Sustainability in the UK domestic sector

A review and analysis of the sustainable energy innovations available to homeowners

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Abstract

The UK Government has set an ambitious legislative goal of reducing greenhouse gas emissions by 80% by 2050. Of the total energy used in the UK, 31% is used in the domestic sector. In the domestic sector energy is used for space and hot water heating, lighting, appliances and cooking. Space and hot water heating make up 82% of the total energy used in the UK domestic sector. Almost all of the energy used in the UK domestic sector originates from depletable resources. In order for the UK to reach its goal of decreasing greenhouse gas emissions by 80% by 2050, the way energy is used in the UK domestic sector needs to change dramatically. The aim of this study is to identify opportunities for homeowners to be more sustainable without compromising their standard of living, by changing the way they use and supply energy. Homeowners’ ways of using and supplying energy today will be reviewed followed by an identification of measures that can be taken to create a more sustainable home from an energy perspective. Identified measures not only include usage of small-scale energy technologies but also application of energy efficiency measures and changes in behaviour that result in homeowners using energy in a more efficient way.

The aim has been achieved by conducting a literature review, collecting statistical data regarding energy use from the Department of Energy and Climate Change and the undertaking of a case study. The literature review revealed that air source and solar assisted heat pumps, solar photovoltaic (solar PV) and fuel cell micro combined heat and power (fuel cell mCHP) are the most promising and widely available microgeneration technologies on the market today. LED light bulbs, wall and loft insulation and energy efficient appliances are the energy efficiency measures identified as having the highest potential to decrease the amount of energy used. The literature review also proved that behaviour in relation to energy use is a key area to address in order to make homeowners use energy in a more efficient way.

The case study consisted of six case houses, based on the most common house types in the UK. The reference heating system used in the case study was a gas boiler connected to a central heating system of the house. 80% of the homes in the UK are heated with a gas boiler and that is why it was chosen as a reference scenario. The case study showed that all of the microgeneration technologies use resources and energy in a more efficient way than the reference scenario. But despite the financial support of governmental subsidies none of the microgeneration technologies were financially viable options compared to a gas boiler. Energy efficiency measures, especially LED lighting, wall and loft insulation, significantly lowered the amount of energy used, they lowered the influence on greenhouse gas emissions and were financially viable options without the support of governmental subsidies.

It was identified that microgeneration technologies are impacted by behaviour and that they can enable demand-side management, especially as the number of supply-driven sources such as wind and solar PV increases.

In summation microgeneration technologies and energy efficiency measures have a large potential to help make homeowners become more sustainable from an energy perspective. Governmental support has a determining role in making them financially viable and therefore accessible to the public.
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Abbreviations

ASHPs – Air Source Heat Pumps

CHM – Cambridge Housing Model

COP – Coefficient of Performance

DECC – Department of Energy and Climate Change

DUKES – Digest of UK Energy Statistics

ECUK – Energy Consumption in the United Kingdom

EPC - Energy Performance Certificates

GHG – Greenhouse Gases

GSHPs - Ground Source Heat Pumps

FIT – Feed-In Tariffs

MCS – Microgeneration Certification Scheme

NEED – National Energy Efficiency Data-Framework

NPC – Net Present Cost

NPV – Net Present Value

PV – Photovoltaic

RHI – Renewable Heat Incentive

SAP – Standard Assessment Procedure

SAHPs - Solar assisted heat pumps

SPF – Seasonal Performance Factor
1 Introduction

In this chapter an introduction to the background of the study is given and the aim for the study is defined. Following the aim are the limitations of the study and a definition of sustainability. Last in this chapter the layout of the report is presented.

The United Kingdom (UK) has set an ambitious goal of reducing their overall greenhouse gas (GHG) emissions by 80 % by 2050 (DECC Heat Strategy Team 2013). Besides this goal the UK has to reach a target set by the European Union (EU): by 2020 the UK has to supply 15 % of the energy demand from renewable sources (DECC 2013b). Her Majesty’s (HM) Government and the Department of Energy and Climate Change (DECC) (2015) states that energy supply security is one of the Governments highest priorities. Since 2004 the UK has been a net importer of energy as their reserves of gas and oil has been declining since 1999, which highlights the importance of establishing an energy system characterised by higher security of supply (DECC 2014b).

The total final energy use in the UK in 2013 was 1 590 TWh (Prime 2014a), which is approximately 12 % of the total final energy use in the EU (EEA 2015). The energy use within the domestic sector in the UK was around a third of the total final energy use in 2013 (Prime 2014a). According to HM Government and DECC (2015), consumers will play a more active part in sourcing and managing their energy in the future. While consumers most likely will play a large part in changing the energy system it is also of importance that this change does not raise the cost of energy for them (HM Government and DECC 2015). As important as developing a more flexible and competitive energy market is the need to decrease the demand for energy, by implementing energy efficiency measures and different solutions for demand-side management (HM Government and DECC 2015). Putting consumers within the domestic sector in control of their energy use will result in lowered energy bills as well as lowered GHG emissions (DECC 2014b). A range of different policies, such as the Green Deal, are in place to support energy efficiency measures and to encourage homeowners to invest in microgeneration technologies allowing them to produce their own electricity and heat (DECC 2014b). This shows that the UK Government firmly believes in making homeowners a part of a low carbon, efficient and sustainable energy system.

