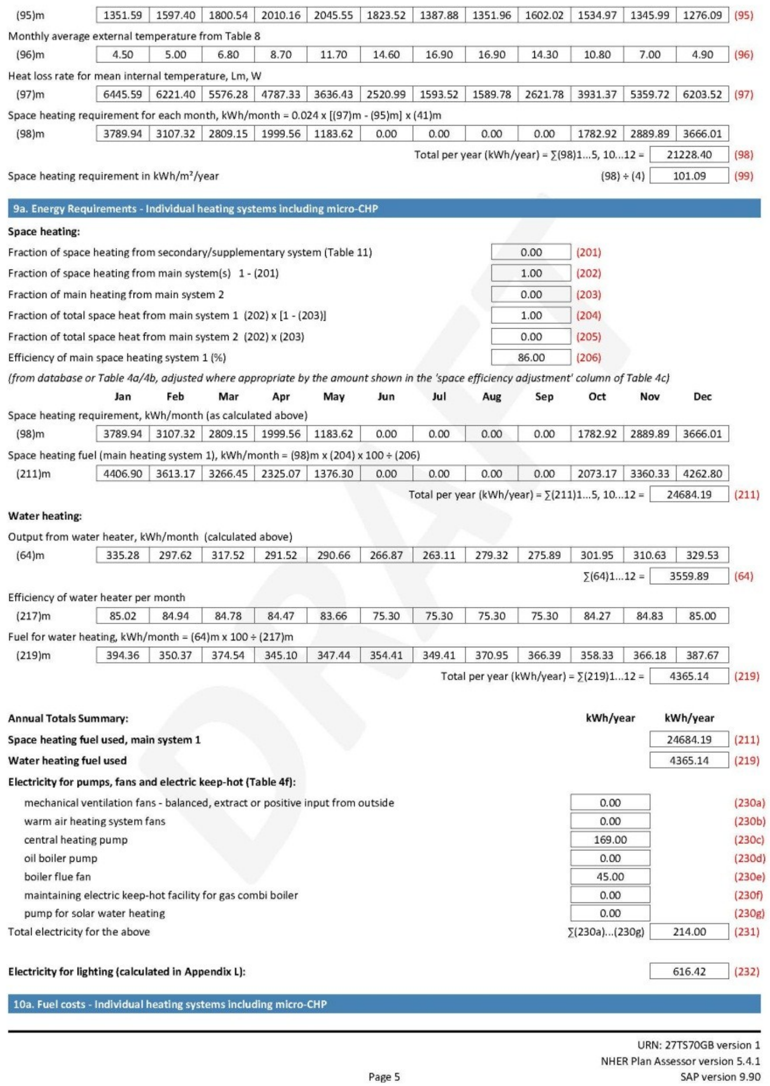

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
(95)m	1351.59	1597.40	1800.54	2010.16	2045.55	1823.52	1387.88	1351.96	1602.02	1534.97	1345.99	1276.09	(95)
Monthly average external temperature from Table 8													
(96)m	4.50	5.00	6.80	8.70	11.70	14.60	16.90	16.90	14.30	10.80	7.00	4.90	(96)
Heat loss rate for mean internal temperature, Lm, W													
(97)m	6445.59	6221.40	5576.28	4787.33	3636.43	2520.99	1593.52	1589.78	2621.78	3931.37	5359.72	6203.52	(97)
Space heating requirement for each month, kWh/month = 0.024 x [(97)m - (95)m] x (41)m													
(98)m	3789.94	3107.32	2809.15	1999.56	1183.62	0.00	0.00	0.00	0.00	1782.92	2889.89	3666.01	

Total per year (kWh/year) = ∑(98)1...5, 10...12 = 21228.40 (98)

Space heating requirement in kWh/m^2/year (98) ÷ (4) 101.09 (99)

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	86.00	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space heating requirement, kWh/month (as calculated above)												
(98)m	3789.94	3107.32	2809.15	1999.56	1183.62	0.00	0.00	0.00	0.00	1782.92	2889.89	3666.01
Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)												
(211)m	4406.90	3613.17	3266.45	2325.07	1376.30	0.00	0.00	0.00	0.00	2073.17	3360.33	4262.80

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 24684.19 (211)

Water heating:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Output from water heater, kWh/month (calculated above)												
(64)m	335.28	297.62	317.52	291.52	290.66	266.87	263.11	279.32	275.89	301.95	310.63	329.53

∑(64)1...12 = 3559.89 (64)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Efficiency of water heater per month												
(217)m	85.02	84.94	84.78	84.47	83.66	75.30	75.30	75.30	75.30	84.27	84.83	85.00
Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m												
(219)m	394.36	350.37	374.54	345.10	347.44	354.41	349.41	370.95	366.39	358.33	366.18	387.67

Total per year (kWh/year) = ∑(219)1...12 = 4365.14 (219)

Annual Totals Summary:		kWh/year	kWh/year	
Space heating fuel used, main system 1			24684.19	(211)
Water heating fuel used			4365.14	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):				
mechanical ventilation fans - balanced, extract or positive input from outside		0.00		(230a)
warm air heating system fans		0.00		(230b)
central heating pump		169.00		(230c)
oil boiler pump		0.00		(230d)
boiler flue fan		45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler		0.00		(230f)
pump for solar water heating		0.00		(230g)
Total electricity for the above	∑(230a)...(230g)		214.00	(231)
Electricity for lighting (calculated in Appendix L):			616.42	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

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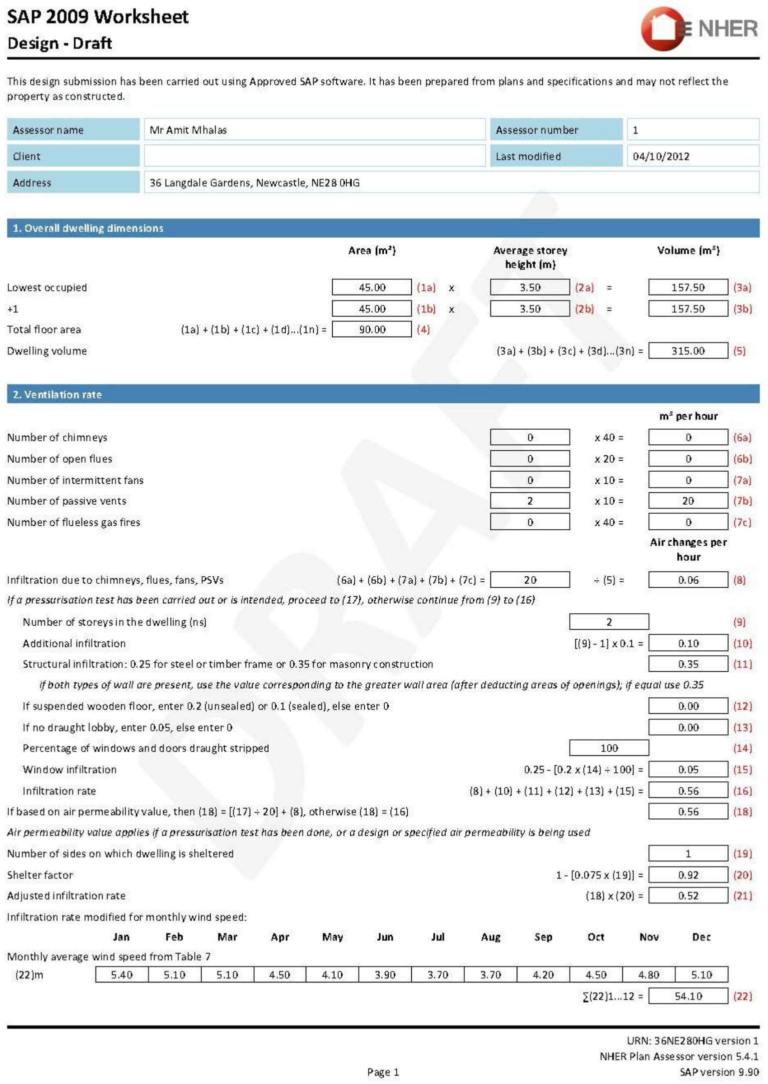

SAP 2009 Worksheet

Design - Draft

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	04/10/2012
Address	36 Langdale Gardens, Newcastle, NE28 0HG		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		45.00	(1a)	x	3.50	(2a)	=	157.50	(3a)
+1		45.00	(1b)	x	3.50	(2b)	=	157.50	(3b)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	90.00	(4)						
Dwelling volume							(3a) + (3b) + (3c) + (3d)...(3n) =	315.00	(5)

2. Ventilation rate

				m³ per hour	
Number of chimneys		0	x 40 =	0	(6a)
Number of open flues		0	x 20 =	0	(6b)
Number of intermittent fans		0	x 10 =	0	(7a)
Number of passive vents		2	x 10 =	20	(7b)
Number of flueless gas fires		0	x 40 =	0	(7c)
				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	20	÷ (5) =	0.06	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		2		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.10	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.00	(12)
If no draught lobby, enter 0.05, else enter 0			0.00	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.56	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.56	(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		1	(19)
Shelter factor	1 - [0.075 x (19)] =	0.92	(20)
Adjusted infiltration rate	(18) x (20) =	0.52	(21)

Infiltration rate modified for monthly wind speed:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average wind speed from Table 7												
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)

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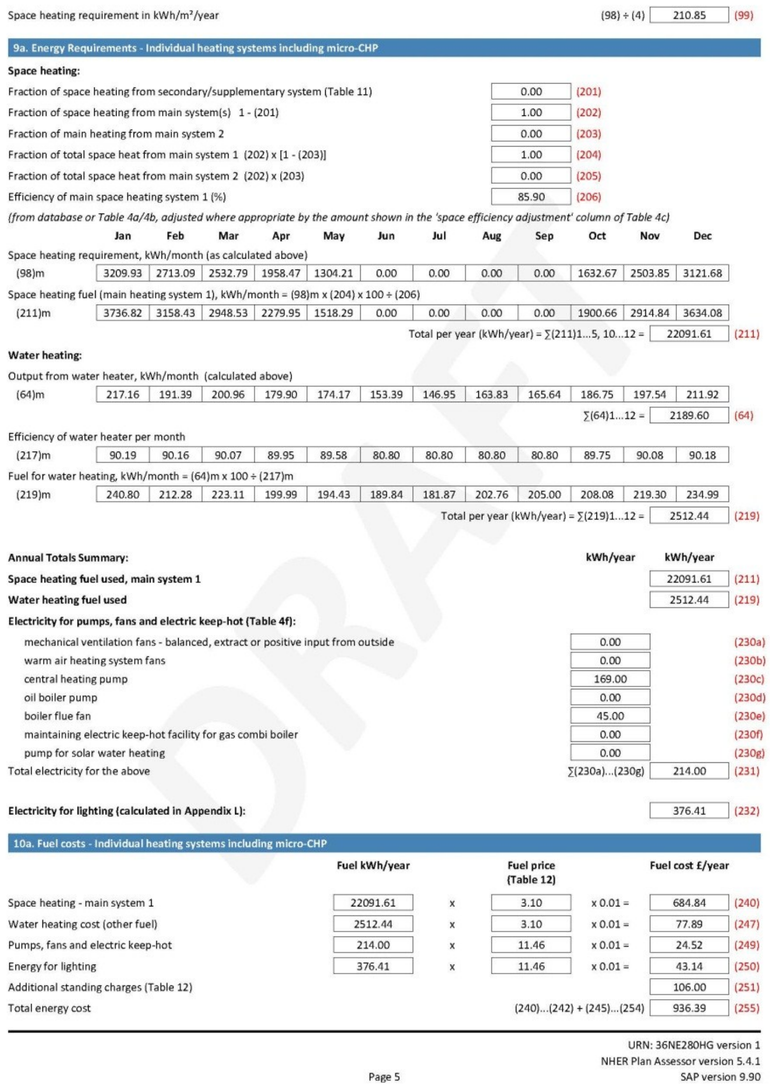

Space heating requirement in kWh/m²/year	(98) ÷ (4)	210.85	(99)

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	85.90	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space heating requirement, kWh/month (as calculated above)												
(98)m	3209.93	2713.09	2532.79	1958.47	1304.21	0.00	0.00	0.00	0.00	1632.67	2503.85	3121.68
Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)												
(211)m	3736.82	3158.43	2948.53	2279.95	1518.29	0.00	0.00	0.00	0.00	1900.66	2914.84	3634.08

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 22091.61 (211)

Water heating:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Output from water heater, kWh/month (calculated above)												
(64)m	217.16	191.39	200.96	179.90	174.17	153.39	146.95	163.83	165.64	186.75	197.54	211.92

∑(64)1...12 = 2189.60 (64)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Efficiency of water heater per month												
(217)m	90.19	90.16	90.07	89.95	89.58	80.80	80.80	80.80	80.80	89.75	90.08	90.18
Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m												
(219)m	240.80	212.28	223.11	199.99	194.43	189.84	181.87	202.76	205.00	208.08	219.30	234.99

Total per year (kWh/year) = ∑(219)1...12 = 2512.44 (219)

Annual Totals Summary:		**kWh/year**	**kWh/year**	
Space heating fuel used, main system 1			22091.61	(211)
Water heating fuel used			2512.44	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):				
mechanical ventilation fans - balanced, extract or positive input from outside		0.00		(230a)
warm air heating system fans		0.00		(230b)
central heating pump		169.00		(230c)
oil boiler pump		0.00		(230d)
boiler flue fan		45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler		0.00		(230f)
pump for solar water heating		0.00		(230g)
Total electricity for the above	∑(230a)...(230g)		214.00	(231)
Electricity for lighting (calculated in Appendix L):			376.41	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	22091.61	x	3.10	x 0.01 =	684.84	(240)
Water heating cost (other fuel)	2512.44	x	3.10	x 0.01 =	77.89	(247)
Pumps, fans and electric keep-hot	214.00	x	11.46	x 0.01 =	24.52	(249)
Energy for lighting	376.41	x	11.46	x 0.01 =	43.14	(250)
Additional standing charges (Table 12)					106.00	(251)
Total energy cost				(240)...(242) + (245)...(254)	936.39	(255)

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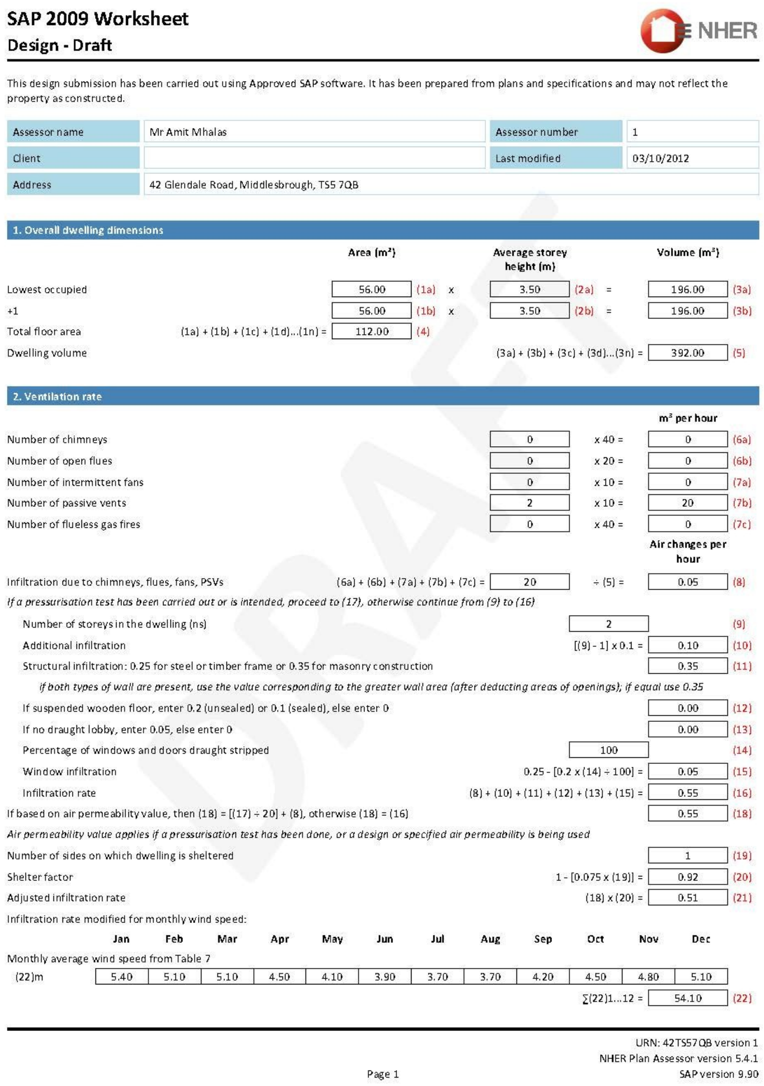

SAP 2009 Worksheet

Design - Draft

NHER

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	03/10/2012
Address	42 Glendale Road, Middlesbrough, TS5 7QB		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		56.00	(1a)	x	3.50	(2a)	=	196.00	(3a)
+1		56.00	(1b)	x	3.50	(2b)	=	196.00	(3b)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	112.00	(4)						
Dwelling volume							(3a) + (3b) + (3c) + (3d)...(3n) =	392.00	(5)

2. Ventilation rate

				m³ per hour	
Number of chimneys		0	x 40 =	0	(6a)
Number of open flues		0	x 20 =	0	(6b)
Number of intermittent fans		0	x 10 =	0	(7a)
Number of passive vents		2	x 10 =	20	(7b)
Number of flueless gas fires		0	x 40 =	0	(7c)
				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	20	÷ (5) =	0.05	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		2		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.10	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.00	(12)
If no draught lobby, enter 0.05, else enter 0			0.00	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.55	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.55	(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		1	(19)
Shelter factor	1 - [0.075 x (19)] =	0.92	(20)
Adjusted infiltration rate	(18) x (20) =	0.51	(21)

Infiltration rate modified for monthly wind speed:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average wind speed from Table 7												
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)

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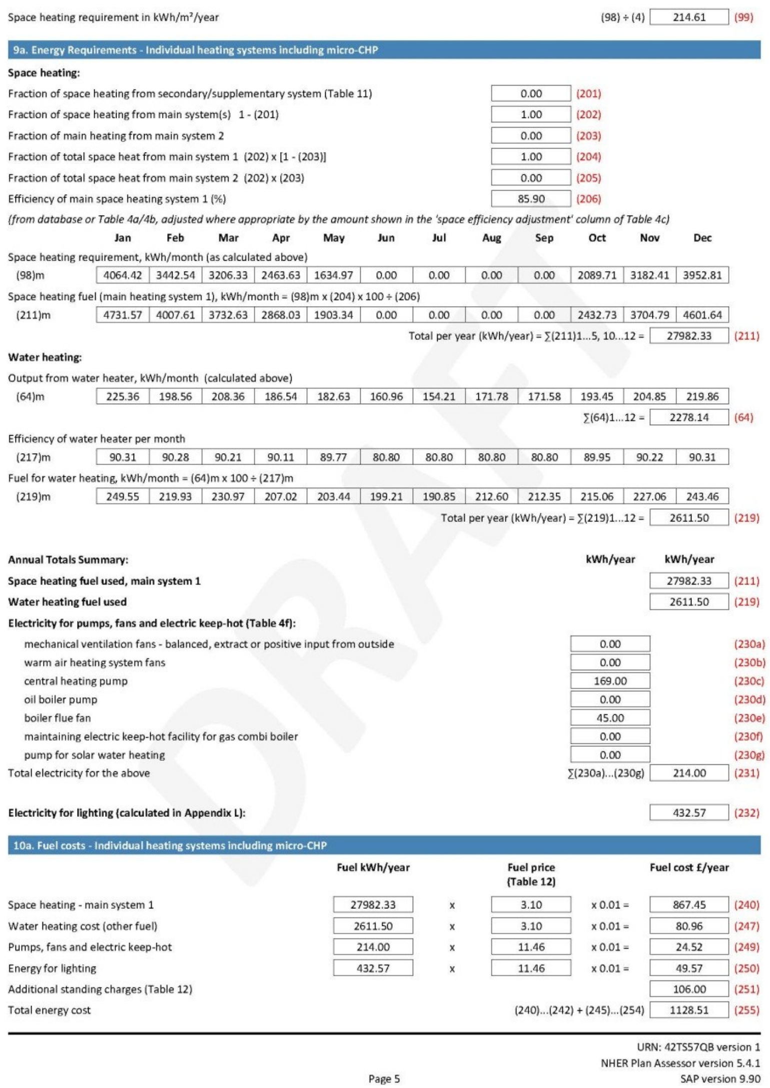

Space heating requirement in kWh/m²/year	(98) ÷ (4)	214.61	(99)

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	85.90	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space heating requirement, kWh/month (as calculated above)												
(98)m	4064.42	3442.54	3206.33	2463.63	1634.97	0.00	0.00	0.00	0.00	2089.71	3182.41	3952.81
Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)												
(211)m	4731.57	4007.61	3732.63	2868.03	1903.34	0.00	0.00	0.00	0.00	2432.73	3704.79	4601.64

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 27982.33 (211)

Water heating:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Output from water heater, kWh/month (calculated above)												
(64)m	225.36	198.56	208.36	186.54	182.63	160.96	154.21	171.78	171.58	193.45	204.85	219.86

∑(64)1...12 = 2278.14 (64)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Efficiency of water heater per month												
(217)m	90.31	90.28	90.21	90.11	89.77	80.80	80.80	80.80	80.80	89.95	90.22	90.31
Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m												
(219)m	249.55	219.93	230.97	207.02	203.44	199.21	190.85	212.60	212.35	215.06	227.06	243.46