The energy market in the UK is centralised with six major energy firms holding most of the market share (DECC 2014b). Microgeneration technologies can increase consumer choice and contribute to a more competitive energy market while improving energy security by reducing fuel imports and utilising resources in a more efficient way (Staffell, et al. 2010; Watson, et al. 2008; Allen, Hammond and McManus 2008). A range of different microgeneration technologies is available on the market today including heat pumps, solar photovoltaic (PV), solar thermal, micro wind turbines and micro combined heat and power (mCHP) (Rogers, et al. 2014).

According to Allen and Hammond (2010) one barrier to the uptake of sustainable energy innovations is quantitative information regarding their performance (both energetic, environmental and economical performance). This study aims at contributing to the research field by bringing more clarity into the energy innovations available to homeowners and how they can be more sustainable in their use and supply of energy.
1.1 ASC Renewables

This study was undertaken on behalf of ASC Renewables, Manchester, UK. ASC Renewables is an ethical business developing renewable energy projects and providing energy solutions. Their aim is to provide sustainable energy without compromise. Their main customers are landowners, local authorities and large energy users. Affecting the energy used in the UK domestic sector is a possible extension of the area of business for ASC Renewables.

1.2 Aim

The aim of this study is to identify opportunities for homeowners to be more sustainable without compromising their standard of living\(^1\) by changing the way they use and supply energy. Homeowners’ ways of using and supplying energy today will be reviewed followed by an identification of measures that can be taken to create a more sustainable home. Identified measures will not only include usage of small-scale energy (microgeneration) technologies but also energy efficiency measures and changes in behaviour that would result in homeowners using and supplying energy in a more efficient way. The identified energy innovations will then be evaluated from an environmental (limited to GHG-emissions) and financial perspective. Providing an overview of possible business opportunities for ASC Renewables to investigate is further aim of this study. The aim will be fulfilled using the following research questions:

\(RQ1.\) What energy innovations (technologies and measures) exist today that would help make individual homeowners use and supply energy in a sustainable manner without compromising their standard of living?

\(RQ2.\) What are the environmental benefits and the economic feasibility of introducing the identified energy innovations (technologies and measures)?

\(RQ3.\) How do governmental policies and changes in human behaviour affect the environmental benefits and economic feasibility of the identified energy innovations?

\(RQ4.\) Can any possible business opportunities be identified among the energy innovations for ASC Renewables to investigate further?

1.3 Limitations

This study is limited to aspects of energy use and supply within the UK domestic sector. The domestic sector is defined as households. The study covers energy used within homes, including energy used for heating, cooking, lighting and appliances. The study is limited to owner-occupied, gas heated dwellings that are connected to the main electricity grid.

Technologies reviewed are limited to small-scale technologies that can be installed and used in a single household located within an urban area in the UK. Microgeneration is defined in the UK’s Energy Act as the production of electricity or heat from a low-carbon source, at an installed electricity capacity of no more than 50 kW\(_{\text{electricity}}\) or a heat capacity of no more than 45 kW\(_{\text{thermal}}\) (Allen and Hammond 2010). The same definition applies to this study.

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\(^1\) Homeowners should not have to compromise their standard of living as a consequence of being more sustainable. Compromising their standard of living could for example mean that homeowners have to involuntarily give up commodities or spend more money on energy than they currently do.
Reducing GHG emissions in relation to energy use is the Government's main environmental strategy; therefore the only environmental aspect considered in this study is GHG emissions. For a full lifecycle analysis, including other environmental aspects than GHG emissions, the reader is referred to studies such as Rogers et al. (2015).

1.4 Definition of sustainability

In order to reach the aim and identify opportunities for homeowners to create a more sustainable home a definition of sustainability is necessary. The most well known definition of sustainable development is from the United Nations’ Bruntland Commission (Bruntland, 1987, p. 43):

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

The non-governmental organisation The Natural Step has set up four ‘Sustainability Principles’, which are a further development of the above definition (Robèrt et al., 2012). The four ‘Sustainability Principles’ state that in a sustainable society, nature is not subject to systematically increasing:

1. Concentrations of substances extracted from the Earth’s crust
2. Concentrations of substances produced by society
3. Degradation by physical means
And in that a sustainable society;
4. People are not subject to conditions that systematically undermine their capacity to meet their needs

Investments in new technologies should, according to Robèrt et al. (2012), provide flexible stepping-stones for future moves towards a sustainable energy system. A technology can contribute to sustainable development even if it uses depletable resources providing it uses resources in a more efficient way than currently used technologies and has the potential to use sustainable resources (instead of depletable resources) in the future as the technology develops.

1.5 Structure of report

This section describes the structure of the report and dependencies between the chapters. The structure is illustrated in Figure 1. The report consists of seven chapters.

Chapter 1 – Introduction: An introduction to the background of the study is presented followed by defining the aim and the four research questions that will be answered to fulfil the aim.

Chapter 2 - Background: Description of the energy use in the UK today, both in total and within the domestic sector. The energy use is presented per type of energy use and energy source. The governmental policies and plans affecting the domestic energy sector are thereafter described. An introduction to the housing stock in the UK is given to provide the reader with an understanding of what typical housing situations look like and where the major areas of improvement can be identified.

Chapter 3 - Theoretical framework: First a technical description of the microgeneration technologies available to homeowners is given. These technologies are thereafter linked to how they are affected by and their influence on demand-side response. A perspective of human behaviour in relation to energy use is given. Last in this chapter an understanding of
financial and environmental evaluation of energy innovations is given based on previous studies.