Total per year (kWh/year) = ∑(219)1...12 = 2611.50 (219)

Annual Totals Summary:		kWh/year	kWh/year	
Space heating fuel used, main system 1			27982.33	(211)
Water heating fuel used			2611.50	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):				
mechanical ventilation fans - balanced, extract or positive input from outside		0.00		(230a)
warm air heating system fans		0.00		(230b)
central heating pump		169.00		(230c)
oil boiler pump		0.00		(230d)
boiler flue fan		45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler		0.00		(230f)
pump for solar water heating		0.00		(230g)
Total electricity for the above	∑(230a)...(230g)		214.00	(231)
Electricity for lighting (calculated in Appendix L):			432.57	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	27982.33	x	3.10	x 0.01 =	867.45	(240)
Water heating cost (other fuel)	2611.50	x	3.10	x 0.01 =	80.96	(247)
Pumps, fans and electric keep-hot	214.00	x	11.46	x 0.01 =	24.52	(249)
Energy for lighting	432.57	x	11.46	x 0.01 =	49.57	(250)
Additional standing charges (Table 12)					106.00	(251)
Total energy cost				(240)...(242) + (245)...(254)	1128.51	(255)

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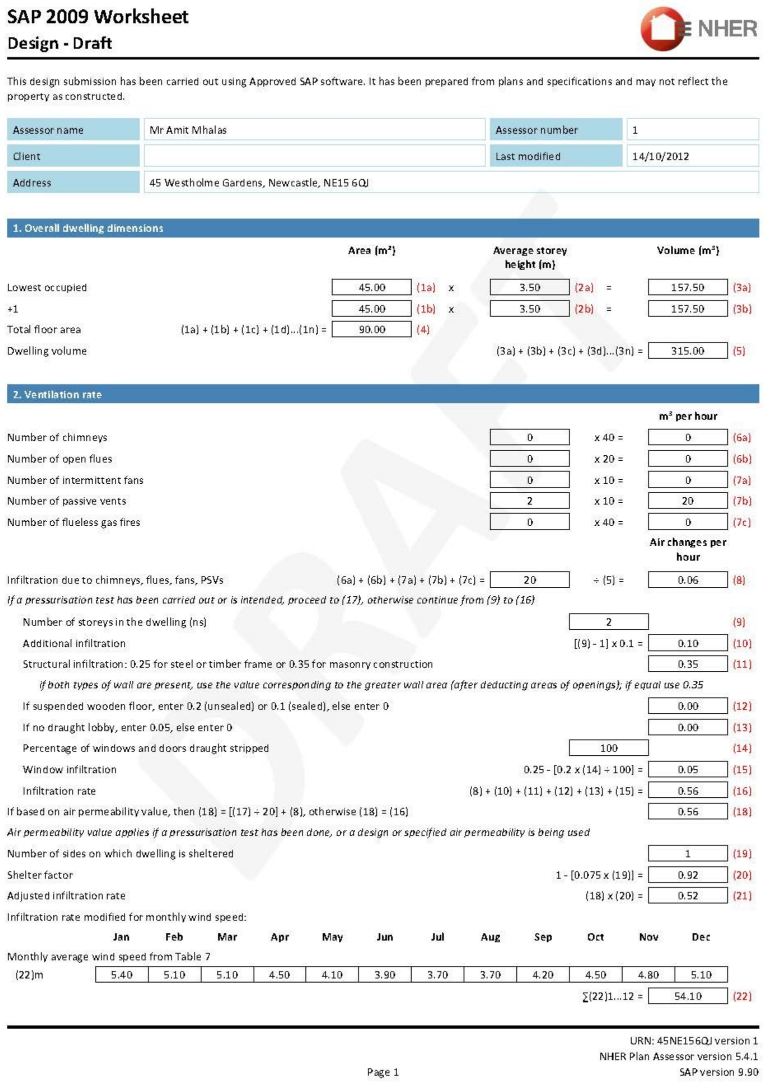

SAP 2009 Worksheet

Design - Draft

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	14/10/2012
Address	45 Westholme Gardens, Newcastle, NE15 6QJ		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		45.00	(1a)	x	3.50	(2a)	=	157.50	(3a)
+1		45.00	(1b)	x	3.50	(2b)	=	157.50	(3b)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	90.00	(4)						
Dwelling volume					(3a) + (3b) + (3c) + (3d)...(3n) =			315.00	(5)

2. Ventilation rate

				m³ per hour	
Number of chimneys		0	x 40 =	0	(6a)
Number of open flues		0	x 20 =	0	(6b)
Number of intermittent fans		0	x 10 =	0	(7a)
Number of passive vents		2	x 10 =	20	(7b)
Number of flueless gas fires		0	x 40 =	0	(7c)
				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	20	÷ (5) =	0.06	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		2		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.10	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.00	(12)
If no draught lobby, enter 0.05, else enter 0			0.00	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.56	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.56	(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		1	(19)
Shelter factor	1 - [0.075 x (19)] =	0.92	(20)
Adjusted infiltration rate	(18) x (20) =	0.52	(21)

Infiltration rate modified for monthly wind speed:

Monthly average wind speed from Table 7

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)

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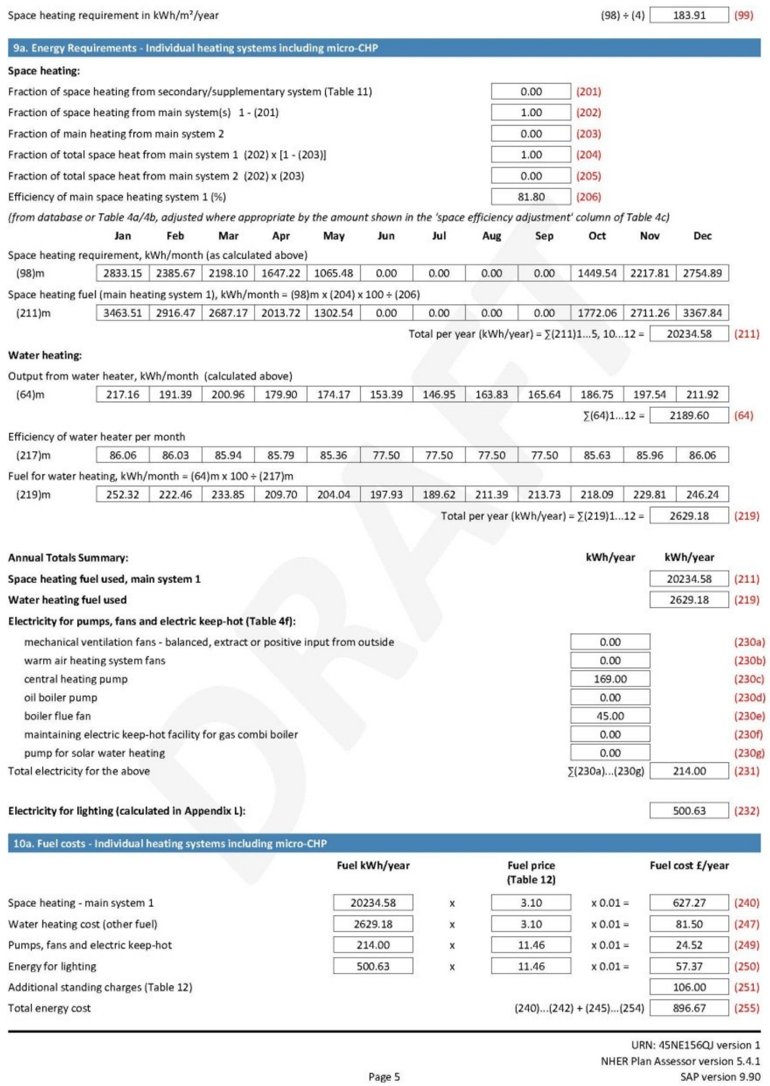

Space heating requirement in kWh/m²/year (98) ÷ (4) 183.91 (99)

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	81.80	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

Space heating requirement, kWh/month (as calculated above)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(98)m	2833.15	2385.67	2198.10	1647.22	1065.48	0.00	0.00	0.00	0.00	1449.54	2217.81	2754.89

Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(211)m	3463.51	2916.47	2687.17	2013.72	1302.54	0.00	0.00	0.00	0.00	1772.06	2711.26	3367.84

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 20234.58 (211)

Water heating:

Output from water heater, kWh/month (calculated above)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(64)m	217.16	191.39	200.96	179.90	174.17	153.39	146.95	163.83	165.64	186.75	197.54	211.92

∑(64)1...12 = 2189.60 (64)

Efficiency of water heater per month

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(217)m	86.06	86.03	85.94	85.79	85.36	77.50	77.50	77.50	77.50	85.63	85.96	86.06

Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(219)m	252.32	222.46	233.85	209.70	204.04	197.93	189.62	211.39	213.73	218.09	229.81	246.24

Total per year (kWh/year) = ∑(219)1...12 = 2629.18 (219)

Annual Totals Summary:		kWh/year	kWh/year	
Space heating fuel used, main system 1			20234.58	(211)
Water heating fuel used			2629.18	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):				
mechanical ventilation fans - balanced, extract or positive input from outside		0.00		(230a)
warm air heating system fans		0.00		(230b)
central heating pump		169.00		(230c)
oil boiler pump		0.00		(230d)
boiler flue fan		45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler		0.00		(230f)
pump for solar water heating		0.00		(230g)
Total electricity for the above	∑(230a)...(230g)		214.00	(231)
Electricity for lighting (calculated in Appendix L):			500.63	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	20234.58	x	3.10	x 0.01 =	627.27	(240)
Water heating cost (other fuel)	2629.18	x	3.10	x 0.01 =	81.50	(247)
Pumps, fans and electric keep-hot	214.00	x	11.46	x 0.01 =	24.52	(249)
Energy for lighting	500.63	x	11.46	x 0.01 =	57.37	(250)
Additional standing charges (Table 12)					106.00	(251)
Total energy cost				(240)...(242) + (245)...(254)	896.67	(255)

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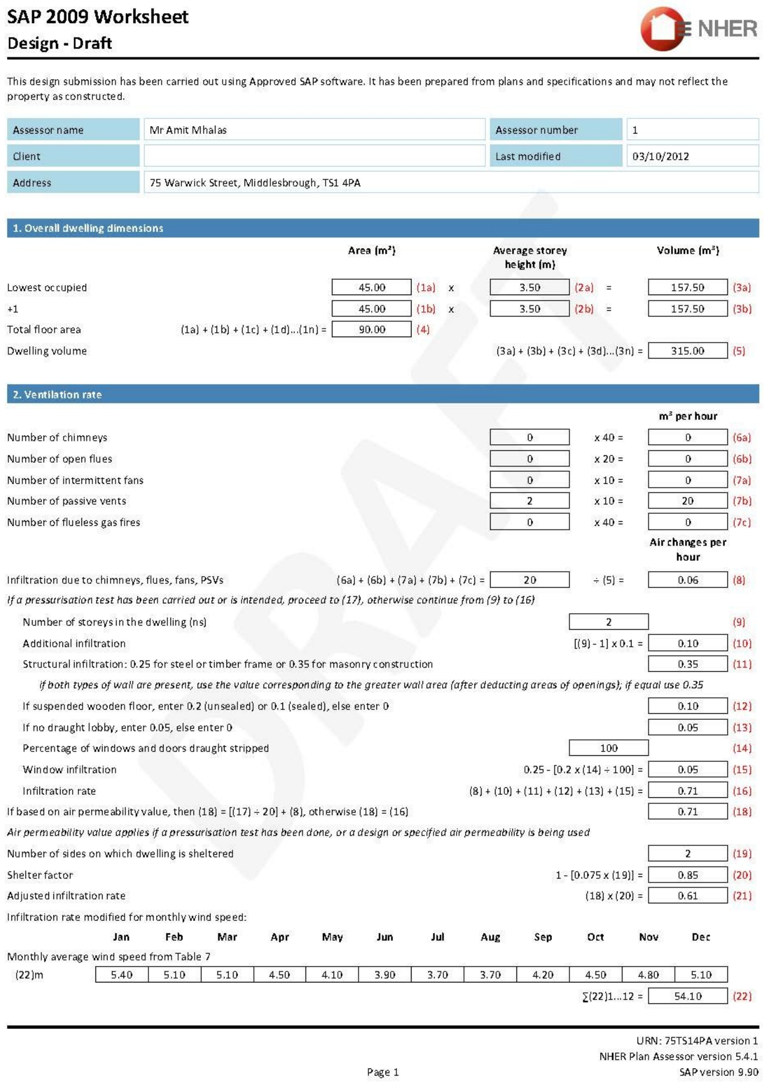

SAP 2009 Worksheet

Design - Draft

NHER

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	03/10/2012
Address	75 Warwick Street, Middlesbrough, TS1 4PA		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		45.00	(1a)	x	3.50	(2a)	=	157.50	(3a)
+1		45.00	(1b)	x	3.50	(2b)	=	157.50	(3b)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	90.00	(4)						
Dwelling volume							(3a) + (3b) + (3c) + (3d)...(3n) =	315.00	(5)

2. Ventilation rate

				m³ per hour	
Number of chimneys		0	x 40 =	0	(6a)
Number of open flues		0	x 20 =	0	(6b)
Number of intermittent fans		0	x 10 =	0	(7a)
Number of passive vents		2	x 10 =	20	(7b)
Number of flueless gas fires		0	x 40 =	0	(7c)
				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	20	÷ (5) =	0.06	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		2		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.10	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.10	(12)
If no draught lobby, enter 0.05, else enter 0			0.05	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.71	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.71	(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		2	(19)
Shelter factor	1 - [0.075 x (19)] =	0.85	(20)
Adjusted infiltration rate	(18) x (20) =	0.61	(21)

Infiltration rate modified for monthly wind speed:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average wind speed from Table 7												
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)

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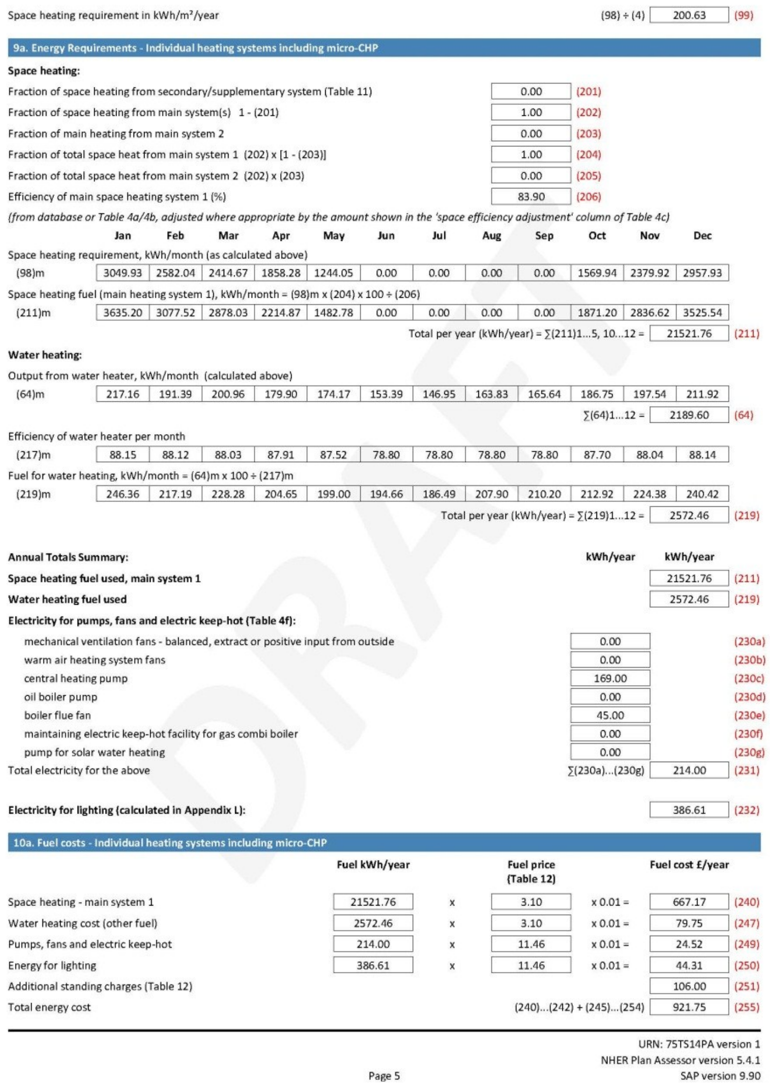

Space heating requirement in kWh/m²/year	(98) ÷ (4)	200.63	(99)

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	83.90	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space heating requirement, kWh/month (as calculated above)												
(98)m	3049.93	2582.04	2414.67	1858.28	1244.05	0.00	0.00	0.00	0.00	1569.94	2379.92	2957.93
Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)												
(211)m	3635.20	3077.52	2878.03	2214.87	1482.78	0.00	0.00	0.00	0.00	1871.20	2836.62	3525.54

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 21521.76 (211)

Water heating:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Output from water heater, kWh/month (calculated above)												
(64)m	217.16	191.39	200.96	179.90	174.17	153.39	146.95	163.83	165.64	186.75	197.54	211.92

∑(64)1...12 = 2189.60 (64)

Efficiency of water heater per month												
(217)m	88.15	88.12	88.03	87.91	87.52	78.80	78.80	78.80	78.80	87.70	88.04	88.14
Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m												
(219)m	246.36	217.19	228.28	204.65	199.00	194.66	186.49	207.90	210.20	212.92	224.38	240.42

Total per year (kWh/year) = ∑(219)1...12 = 2572.46 (219)

Annual Totals Summary:		kWh/year	kWh/year	
Space heating fuel used, main system 1			21521.76	(211)
Water heating fuel used			2572.46	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):				
mechanical ventilation fans - balanced, extract or positive input from outside		0.00		(230a)
warm air heating system fans		0.00		(230b)
central heating pump		169.00		(230c)
oil boiler pump		0.00		(230d)
boiler flue fan		45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler		0.00		(230f)
pump for solar water heating		0.00		(230g)
Total electricity for the above	∑(230a)...(230g)		214.00	(231)
Electricity for lighting (calculated in Appendix L):			386.61	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	21521.76	x	3.10	x 0.01 =	667.17	(240)
Water heating cost (other fuel)	2572.46	x	3.10	x 0.01 =	79.75	(247)
Pumps, fans and electric keep-hot	214.00	x	11.46	x 0.01 =	24.52	(249)
Energy for lighting	386.61	x	11.46	x 0.01 =	44.31	(250)
Additional standing charges (Table 12)					106.00	(251)
Total energy cost				(240)...(242) + (245)...(254)	921.75	(255)

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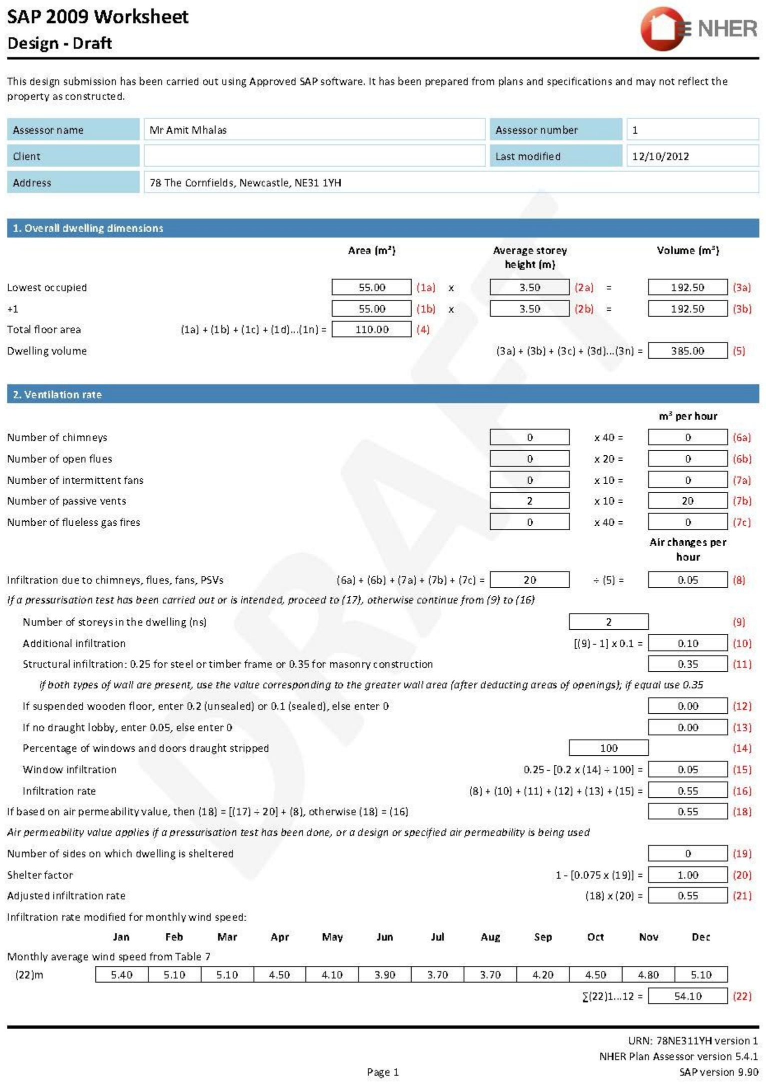