Chapter 4 - Methodology: The method and work process used in the study is described. The case study, including six case houses, used to evaluate the energy innovations available to homeowners is described. Eight scenarios are set up to represent the energy innovations evaluated and a reference scenario for comparison. The eight scenarios are compared within each of the six case houses.

Chapter 5 – Results: case study and sensitivity analysis: The results from the study are presented. Changes in energy use, influence on global GHG emissions as well as costs, savings and payback time are presented and compared for the eight scenarios within each case house. Various different factors, for example carbon intensity of electricity generation, affect the results. These factors are included in a sensitivity analysis presented in the latter part of this chapter.

Chapter 6 - Discussion: In this chapter the limitations set to the study are discussed as well as possible implications of the method used. Suggestions for further research are provided as well as a discussion of the wider context of the study.

Chapter 7 – Conclusions and Recommendations: The results and discussion are summarised in order to answer the four research questions and to fulfil the aim.
Figure 1: The structure of the report.
2 Background

This chapter aims at giving an understanding of the energy use in the domestic sector in the UK today and an overview of the Government’s plans and policies regarding domestic energy usage. A description of the housing stock is given as a background for the case study that is presented in chapter 4. The latter part of the chapter covers three of the key areas to support homeowners in producing and using heat and electricity in a more sustainable way; energy efficiency, microgeneration and demand-side management.

2.1 Energy use in the UK

The total final energy use in the UK in 2013 was 1 590 TWh (Prime 2014a), which is approximately 12 % of the total final energy use in the EU (EEA 2015). Figure 2 and Figure 3 show the total final energy use in the UK divided by sector and by source.

![Total energy use by sector](image1)

Approximately 47 % of the total energy use in 2013 was imported (DECC 2014a); 50 % of the natural gas, 4 % of the electricity and 81 % of the coal were imported (DECC 2014a). Table 1 shows the country of origin for natural gas and coal. The electricity generation by fuel source is shown in Figure 4. The amount of imported energy relates to the Governmental vision of increasing energy supply security described in chapter 1.

![Total energy use by source](image2)

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Country of origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>Norway, Qatar, Netherlands, Belgium</td>
</tr>
<tr>
<td>Coal</td>
<td>Russia, USA, Colombia, Australia, the EU, Canada, South Africa</td>
</tr>
<tr>
<td>Electricity</td>
<td>France, Netherlands, Ireland</td>
</tr>
</tbody>
</table>

Figure 2: Total energy use in the UK by sector. (Prime 2014a)

Figure 3: Total energy use by source. Solid fuels include coal, coke and breeze, coke oven gas and other solid fuels. (Prime 2014a)

Table 1: Country of origin for the imports of natural gas, coal and electricity. The countries are arranged in order of magnitude. (DECC 2014a)
Figure 4: Annual electricity generation by energy source (total 360 TWh) (DECC 2014a).

Figure 5: Annual domestic energy use (total 509 TWh) by type of energy source (Prime 2014b).

Figure 6: Annual domestic energy use (total 509 TWh) by end-use (Prime 2014b)

Table 2: Annual domestic energy use in TWh by type of end-use and energy source (Prime 2014b).
As shown in Figure 2 the domestic sector uses 31% of total energy, which amounts to 359 TWh per year. Figure 5 and Figure 6 show domestic energy use by type of energy source and end-use. An average household consumes 4,192 kWh of electricity and 15,462 kWh of gas per year (Prime 2014b).

As shown in Figure 5 and Figure 6 space heating is the dominant area of energy use within the domestic sector, with gas as the main source of energy used. Table 2 shows that gas is the main fuel used for both space heating and for heating water. According to Prime (2014b) the most common way to heat a house in the UK today is using a central heating system and a gas boiler. Approximately 84% of all dwellings have gas central heating installed. There are different types of gas boilers in use, the most common being a standard boiler (heats central heating system and hot water tank separately) or a condensing combination boiler (provides both hot water and space heating simultaneously and on demand and utilises heat from the flue gases which increases efficiency). Central heating systems are water based and have regular radiators with a minimum operating temperature of 45 °C (Staffell, et al. 2010).

Although the amount of gas used in the domestic sector is three times the electricity used, cost and GHG emissions related to electricity use are higher than those related to gas use. The average cost for a kWh of gas in 2014 was 5.02 pence, for electricity the equivalent was 15.57 pence (DECC 2014c). Because coal is used in electricity generation, a more carbon intensive energy source than gas, the GHG emissions associated with electricity use are higher than those associated with gas use (Palmer and Cooper, United Kingdom housing energy fact file 2014).

2.2 The housing stock

The UK population in 2011 was at 63 million with the number of dwellings at 27.4 million. The housing stock consists of semi-detached, terraced and detached houses as well as flats and bungalows. Terraced, semi-detached and detached houses make up the majority of the housing stock, at 71%. Approximately 65% of homes are owner-occupied, while the remaining 35% are either privately rented or local authority housing. 85% of UK dwellings date back to pre 1990. Around 20% were built before 1918. (Palmer and Cooper, United Kingdom housing energy fact file 2014)

According to the National Energy Efficiency Data-Framework (NEED) (DECC 2015), a statistical framework published by DECC with the aim of providing a better understanding of energy use and energy efficiency in domestic buildings, the categories in the housing stock that use the most gas and electricity are owner-occupied, detached and old buildings. Owner-occupied dwellings use on average 3,700 kWh of gas per year more than privately rented dwellings.