SAP 2009 Worksheet

Design - Draft

NHER

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	12/10/2012
Address	78 The Cornfields, Newcastle, NE31 1YH		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		55.00	(1a)	x	3.50	(2a)	=	192.50	(3a)
+1		55.00	(1b)	x	3.50	(2b)	=	192.50	(3b)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	110.00	(4)						
Dwelling volume					(3a) + (3b) + (3c) + (3d)...(3n) =			385.00	(5)

2. Ventilation rate

				m³ per hour	
Number of chimneys		0	x 40 =	0	(6a)
Number of open flues		0	x 20 =	0	(6b)
Number of intermittent fans		0	x 10 =	0	(7a)
Number of passive vents		2	x 10 =	20	(7b)
Number of flueless gas fires		0	x 40 =	0	(7c)
				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	20	÷ (5) =	0.05	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		2		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.10	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.00	(12)
If no draught lobby, enter 0.05, else enter 0			0.00	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.55	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.55	(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		0	(19)
Shelter factor	1 - [0.075 x (19)] =	1.00	(20)
Adjusted infiltration rate	(18) x (20) =	0.55	(21)

Infiltration rate modified for monthly wind speed:

Monthly average wind speed from Table 7

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)

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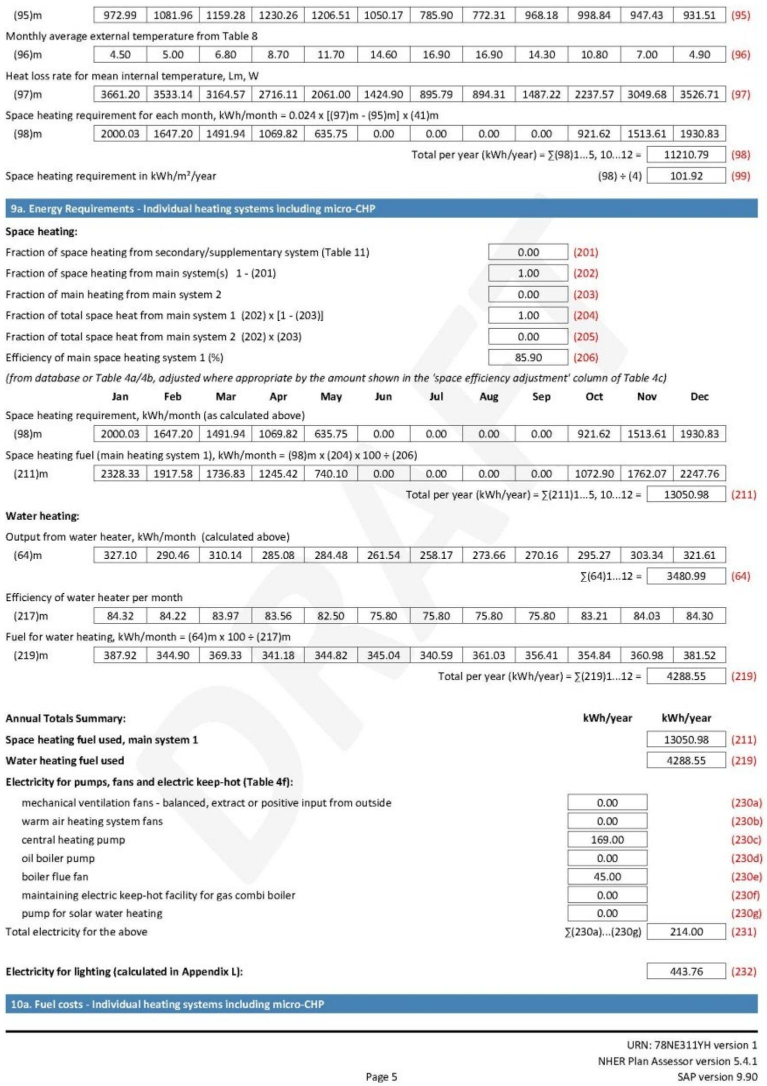

(95)m	972.99	1081.96	1159.28	1230.26	1206.51	1050.17	785.90	772.31	968.18	998.84	947.43	931.51	(95)

Monthly average external temperature from Table 8

(96)m	4.50	5.00	6.80	8.70	11.70	14.60	16.90	16.90	14.30	10.80	7.00	4.90	(96)

Heat loss rate for mean internal temperature, Lm, W

(97)m	3661.20	3533.14	3164.57	2716.11	2061.00	1424.90	895.79	894.31	1487.22	2237.57	3049.68	3526.71	(97)

Space heating requirement for each month, kWh/month = 0.024 x [(97)m - (95)m] x (41)m

(98)m	2000.03	1647.20	1491.94	1069.82	635.75	0.00	0.00	0.00	0.00	921.62	1513.61	1930.83

Total per year (kWh/year) = ∑(98)1...5, 10...12 = 11210.79 (98)

Space heating requirement in kWh/m²/year (98) ÷ (4) 101.92 (99)

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	85.90	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

Space heating requirement, kWh/month (as calculated above)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(98)m	2000.03	1647.20	1491.94	1069.82	635.75	0.00	0.00	0.00	0.00	921.62	1513.61	1930.83

Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)

(211)m	2328.33	1917.58	1736.83	1245.42	740.10	0.00	0.00	0.00	0.00	1072.90	1762.07	2247.76

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 13050.98 (211)

Water heating:

Output from water heater, kWh/month (calculated above)

(64)m	327.10	290.46	310.14	285.08	284.48	261.54	258.17	273.66	270.16	295.27	303.34	321.61

∑(64)1...12 = 3480.99 (64)

Efficiency of water heater per month

(217)m	84.32	84.22	83.97	83.56	82.50	75.80	75.80	75.80	75.80	83.21	84.03	84.30

Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m

(219)m	387.92	344.90	369.33	341.18	344.82	345.04	340.59	361.03	356.41	354.84	360.98	381.52

Total per year (kWh/year) = ∑(219)1...12 = 4288.55 (219)

Annual Totals Summary:		kWh/year	kWh/year	
Space heating fuel used, main system 1			13050.98	(211)
Water heating fuel used			4288.55	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):				
mechanical ventilation fans - balanced, extract or positive input from outside		0.00		(230a)
warm air heating system fans		0.00		(230b)
central heating pump		169.00		(230c)
oil boiler pump		0.00		(230d)
boiler flue fan		45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler		0.00		(230f)
pump for solar water heating		0.00		(230g)
Total electricity for the above	∑(230a)...(230g)		214.00	(231)
Electricity for lighting (calculated in Appendix L):			443.76	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

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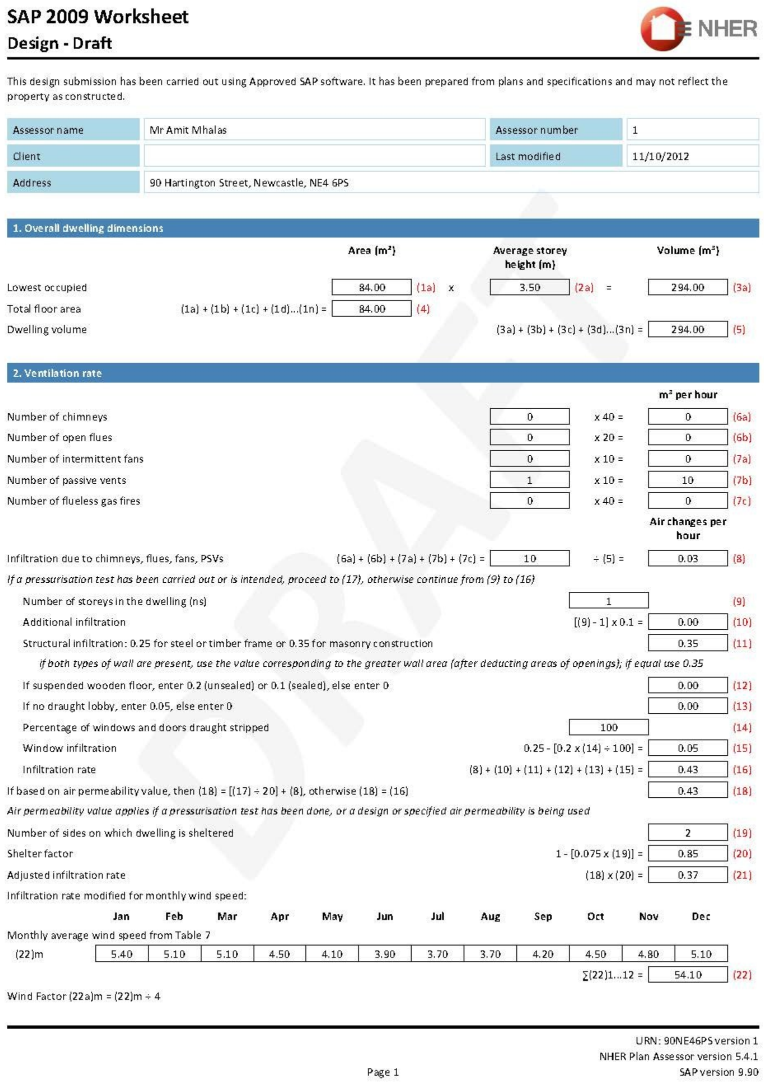

SAP 2009 Worksheet

Design - Draft

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	11/10/2012
Address	90 Hartington Street, Newcastle, NE4 6PS		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		84.00	(1a)	x	3.50	(2a)	=	294.00	(3a)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	84.00	(4)						
Dwelling volume					(3a) + (3b) + (3c) + (3d)...(3n) =			294.00	(5)

2. Ventilation rate

				m³ per hour	
Number of chimneys		0	x 40 =	0	(6a)
Number of open flues		0	x 20 =	0	(6b)
Number of intermittent fans		0	x 10 =	0	(7a)
Number of passive vents		1	x 10 =	10	(7b)
Number of flueless gas fires		0	x 40 =	0	(7c)
				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	10	÷ (5) =	0.03	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		1		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.00	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.00	(12)
If no draught lobby, enter 0.05, else enter 0			0.00	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.43	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.43	(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		2	(19)
Shelter factor	1 - [0.075 x (19)] =	0.85	(20)
Adjusted infiltration rate	(18) x (20) =	0.37	(21)

Infiltration rate modified for monthly wind speed:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average wind speed from Table 7												
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)

Wind Factor (22a)m = (22)m ÷ 4

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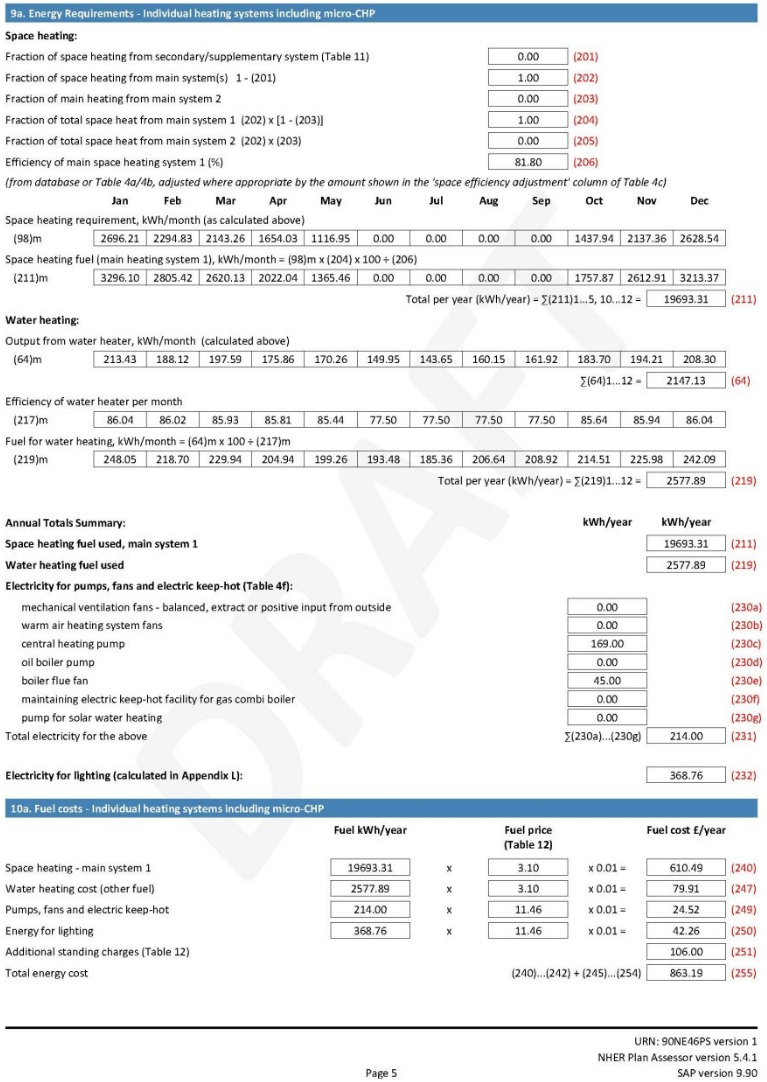

9a. Energy Requirements - Individual heating systems including micro-CHP

Space heating:

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	81.80	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space heating requirement, kWh/month (as calculated above)												
(98)m	2696.21	2294.83	2143.26	1654.03	1116.95	0.00	0.00	0.00	0.00	1437.94	2137.36	2628.54
Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)												
(211)m	3296.10	2805.42	2620.13	2022.04	1365.46	0.00	0.00	0.00	0.00	1757.87	2612.91	3213.37

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 19693.31 (211)

Water heating:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Output from water heater, kWh/month (calculated above)												
(64)m	213.43	188.12	197.59	175.86	170.26	149.95	143.65	160.15	161.92	183.70	194.21	208.30

∑(64)1...12 = 2147.13 (64)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Efficiency of water heater per month												
(217)m	86.04	86.02	85.93	85.81	85.44	77.50	77.50	77.50	77.50	85.64	85.94	86.04
Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m												
(219)m	248.05	218.70	229.94	204.94	199.26	193.48	185.36	206.64	208.92	214.51	225.98	242.09

Total per year (kWh/year) = ∑(219)1...12 = 2577.89 (219)

Annual Totals Summary:		**kWh/year**	**kWh/year**	
Space heating fuel used, main system 1			19693.31	(211)
Water heating fuel used			2577.89	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):				
mechanical ventilation fans - balanced, extract or positive input from outside		0.00		(230a)
warm air heating system fans		0.00		(230b)
central heating pump		169.00		(230c)
oil boiler pump		0.00		(230d)
boiler flue fan		45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler		0.00		(230f)
pump for solar water heating		0.00		(230g)
Total electricity for the above	∑(230a)...(230g)		214.00	(231)
Electricity for lighting (calculated in Appendix L):			368.76	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	19693.31	x	3.10	x 0.01 =	610.49	(240)
Water heating cost (other fuel)	2577.89	x	3.10	x 0.01 =	79.91	(247)
Pumps, fans and electric keep-hot	214.00	x	11.46	x 0.01 =	24.52	(249)
Energy for lighting	368.76	x	11.46	x 0.01 =	42.26	(250)
Additional standing charges (Table 12)					106.00	(251)
Total energy cost				(240)...(242) + (245)...(254)	863.19	(255)

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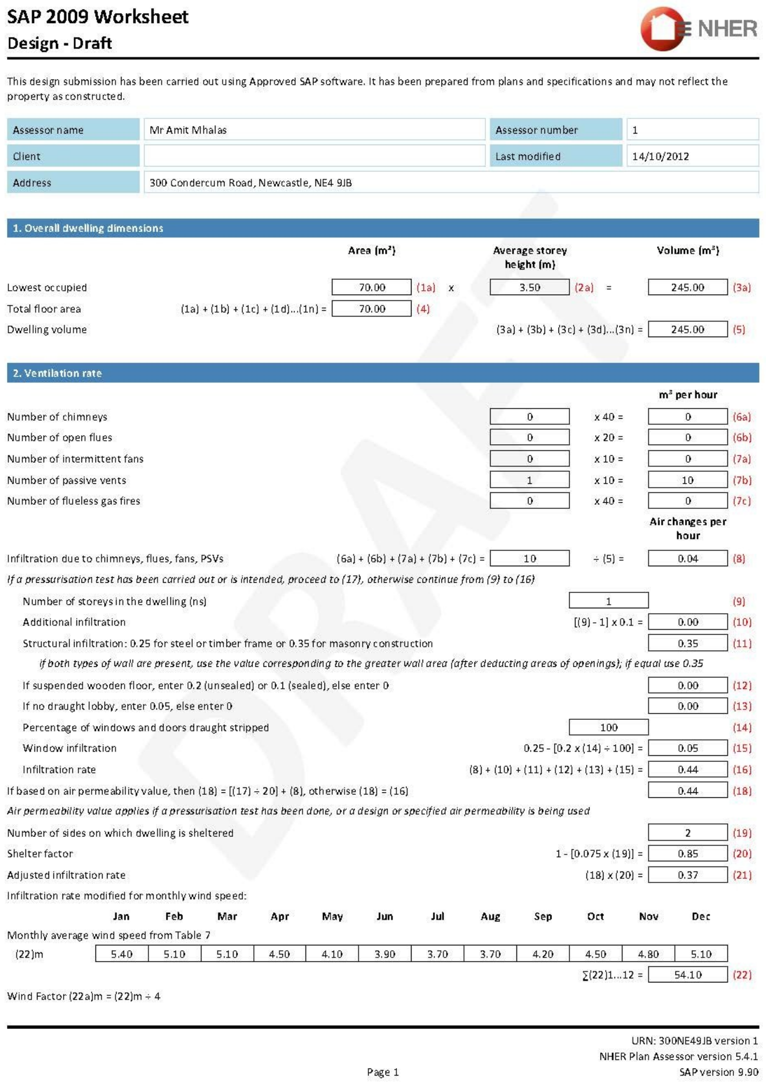

SAP 2009 Worksheet

Design - Draft

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	Mr Amit Mhalas	Assessor number	1
Client		Last modified	14/10/2012
Address	300 Condercum Road, Newcastle, NE4 9JB		

1. Overall dwelling dimensions

		Area (m²)			Average storey height (m)			Volume (m³)	
Lowest occupied		70.00	(1a)	x	3.50	(2a)	=	245.00	(3a)
Total floor area	(1a) + (1b) + (1c) + (1d)...(1n) =	70.00	(4)						
Dwelling volume							(3a) + (3b) + (3c) + (3d)...(3n) =	245.00	(5)

2. Ventilation rate

				m³ per hour	
Number of chimneys		0	x 40 =	0	(6a)
Number of open flues		0	x 20 =	0	(6b)
Number of intermittent fans		0	x 10 =	0	(7a)
Number of passive vents		1	x 10 =	10	(7b)
Number of flueless gas fires		0	x 40 =	0	(7c)
				Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a) + (6b) + (7a) + (7b) + (7c) =	10	÷ (5) =	0.04	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		1		(9)
Additional infiltration	[(9) - 1] x 0.1 =		0.00	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction			0.35	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0			0.00	(12)
If no draught lobby, enter 0.05, else enter 0			0.00	(13)
Percentage of windows and doors draught stripped		100		(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =		0.05	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		0.44	(16)
If based on air permeability value, then (18) = [(17) ÷ 20] + (8), otherwise (18) = (16)			0.44	(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		2	(19)
Shelter factor	1 - [0.075 x (19)] =	0.85	(20)
Adjusted infiltration rate	(18) x (20) =	0.37	(21)

Infiltration rate modified for monthly wind speed:

Monthly average wind speed from Table 7

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(22)m	5.40	5.10	5.10	4.50	4.10	3.90	3.70	3.70	4.20	4.50	4.80	5.10

∑(22)1...12 = 54.10 (22)

Wind Factor (22a)m = (22)m ÷ 4

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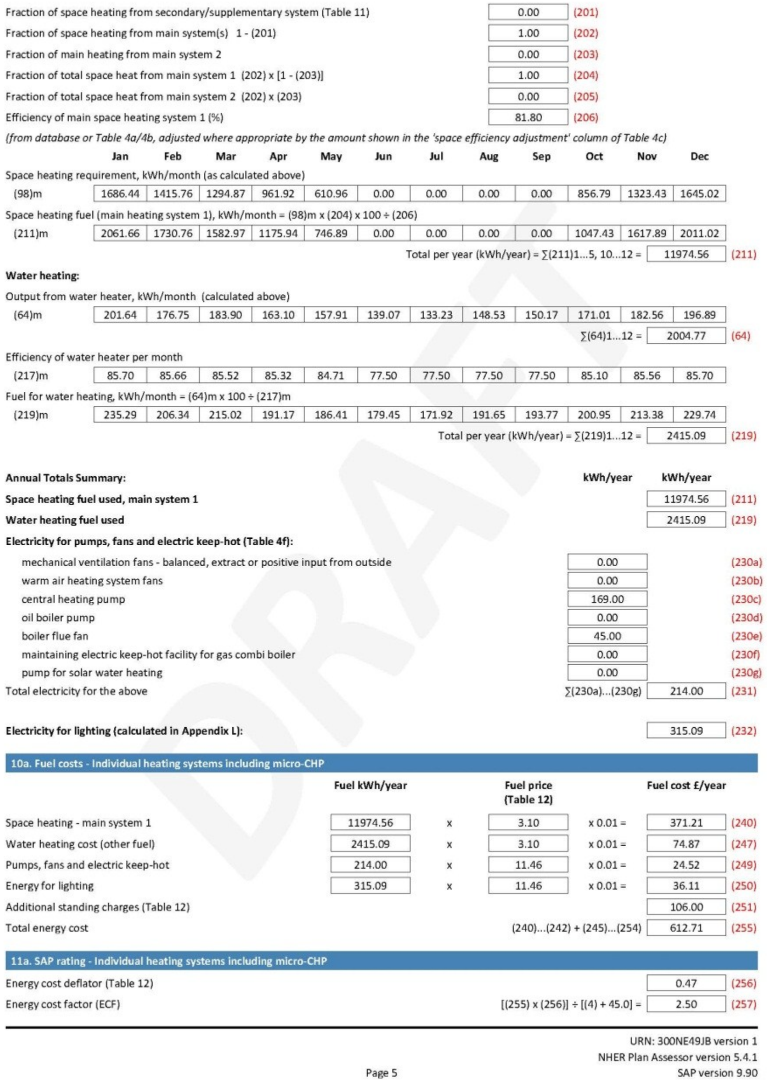