2.3 Energy efficiency of domestic buildings

2.3.1 Insulation measures
There are four major insulation measures available to improve energy efficiency in domestic buildings: cavity wall insulation, solid wall insulation, double-glazing, and loft insulation (Prime 2014b). Cavity and solid wall are two different wall types, dictated at the point of constructing a house. Solid walls are considered to be harder to treat than cavity walls and solid wall insulation are therefore less common (Palmer and Cooper, United Kingdom housing energy fact file 2014). Table 3 shows the percentage of available properties treated with these four measures of energy efficiency.

Table 3: Percentage of UK households treated with the four most common measures for energy efficiency. The percentage is calculated using the total number of properties known to have cavity walls/lofts/solid walls and the number of properties known to having already installed the measure. Double-glazing can be installed in all types of dwellings and is therefore calculated using the entire housing stock. (Prime 2014b)

<table>
<thead>
<tr>
<th>Energy efficiency measures</th>
<th>Percentage of households treated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity wall insulation</td>
<td>69.8 %</td>
</tr>
<tr>
<td>Double-glazing</td>
<td>94.1 %</td>
</tr>
<tr>
<td>Loft insulation</td>
<td>68.8 %</td>
</tr>
<tr>
<td>Solid wall insulation</td>
<td>3.3 %</td>
</tr>
</tbody>
</table>

2.3.2 Lighting and appliances
As seen in Table 2 most electricity used in the domestic sector is currently used for lighting and appliances. As mentioned previously, electricity is more expensive and carbon intensive to produce than gas meaning that lowering electricity use will have both global environmental benefits and financial benefits for consumers. More efficient lighting and appliances are, according to the Carbon Plan (HM Government 2011), important in order to reduce the demand for energy in dwellings. According to Palmer and Terry (2014) lighting and appliances have large energy saving potential, both in relation to what level of energy rating the appliances in use have and how they are used.

2.3.3 Energy rating
Two systems for energy efficiency rating of buildings have been implemented in the UK: the Standard Assessment Procedure (SAP) and Energy Performance Certificates (EPC).

SAP is a governmental approved method of evaluating and rating dwellings based on their energy efficiency. In use since 1993, the SAP is based on the annual energy costs for space heating, water heating, ventilation and lighting (minus any savings from energy generation technologies) under standardised conditions. The SAP rates buildings going on a 1 to 100 scale; the higher the rating the more energy efficient the building is and the lower the annual energy costs are. (Palmer and Cooper, United Kingdom housing energy fact file 2014)

EPC was introduced in 2007 and is required whenever a property is built, sold or rented. An EPC contains information about a property’s energy use and typical energy costs, alongside recommendations about how to reduce energy usage. The EPC rates properties from A (most efficient) to D (least efficient). (DECC 2015)
2.3.4 Energy efficiency policies

The Government has implemented a range of policies to increase energy efficiency. Energy Company Obligation (ECO) has been in place since 2013 and places legal obligations on energy providers to deliver energy efficiency measures to domestic energy users. ECO is geared towards supporting low income and vulnerable households as well as hard-to-treat buildings, such as solid walls (Ofgem 2015a). The Green Deal was introduced in 2013 and allows households to make energy efficiency improvements with some or all of the cost covered from the savings on their energy bills (DECC Heat Strategy Team 2013). The energy efficiency improvements may include insulation as well as installation of heat technologies such as heat pumps or a new, more efficient boiler (DECC Heat Strategy Team 2013). Energy efficiency of new houses is legally regulated in the 2010 Building Regulations (Palmer and Cooper, United Kingdom housing energy fact file 2014).

2.4 Microgeneration

A move away from traditional ways of using fossil fuels for production of heating and electricity and instead implementing low carbon and renewable alternatives (such as heat pumps and combined heat and power (CHP)), will reduce dependence on imports and thereby improve energy supply security (HM Government 2011). While energy efficiency measures have been a topic of interest for a long time, microgeneration is a newer area of interest to improve energy used in domestic buildings and lowering GHG-emissions (Palmer and Cooper, United Kingdom housing energy fact file 2014). Previous studies on microgeneration show that decentralised technologies can provide a dramatic increase in the efficiency of fossil fuel use but also reduce GHG emissions and enhance energy security for the UK (Allen and Hammond 2010, Rogers, et al. 2014).

Table 4 shows the low carbon and renewable technologies for microgeneration of heat and electricity available on the market today. Microgeneration technologies can be categorised into three categories: low carbon heating, renewables and micro combined heat and power (mCHP). Single-family residential dwellings present the least exploited market for distributed energy technologies, even though they have significant potential to reduce both fuel bills for consumers and environmental impacts from the domestic sector. (Staffell, et al. 2010)

The Government aims to cultivate a market environment where a portfolio of technologies will compete, with the most cost effective ones succeeding over time. The Government will constructively enable the market through different policies and provide clear, long-term signals to create conditions for the investment that will be fundamental to move into a low carbon economy. (HM Government 2011)
Table 4: The low carbon and renewable energy technologies for microgeneration of heat and electricity available on the market today (Staffell, et al. 2010).

<table>
<thead>
<tr>
<th>Technology</th>
<th>Category</th>
<th>Source -&gt; Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass boilers</td>
<td>Low carbon</td>
<td>Sustainable fuel -&gt; Heat</td>
</tr>
<tr>
<td>Air source heat pump</td>
<td>Low carbon/renewables(^2)</td>
<td>Electricity + Sun -&gt; Heat</td>
</tr>
<tr>
<td>Ground source heat pump</td>
<td>Low carbon/renewables</td>
<td>Electricity + Sun -&gt; Heat</td>
</tr>
<tr>
<td>Solar photovoltaic (PV)</td>
<td>Renewables</td>
<td>Sun -&gt; Electricity</td>
</tr>
<tr>
<td>Solar thermal</td>
<td>Renewables</td>
<td>Sun -&gt; Heat</td>
</tr>
<tr>
<td>Micro wind</td>
<td>Renewables</td>
<td>Sun(^1) -&gt; Electricity</td>
</tr>
<tr>
<td>Internal combustion engines</td>
<td>Micro CHP</td>
<td>Gas -&gt; Heat + Electricity</td>
</tr>
<tr>
<td>Stirling engines</td>
<td>Micro CHP</td>
<td>Gas -&gt; Heat + Electricity</td>
</tr>
<tr>
<td>Fuel cells</td>
<td>Micro CHP</td>
<td>Gas -&gt; Heat + Electricity</td>
</tr>
</tbody>
</table>

The Government has implemented policies to encourage uptake of microgeneration technologies. The domestic Renewable Heat Incentive (RHI) is a financial incentive, launched in April 2014, aiming to promote the use of renewable heat (Ofgem 2015b). In joining the scheme, homeowners receive quarterly payments over seven years; equal to the amount of renewable heat their system produces. Technologies supported by the RHI are heat pumps (air and ground sourced), biomass boilers and solar thermal (DECC 2014b). According to Ofgem (2015d) it is a requirement of the RHI that all technologies are certified by the Microgeneration Certification Scheme (MCS). The MCS is an internationally recognised quality assurance scheme accredited by DECC.

The Feed-in Tariff (FIT) scheme was introduced in 2010 and set out to encourage deployment of small-scale, low-carbon electricity generation by actors who traditionally not been engaged in the electricity market, e.g. homeowners or landlords (DECC 2014b). The technologies supported are solar PV, wind, hydro, anaerobic digestion and micro CHP. The FIT scheme is part of a movement aimed at creating a more diverse and competitive electricity market (HM Government 2011). According to The Energy Saving Trust (2014e) the FIT payments consist of a generation tariff and an export tariff. The generation tariff is paid for every kWh of generated electricity. The export tariff is paid for every kWh exported to the grid. Currently the export is automatically assumed to be 50 % of the total amount generated (export meters are usually not installed on domestic systems). Energy efficiency measures and demand reduction is highly recommended alongside installation of microgeneration, in order to maximise the efficiency and performance of the microgeneration technologies (Allen and Hammond 2010).

### 2.5 Demand-side response

HM Government and DECC (2015) have created a strategy for the energy system: it will become secure, safe, low carbon and affordable. Making the energy system more flexible and smarter is part of this strategy. Flexibility will be accomplished by utilising different storage technologies such as batteries or hot water tanks. Energy is stored when electricity is cheap and the stored energy is used during peak demand when electricity is most expensive. A

\(^2\) Heat pumps can be considered to be renewable if the electricity they use is generated from renewable sources. If the electricity is generated from traditional power plants heat pumps are considered to be low carbon since they use resources in a more efficient way than for example a gas boiler.

\(^1\) The radiation from the sun causes atmospheric motions.
A smarter energy system will be accomplished by developing demand-side response mechanisms. Smart meters are a key part in demand-side response. DECC (2014b) believes smart meters will help put consumers in control of their energy use, with access to near real-time information about their electricity and gas use. Consumers will be able to make more-informed decisions around their energy use. These smart meters will also facilitate switching between energy suppliers in order to drive a more vibrant and competitive retail energy market. Appliances that may be connected to the smart meters will help consumers to benefit from using energy at the cheapest times of the day (HM Government and DECC 2015). The Government want all homes to have a smart meter installed by 2020, and they will be installed between 2015 and 2020 (Ofgem 2015c).

2.6 Chapter summary

This chapter has reviewed how energy is used in the UK domestic sector today and what policies there are in place to shape and affect the energy used. Gas and electricity make up 68% and 22% respectively of the total energy used in the domestic sector. Of the total energy used, 65% is used for heating. Gas boilers with central heating system are the most common way to heat a house in the UK. 80% of the entire housing stock has an individual gas boiler. Cavity and solid walls are the two main ways of constructing a house in the UK. There are four major energy efficiency measures in use: cavity and solid wall insulation, loft insulation and double glazing. The two systems for energy efficiency rating of buildings are SAP and EPC, these will be referred to later in the report. There is a range of microgeneration technologies available to homeowners and the policies supporting them are Green Deal, Feed-In Tarriffs (FITs) and domestic Renewable Heat incentive (RHI).
3 Theoretical framework

This chapter begins with a technical description of the microgeneration technologies that will be reviewed in this study followed by an overview of aspects of behaviour in relation to energy use. A description of how microgeneration technologies and behavioural aspects affect and interact with the area of demand-side response is then given. Previous studies regarding financial and environmental evaluation of the chosen technologies are described in the last part of this chapter.