Fraction of space heating from secondary/supplementary system (Table 11)	0.00	(201)
Fraction of space heating from main system(s) 1 - (201)	1.00	(202)
Fraction of main heating from main system 2	0.00	(203)
Fraction of total space heat from main system 1 (202) x [1 - (203)]	1.00	(204)
Fraction of total space heat from main system 2 (202) x (203)	0.00	(205)
Efficiency of main space heating system 1 (%)	81.80	(206)

(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space heating requirement, kWh/month (as calculated above)												
(98)m	1686.44	1415.76	1294.87	961.92	610.96	0.00	0.00	0.00	0.00	856.79	1323.43	1645.02
Space heating fuel (main heating system 1), kWh/month = (98)m x (204) x 100 ÷ (206)												
(211)m	2061.66	1730.76	1582.97	1175.94	746.89	0.00	0.00	0.00	0.00	1047.43	1617.89	2011.02

Total per year (kWh/year) = ∑(211)1...5, 10...12 = 11974.56 (211)

Water heating:

Output from water heater, kWh/month (calculated above)												
(64)m	201.64	176.75	183.90	163.10	157.91	139.07	133.23	148.53	150.17	171.01	182.56	196.89

∑(64)1...12 = 2004.77 (64)

Efficiency of water heater per month												
(217)m	85.70	85.66	85.52	85.32	84.71	77.50	77.50	77.50	77.50	85.10	85.56	85.70
Fuel for water heating, kWh/month = (64)m x 100 ÷ (217)m												
(219)m	235.29	206.34	215.02	191.17	186.41	179.45	171.92	191.65	193.77	200.95	213.38	229.74

Total per year (kWh/year) = ∑(219)1...12 = 2415.09 (219)

Annual Totals Summary:	kWh/year	kWh/year	
Space heating fuel used, main system 1		11974.56	(211)
Water heating fuel used		2415.09	(219)
Electricity for pumps, fans and electric keep-hot (Table 4f):			
mechanical ventilation fans - balanced, extract or positive input from outside	0.00		(230a)
warm air heating system fans	0.00		(230b)
central heating pump	169.00		(230c)
oil boiler pump	0.00		(230d)
boiler flue fan	45.00		(230e)
maintaining electric keep-hot facility for gas combi boiler	0.00		(230f)
pump for solar water heating	0.00		(230g)
Total electricity for the above	∑(230a)...(230g)	214.00	(231)
Electricity for lighting (calculated in Appendix L):		315.09	(232)

10a. Fuel costs - Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	11974.56	x	3.10	x 0.01 =	371.21	(240)
Water heating cost (other fuel)	2415.09	x	3.10	x 0.01 =	74.87	(247)
Pumps, fans and electric keep-hot	214.00	x	11.46	x 0.01 =	24.52	(249)
Energy for lighting	315.09	x	11.46	x 0.01 =	36.11	(250)
Additional standing charges (Table 12)					106.00	(251)
Total energy cost				(240)...(242) + (245)...(254)	612.71	(255)

11a. SAP rating - Individual heating systems including micro-CHP

Energy cost deflator (Table 12)		0.47	(256)
Energy cost factor (ECF)	[(255) x (256)] ÷ [(4) + 45.0] =	2.50	(257)

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Appendix D Validation Results (Your Homes Newcastle)

Location		Primary Energy (kWh/m^2)			SAP Rating		
No.	Post Code	Prototype	YHN	% Diff.	Prototype	YHN	% Diff.
31	NE4 7JU	166.86	159.50	4.41%	75	72	3.44%
35	NE4 7JU	204.08	194.24	4.82%	70	67	4.27%
40	NE4 7DR	252.47	258.53	-2.40%	61	60	1.57%
4	NE4 6HZ	233.38	216.35	7.30%	68	66	3.55%
9	NE4 7DR	265.25	243.09	8.35%	50	50	0.08%
1	NE4 7DR	240.94	219.80	8.77%	60	57	4.36%
3	NE4 7DR	240.94	217.56	9.70%	66	60	8.72%
5	NE4 7DR	238.22	222.62	6.55%	62	60	3.11%
11	NE4 7DR	238.22	244.82	-2.77%	56	61	-9.03%
34	NE4 7HP	167.31	159.58	4.62%	75	71	4.93%
52	NE4 7HP	172.16	175.73	-2.08%	72	75	-4.63%
18	NE4 6JA	172.19	190.52	-10.65%	67	70	-4.76%
20	NE4 6JA	170.69	198.21	-16.12%	65	71	-8.61%
14	NE4 6EU	231.61	204.35	11.77%	65	61	5.89%
68	NE4 6HX	142.22	144.15	-1.36%	73	75	-2.16%
13	NE4 7HJ	219.66	234.72	-6.85%	59	64	-7.58%
205	NE4 6RZ	219.56	187.80	14.47%	72	64	10.93%
203	NE4 6RZ	136.04	142.24	-4.56%	67	73	-8.16%
23	NE4 7HJ	219.66	245.39	-11.71%	61	64	-4.99%
13	NE4 6EQ	204.08	174.59	14.45%	73	67	8.10%

Location		Primary Energy (kWh/m^2)			SAP Rating		
No.	**Post Code**	**Prototype**	**YHN**	**% Diff.**	**Prototype**	**YHN**	**% Diff.**
21	NE4 6EQ	205.09	208.48	-1.65%	71	75	-6.28%
10	NE4 7EB	214.66	243.84	-13.59%	60	64	-6.40%
115	NE4 6RL	198.67	176.89	10.97%	68	64	6.01%
113	NE4 6RL	198.67	183.54	7.62%	67	66	2.09%
107	NE4 6RL	198.67	195.07	1.81%	66	65	0.84%
105	NE4 6RL	198.67	184.81	6.98%	66	65	0.84%
103	NE4 6RL	198.67	182.32	8.23%	68	65	3.89%
101	NE4 6RL	198.67	190.27	4.23%	65	65	0.03%
159	NE4 6RZ	174.47	183.77	-5.33%	70	71	-1.43%
3	NE4 6RE	177.32	181.88	-2.57%	70	68	3.33%
33	NE4 6RG	183.31	191.95	-4.71%	62	65	-4.45%
31	NE4 6RG	183.31	174.69	4.70%	72	69	4.13%
14	NE4 6RJ	241.68	228.17	5.59%	64	63	1.62%
30	NE4 6ET	237.00	221.81	6.41%	62	61	2.24%
35	NE4 7HR	183.76	166.94	9.15%	72	69	4.78%
54	NE4 6HT	189.71	212.08	-11.79%	64	68	-6.18%
66	NE4 6HT	146.43	152.02	-3.82%	75	74	1.44%
5	NE4 7HS	176.06	170.16	3.35%	74	70	5.52%
38	NE4 7DS	226.67	232.29	-2.48%	60	63	-4.95%
15	NE4 7HS	235.86	227.43	3.57%	65	62	4.50%

Location		Primary Energy (kWh/m^2)			SAP Rating		
No.	Post Code	Prototype	YHN	% Diff.	Prototype	YHN	% Diff.
7	NE4 7DT	273.36	264.03	3.41%	56	56	-0.59%
24	NE4 7DT	240.44	249.79	-3.89%	58	61	-5.08%
22	NE4 7DT	218.32	211.73	3.02%	68	64	5.31%
19	NE4 7DT	264.60	250.76	5.23%	59	56	5.71%
71	NE4 6RS	182.62	156.11	14.52%	73	65	11.13%
48	NE4 6RS	164.11	163.91	0.12%	70	69	1.58%
85	NE4 6RL	171.28	174.98	-2.16%	72	71	1.68%
57	NE4 6RS	159.93	152.72	4.51%	76	73	4.25%
47	NE4 6RS	164.11	147.86	9.90%	77	72	6.55%
35	NE4 6RS	294.51	277.50	5.77%	55	55	0.80%
46	NE4 6RP	224.13	227.19	-1.36%	63	63	0.36%
48	NE4 6RP	173.08	177.50	-2.56%	68	70	-3.61%
62	NE4 6RP	224.13	233.60	-4.22%	62	63	-2.39%
18	NE4 6RP	175.00	177.40	-1.37%	68	70	-2.43%
20	NE4 6RP	175.00	184.74	-5.57%	68	69	-2.10%
26	NE4 6RQ	245.12	248.48	-1.37%	57	60	-5.76%
54	NE4 6RQ	316.24	293.11	7.31%	49	49	-0.06%
43	NE4 6RQ	230.21	241.88	-5.07%	60	62	-2.67%
57	NE4 6RQ	253.15	263.92	-4.25%	53	58	-9.35%
160	NE4 7JT	201.62	199.69	0.96%	66	67	-2.10%

Location		Primary Energy (kWh/m^2)			SAP Rating		
No.	**Post Code**	**Prototype**	**YHN**	**% Diff.**	**Prototype**	**YHN**	**% Diff.**
150	NE4 7JT	210.94	194.93	7.59%	74	68	7.88%
152	NE4 7JT	210.94	225.68	-6.99%	60	65	-8.68%
156	NE4 7JT	156.87	154.70	1.38%	76	73	4.02%

Appendix E Middlesbrough Case Study: Decision Support

Pairwise Comparison for Ranking of Criteria

Element			
A	**B**	**Importance**	**Intensity (1-9)**
Annual Reduction in CO2 Levels	Initial Investment	B	3
	Return on Investment	B	5
	Social Acceptability	A	1
	Ease of Implementation	A	1
Initial Investment	Return on Investment	A	3
	Social Acceptability	A	5
	Ease of Implementation	A	3
Return on Investment	Social Acceptability	A	3
	Ease of Implementation	A	1
Social Acceptability	Ease of Implementation	B	3

Matrix	1	2	3	4	5
1	1	1/3	1/5	1	1
2	3	1	3	5	3
3	5	1/3	1	3	1
4	1	1/5	1/3	1	1/3
5	1	1/3	1	3	1

The above matrix is evaluated per the following equation up to 4th iteration to obtain consistent eigen vectors:

$$(A - \lambda I)v = 0$$

Where,

A is the normalised matrix developed based on initial weightages
I is the identity matrix
λ is the eigen-value
v is the eigen vector

4th Iteration	1	2	3	4	5	Eigen Vector
1	0.12	0.12	0.12	0.12	0.12	0.12
2	0.45	0.45	0.45	0.45	0.45	0.45
3	0.20	0.20	0.20	0.20	0.20	0.20
4	0.08	0.08	0.08	0.08	0.08	0.08
5	0.16	0.16	0.16	0.16	0.16	0.16

Consistency Index: 0.0859

Pairwise Comparison of Interventions for Annual Reduction in CO_2 Levels

Element			
A	**B**	**Importance**	**Intensity (1-9)**
Solar Panels	Heating System	A	3
	Micro CHP	B	3
	ASHP	A	5
	Fabric Insulation	B	5
Heating System	Micro CHP	B	5
	ASHP	A	1
	Fabric Insulation	B	9
Micro CHP	ASHP	A	5
	Fabric Insulation	B	3
ASHP	Fabric Insulation	B	9

A similar process of matrix evaluation as described earlier is adopted for all pairwise comparisons.