3.1 Microgeneration technologies

Previous studies evaluating microgeneration technologies, such as Staffell et al. (2010) and Fubara, Cecelja and Yang (2014), use a condensing boiler and electricity supplied from the grid as a reference scenario. Rogers et al. (2015) use a generic condensing boiler with an efficiency of 90% as a reference scenario. Allen and Hammond (2010) use a gas boiler with an efficiency of 86%. In this study six case houses will be used for the evaluation. The case dwellings all use gas boilers as a heating system as well as electricity from the grid. The efficiencies of the gas boilers in use varies and are given in the Cambridge Housing Model (CHM). The CHM is the model applied in the study and will be further explained in the following chapter 4.

3.1.1 Heat pumps

The two heat pump types mainly used in the domestic sector are air source heat pumps (ASHPs) and ground source heat pumps (GSHPs). An emerging heat pump technology is solar assisted heat pumps (SAHPs). In this study ASHPs and SAHPs will be included because of their viability for highly populated urban areas with little surrounding land. (Staffell, Brett, et al. 2012)

A heat pump’s efficiency is represented by its Coefficient of Performance (COP) value, which is total heat output per unit of electricity consumed. The COP is a function of the temperature difference between the heat source and the sink (the temperature of the central heating system) (Rogers, et al. 2014). Rogers et al. (2014) explains that this difference can be minimised by operating the heat pump continually and controlling its output temperature such that the heat delivered only supplies the net thermal losses of the building. This is supported by Dodds and Hawkes (2014) stating that heat pumps are best suited for a constant continuous operation. According to Staffell et al. (2010) a COP of over 2.5 is needed to provide lower primary energy use and GHG emissions than a condensing boiler.

Staffell et al. (2012) reference the seasonal performance factor (SPF) instead of the COP value when reviewing domestic heat pumps. SPF is a measure of the average annual performance in a specific location given the annual average temperatures over a year. SPF, compared to COP, accounts for the efficiency of the whole system, including back-up heater (if any) and the electricity needed to defrost an ASHP system. According to Staffell et al. (2012) a heat pump would need an SPF of 2.51 to consume less fuel than a condensing boiler.
ASHPs work by extracting ambient heat from the outside air and upgrading its temperature for space and water heating. They require electricity to run and are easy to retrofit into existing houses. (Staffell, et al. 2010) According to Staffell and Brett (2012) most ASHPs are able to operate with an existing central heating system and hot water tanks. In cold conditions (below 5 °C) the outside unit of the ASHP needs defrosting (Staffell, et al. 2010).

SAHP systems have solar thermal panels on the roof of the house operating separately from, instead of, or in conjunction with air or ground-based heat exchangers. The different operation strategies give rise to the classification of SAHP systems: parallel, series and hybrid. (Staffell, Brett, et al. 2012) According to Kamel, Fung and Dash (2015) the heat pump performance (COP) is improved with utilisation of solar energy. According to Sparber et al. (2011) the SPF value is claimed to be up to approximately 5 for some commercial SAHP presentations. Practical experiences with SAHP systems are limited, and published monitoring results are only partly in line with the expectations of such high SPF values. Sparber et al.’s (2011) review of monitoring results show SPF values for SAHPs varied between 2.8 and 4.3 for solar thermal combined with ASHP systems. There is only one SAHP system that is approved by the Microgeneration Certification Scheme (MCS) and that is a system called Minus 7 (MCS 2015). Minus 7 (2015) consists of solar thermal panels integrated to the tiles on the roof. The solar thermal panels are connected to a low temperature thermal store. A heat pump unit is upgrading heat from the low temperature thermal store (cold store) to a high temperature thermal store (hot store). The hot store is designed to hold a temperature of minimum 38 °C. The solar thermal panels can provide heat to the high temperature thermal store on warm and sunny days. The central heating system and hot water system are connected via heat exchangers to the high temperature thermal store. The system supplies central heating at a temperature of 35 °C, which means low temperature radiators or under floor heating are needed. The Minus 7 system has an average annual SPF of 3.9.

3.1.2 Solar PV

Solar resource is relatively reliable and predictable compared to wind, which is much more difficult to predict, especially in urban areas (Allen, Hammond and McManus 2008). According to Staffell et al. (2010) crystalline silicon solar panels currently offer the highest efficiency of solar panels available on the market today. Crystalline silicon panels are also referred to as first generation panels, with second generation thin films becoming more widely available. Performance of solar PV is measured in terms of the annual energy yield, expressed per kW of peak output (kW_{e, pk}) of the panels installed. The performance depends on the level of insolation received, the spectral quality of the light and panel temperature. Solar panels have good reliability and durability with an expected lifetime of 25 years and requiring minimal maintenance.

According to Allen, Hammond and McManus (2008) the electricity supply from solar panels will in many cases not match the profile demand of the household. The possibility and economics of exporting and importing the electricity to the grid have a large effect on the feasibility of a grid-tied PV installation. Charging batteries with solar electricity during the day and discharge at night when electricity is needed is a potential model to meet the difference in demand and supply (McKenna, et al. 2013). This is further explained under section 3.4.

3.1.3 Micro combined heat and power

The chief benefit of micro combined heat and power (mCHP) is a reduction in primary energy use and fuel costs, gained by converting natural gas (or other fuel) into both heat and electricity at the point of use. Today, natural gas is the most widely used fuel for domestic
mCHP due to its low cost and widespread infrastructure. A mCHP based on fossil fuel can be seen as a stepping-stone towards renewable mCHP systems powered by, for example, biomass. (Staffell, et al. 2010) According to Rogers et al. (2014) should gas-fired mCHP systems have high energy utilisation and a high power to heat ratio. Stirling engines, international combustion (IC) engines and fuel cells are the prime movers for mCHP (Allen, Hammond and McManus 2008). According to Staffell et al.’s (2010) review of microgeneration technologies it is stated that Stirling engines have a low power to heat ratio and are therefore more suitable for houses with a heat demand above 20 MWh<sub>th</sub>. The emission level of a Stirling engine is one similar to that of a gas boiler. A major disadvantage of IC engines is their high noise and emission levels. In this study, IC and Sterling engines will be excluded due to the high emission levels and unsuitability for average sized houses.

Fuel cell mCHP is an emerging technology in need of more research and development before becoming commercially available (Staffell, et al. 2010). Proton exchange membrane fuel cells (PEMFCs) are the most developed fuel cell technology and also the most widely used in the residential heating sector (Dodds, et al. 2015). According to Staffell et al. (2010) fuel cells electrochemically convert hydrogen into a DC current. In current fuel cell mCHPs, a fuel processor is integrated producing hydrogen from natural gas on demand. This means that natural gas is not combusted, resulting in low emission levels. In the future hydrogen can be produced from low carbon energy sources such as renewable electricity, and delivered using the existing gas infrastructure (Dodds, et al. 2015).

High up-front costs constrain fuel cell mCHPs to recover their initial costs within their expected lifetime, even with current subsidies offered, but costs are falling as production increases and the industry is ‘learning by doing’. Steady cost reductions through innovations are bringing fuel cells closer to commercialisation. (Dodds, et al. 2015) According to Staffell and Green (2013) the price for a whole domestic system is projected to be around £3500 between 2020 and 2030. Japan, South Korea and Germany are currently the main markets for fuel cells mCHPs and the most commercially mature model is the Enefarm model.

3.1.4 Microgeneration excluded from the study
Micro wind will not be included in this study since it is not suitable for urban areas according to Staffell et al. (2010), a conclusion supported by Allen, Hammond and McManus (2008). Biomass boilers are considered to have limited scope to increase in the UK and it is a technology more suitable for off-grid customers, and therefore falls outside the limits of this study (Staffell, et al. 2010, Rogers, et al. 2014). Solar thermal is excluded due to its heat output providing a poor match with space heating requirements (Staffell, et al. 2010). GSHP are excluded due to the often limited access to the required space of land and because GSHP are more suitable for new builds (Allen, Hammond and McManus 2008). IC and Sterling engines will not be included, as mentioned in section 3.1.3.

3.1.5 Matching capacity with demand
It is common practice to under-size microgeneration heating systems with respect to the peak load and instead uses a low cost gas boiler to boost the heat output in cold weather (Rogers, et al. 2014). The logic for under-sizing the systems is due to two reasons: the high capital cost of most microgeneration technologies and the fact that most technologies have lower efficiency when run on partial load (Staffell, et al. 2010, Rogers, et al. 2014). According to Staffell et al (2012) electric immersion heaters are usually used as back-up heaters in heat pump systems. They are however inefficient and have high operating costs which further increase the importance of dimensioning the heat pump.
Choosing an unsuitable technology for a specific house can result in significantly lowering the performance (Staffell, et al. 2010). There are several studies available using different methodologies to match the capacity of the microgeneration technology with the heat and power loads of an individual house. Allen and Hammond (2010) first calculated microgeneration output estimations with a focus on annual values, before being contextualised against typical yearly household demands. Dodds et al. (2015) used residential data from several UK field trials for their comparative analysis of heating technologies. All data used in Dodds et al.’s (2015) study was secondary data. When comparing different heating technologies and their impact on the energy system Dodds et al. (2015) only took peak heating and electricity demand into consideration. Fubara, Cecelja and Yang (2014) based their analysis on hourly household usage for 3, 4 and 5 bedroom houses and divided a year into four seasons. Three days of the week were used to capture the demand variations during the week for each of the seasons. The houses were of UK conventional design and already had energy efficiency measures installed.

3.2 Aspects of behaviour in relation to energy use

According to Fell and King (2012) households use very different amounts of gas, modelling by DECC found that less than 40 % of the variation in gas use can be explained by the property size and age, type of property, household income and tenure. With a fuller understanding of behaviour related to energy use it would be possible to design the appropriate support and interventions to reduce energy use in the domestic sector. Fell and King (2012) have undertaken a qualitative research study on behalf of DECC to further improve the understanding of the factors that might explain the remaining 60 % in variation in energy usage between apparently comparable dwellings. The result of Fell and Kings (2012) study shows that householders display a very wide range of behaviours that affect their gas use. These behaviours can be grouped under four themes, which are shown and explained in Table 5.

Table 5: Four broad headings in which behaviours can be grouped that affect how energy is being used in households.

<table>
<thead>
<tr>
<th>Conceptualisation of the home</th>
<th>What people mean by ‘comfort’ and how it affects energy behaviours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature management</td>
<td>How people manage the temperature in their homes and their awareness of energy implications of their actions</td>
</tr>
<tr>
<td>People in the home</td>
<td>Who is in the home, when and what they are doing</td>
</tr>
<tr>
<td>Physical properties of the home</td>
<td>The particular physical environment in which people live</td>
</tr>
</tbody>
</table>

The study by Fell and King (2012) shows that householders try to be energy-efficient but mostly in relation to electricity use. Gas use needs to be included within this concept of energy efficiency.