Matrix	1	2	3	4	5
1	1	3	1/3	5	1/5
2	1/3	1	1/5	1	1/9
3	3	5	1	5	1/3
4	1/5	1	1/5	1	1/9
5	5	9	3	9	1

4th Iteration	1	2	3	4	5	Eigen Vector
1	0.11	0.11	0.11	0.11	0.11	0.11
2	0.05	0.05	0.05	0.05	0.05	0.05
3	0.22	0.22	0.22	0.22	0.22	0.22
4	0.05	0.05	0.05	0.05	0.05	0.05
5	0.57	0.57	0.57	0.57	0.57	0.57

Consistency Index: 0.0570

Pairwise Comparison of Interventions for Initial Investment

Element			
A	B	Importance	Intensity (1-9)
Solar Panels	Heating System	A	3
	Micro CHP	B	1
	ASHP	A	7
	Fabric Insulation	B	1
Heating System	Micro CHP	B	3
	ASHP	A	3
	Fabric Insulation	B	5
Micro CHP	ASHP	A	5
	Fabric Insulation	B	1
ASHP	Fabric Insulation	B	9

Matrix	1	2	3	4	5
1	1	3	1	7	1
2	1/3	1	1/3	3	1/5
3	1	3	1	5	1
4	1/7	1/3	1/5	1	1/9
5	1	5	1	9	1

4th Iteration	1	2	3	4	5	Eigen Vector
1	0.29	0.29	0.29	0.29	0.29	0.29
2	0.08	0.08	0.08	0.08	0.08	0.08
3	0.28	0.28	0.28	0.28	0.28	0.28
4	0.04	0.04	0.04	0.04	0.04	0.04
5	0.30	0.30	0.30	0.30	0.30	0.30

Consistency Index: 0.0199

Pairwise Comparison of Interventions for Return on Investment

Element			
A	**B**	**Importance**	**Intensity (1-9)**
Solar Panels	Heating Systems	A	1
	Micro CHP	A	3
	Heat Pump	A	3
	Fabric Insulation	B	5
Heating Systems	Micro CHP	A	5
	Heat Pump	A	3
	Fabric Insulation	A	1
Micro CHP	Heat Pump	B	3
	Fabric Insulation	B	5
Heat Pump	Fabric Insulation	B	5

Matrix	**1**	**2**	**3**	**4**	**5**
1	1	1	3	3	1/5
2	1	1	5	3	1
3	1/3	1/5	1	1/3	1/5
4	1/3	1/3	3	1	1/5
5	5	1	5	5	1

4th Iteration	**1**	**2**	**3**	**4**	**5**	**Eigen Vector**
1	0.17	0.17	0.17	0.17	0.17	0.17
2	0.30	0.30	0.30	0.30	0.30	0.30
3	0.06	0.06	0.06	0.06	0.06	0.06
4	0.08	0.08	0.08	0.08	0.08	0.08
5	0.40	0.40	0.40	0.40	0.40	0.40

Consistency Index: 0.0856

Pairwise Comparison of Interventions for Social Acceptability

Element			
A	**B**	**Importance**	**Intensity (1-9)**
Solar Panels	Wind Turbines	A	5
	Micro CHP	A	3
	Heat Pump	A	5
	Fabric Insulation	A	3
Wind Turbines	Micro CHP	B	3
	Heat Pump	B	1
	Fabric Insulation	B	5
Micro CHP	Heat Pump	A	3
	Fabric Insulation	A	3
Heat Pump	Fabric Insulation	B	3

Matrix	1	2	3	4	5
1	1	5	3	5	3
2	1/5	1	1/3	1	1/5
3	1/3	3	1	3	3
4	1/5	1	1/3	1	1/3
5	1/3	5	1/3	3	1

4th Iteration	1	2	3	4	5	Eigen Vector
1	0.48	0.48	0.48	0.48	0.48	0.48
2	0.08	0.08	0.08	0.08	0.08	0.08
3	0.21	0.21	0.21	0.21	0.21	0.21
4	0.08	0.08	0.08	0.08	0.08	0.08
5	0.15	0.15	0.15	0.15	0.15	0.15

Consistency Index: 0.0825

Pairwise Comparison of Interventions for Ease of Implementation

Element			
A	B	Importance	Intensity (1-9)
Solar Panels	Heating Systems	A	3
	Micro CHP	A	3
	Heat Pump	A	5
	Fabric Insulation	A	5
Heating Systems	Micro CHP	B	3
	Heat Pump	A	1
	Fabric Insulation	A	1
Micro CHP	Heat Pump	A	3
	Fabric Insulation	B	1
Heat Pump	Fabric Insulation	B	3

Matrix	1	2	3	4	5
1	1	3	3	5	5
2	1/3	1	1/3	1	1
3	1/3	3	1	3	1
4	1/5	1	1/3	1	1/3
5	1/5	1	1	3	1

4th Iteration	1	2	3	4	5	Eigen Vector
1	0.48	0.48	0.48	0.48	0.48	0.48
2	0.12	0.12	0.12	0.12	0.12	0.12
3	0.19	0.19	0.19	0.19	0.19	0.19
4	0.08	0.08	0.08	0.08	0.08	0.08
5	0.13	0.13	0.13	0.13	0.13	0.13

Consistency Index: 0.0689

Final Determinant Matrix of all Comparisons

Alternative	CO_2 Reduced	Init. Invst.	Ret. on Inv.	SA	EoI	**Goal**
Solar Panels	0.0131	0.1285	0.0333	0.0370	0.0756	**28.75%**
Heating System	0.0063	0.0379	0.0590	0.0059	0.0195	**12.85%**
Micro CHP	0.0251	0.1270	0.0120	0.0167	0.0293	**21.01%**
ASHP	0.0061	0.0188	0.0166	0.0061	0.0130	**6.06%**
Fabric Change	0.0660	0.1362	0.0790	0.0120	0.0201	**31.33%**

Appendix F Newcastle Case Study: Decision Support

Matrices are prepared and evaluated in a similar way as described in Appendix E.

Pairwise Comparison of Criteria

Element			
A	**B**	**Importance**	**Intensity (1-9)**
Annual Reduction in CO2 Levels	Initial Investment	A	3
	Return on Investment	A	3
	Social Acceptability	A	5
	Ease of Implementation	A	7
Initial Investment	Return on Investment	A	3
	Social Acceptability	A	5
	Ease of Implementation	A	3
Return on Investment	Social Acceptability	A	3
	Ease of Implementation	A	1
Social Acceptability	Ease of Implementation	B	3

Consistency Index: 0.0989

Pairwise Comparison of Interventions for Annual Reduction in CO_2 Levels

Element			
A	**B**	**Importance**	**Intensity (1-9)**
Solar Panels	Heating System	A	5
	Micro CHP	A	3
	GSHP	A	3
	Fabric Insulation	B	3
Heating System	Micro CHP	B	5
	GSHP	B	3
	Fabric Insulation	B	9
Micro CHP	GSHP	B	3
	Fabric Insulation	B	3
GSHP	Fabric Insulation	B	3

Consistency Index: 0.0973

Pairwise Comparison of Interventions for Initial Investment

Element			
A	**B**	**Importance**	**Intensity (1-9)**
Solar Panels	Heating System	A	3
	Micro CHP	B	1
	GSHP	A	3
	Fabric Insulation	B	3
Heating System	Micro CHP	B	3
	GSHP	B	3
	Fabric Insulation	B	5
Micro CHP	GSHP	A	5
	Fabric Insulation	B	3
GSHP	Fabric Insulation	B	5

Consistency Index: 0.0936

Pairwise Comparison of Interventions for Return on Investment

Element			
A	**B**	**Importance**	**Intensity (1-9)**
Solar Panels	Heating Systems	A	3
	Micro CHP	A	1
	GSHP	A	3
	Fabric Insulation	B	5
Heating Systems	Micro CHP	B	5
	GSHP	B	3
	Fabric Insulation	B	7
Micro CHP	GSHP	B	1
	Fabric Insulation	B	3
GSHP	Fabric Insulation	B	3

Consistency Index: 0.0781

Pairwise Comparison of Interventions for Social Acceptability

Element			
A	**B**	**Importance**	**Intensity (1-9)**
Solar Panels	Heating System	A	3
	Micro CHP	A	1
	GSHP	A	3
	Fabric Insulation	A	5
Heating System	Micro CHP	B	5
	GSHP	B	3
	Fabric Insulation	B	3
Micro CHP	GSHP	A	3
	Fabric Insulation	A	3
GSHP	Fabric Insulation	A	1

Consistency Index: 0.0679

Pairwise Comparison of Interventions for Ease of Implementation

Element			
A	**B**	**Importance**	**Intensity (1-9)**
Solar Panels	Heating Systems	A	3
	Micro CHP	A	3
	GSHP	A	5
	Fabric Insulation	A	5
Heating Systems	Micro CHP	B	3
	GSHP	A	1
	Fabric Insulation	A	1
Micro CHP	GSHP	A	3
	Fabric Insulation	B	1
GSHP	Fabric Insulation	B	3

Consistency Index: 0.0689

Final Determinant Matrix of all Comparisons

Alternative	CO_2 Reduced	Int. Inv.	Ret. on Inv.	SA	EoI	**Goal**
Solar Panels	0.1101	0.0376	0.0203	0.0247	0.0409	**23.37%**
Heating System	0.0221	0.0162	0.0073	0.0055	0.0106	**6.16%**
Micro CHP	0.0580	0.0402	0.0210	0.0240	0.0158	**15.90%**
GSHP	0.0739	0.0182	0.0185	0.0085	0.0070	**12.60%**
Fabric Change	0.2327	0.1035	0.0652	0.0073	0.0109	**41.97%**