Palmer and Cooper (2014) describe four different ways in which behaviour affects energy use:

- Investment decisions leading to long-term locked-in consequences
- Infrequent actions that have persistent effects
- Frequently repeated actions
- Spontaneous reactions with one-off effects
Householders seem to have poor understanding of the size of their energy bill in comparison to similar households, but there is also a lacking understanding of what type of appliances or actions that affect the energy bill the most.

Rebound effect is a term referring to behavioural responses to energy efficiency measures resulting in savings being less than anticipated. Rebound effects can be both direct and indirect. An example of direct rebound effects would be replacing traditional light bulbs with energy efficient light bulbs, which will make lighting cheaper leading to people not switching off the light as often when leaving a room. Indirect rebound effects are increased consumption of other goods and resources, i.e. not energy, as a result of spending less on energy. (Chitnis, et al. 2013)

The previous studies mentioned under section 3.1 included the aspect of behaviour. Staffell et al. (2010) emphasise that microgeneration technologies in order to have the best possible performance must be treated correctly, which includes awareness of our energy habits and behavioural issues. Allen, Hammond and McManus (2008) mention that behavioural patterns affect the domestic energy demand while Staffell et al. (2012) believe the trade-offs between saving energy and increased standards of living (the rebound effect mentioned above) should be factored into savings potentials. The rollout of smart meters might have a positive impact on energy behaviour and raise awareness of gas efficiency issues (Fell and King 2012).

3.3 Demand-side response

The electricity system was designed for centralised generation and optimised for a one-way flow (from central power plants to customers). This means network changes will be required if distributed generators are to contribute significantly to the energy mix (Allen and Hammond 2010). Daily peak heat demand occurs in the morning and evening, and peak electricity demand occurs around 5.30 pm (Dodds and Hawkes 2014). Figure 7 shows average daily electricity demand. The heating category is electric heating (since Figure 7 only shows electricity use). The demand curve for gas heating would look slightly different because peak heat demand occurs in the morning and the evening. It is clear from Figure 7 that peak electricity demand occurs around 5.30 pm and that the peak is significantly higher than the demand during the rest of the day.
Behaviour changes and smart controls of appliances could reduce peak electricity demand by as much as 18% according to Palmer and Cooper (2014). According to Palmer and Terry (2014) lighting and appliances are key components in reducing and shifting peak demand. According to Staffell et al. (2012) smart meters will make suppliers understand when customers are demanding electricity, which will enable for daily fluctuations in the electricity price.

Increasing the number of heat pumps will further increase peak demand and pressure on the electricity grid. Previous literature has put heat pumps and mCHP as rival or competing technologies but combining the two can have advantages when tackling peak demand. (Dodds, et al. 2015) According to Staffell et al. (2012) heat pumps are seen as an enabling technology for demand shifting. Letting the house act as a thermal storage means the production of heat can be delayed or pushed forward without a noticeable change of thermal comfort. The value of ‘smart’ heat pumps will increase as the share of supply-driven sources such as wind and solar increases. By slightly over-heating the central heating system and the hot water tank, they can effectively be used as thermal storage. According to Dodds et al. (2015), the power output of fuel cells can be changed almost instantaneously to follow the electrical demand of a house. Fuel cell mCHP can contribute to tackle peak demand of both heat and electricity meaning that the value of fuel cell mCHPs will only become greater as the number of heat pumps increases.

According to Parra, Walker and Scott (2014) energy storage is one approach to add flexibility to the electricity system and manage increasing peaks in demand. Traditionally these issues are approached by different plans for upgrading the grid. Battery and hydrogen are the most suitable storage technologies for time-shift and demand management. Thomas (2009) suggests that battery storage will be more economical as a short-term storage (less than 36 hours), but hydrogen storage will be more economical for a long-term storage (a few days or more). Variations in demand and variations in supply from renewable electricity sources will contribute to the need for more stationary storage, which will in turn shift the balance in
favour of hydrogen storage over battery storage. Another advantage of hydrogen storage within an energy system with large quantities of supply-driven electricity sources is that electricity must be used immediately when it is produced, however hydrogen can be stored indefinitely, providing more flexibility. Energy storage will have potential as a business model that electricity suppliers may explore, especially if dynamic real time energy tariffs are implemented.

3.4 Financial evaluation

According to Rogers et al. (2014) a financial evaluation should consider the economic feasibility of a project from the owner’s perspective.

Rogers et al. (2014) have compared different microgeneration technologies with the aim of reducing net GHG emissions from existing UK houses down to 20 % (based on the 1990 levels). Because different technologies qualify for different governmental subsidies Rogers et al (2014) have used net present value (NPV) to be able to compare different technologies. In the calculations costs are negative and incomes are positive. Since the installation provide a service where energy costs occur during the economic lifetime of the technology the NPV is likely to be negative and Rogers et al. (2014) therefore present the NPV as net present cost (NPC). A subsidy free NPC were calculated to view the impact of subsidies. Capital costs were taken from retailers or published papers. The microgeneration technologies are profitable if the NPC for the microgeneration technologies is lower than the NPC of the reference scenario.

Fubara, Cecelja and Yang (2014) apply a cost-benefit analysis from the consumers’ perspective. All operating and capital costs are marginal costs, accounting for the difference between the technology analysed and the reference scenario. Annual operating costs are costs for gas, electricity and maintenance. Costs for gas and electricity are calculated on annual energy usage and price per kWh. A 10-year operation period was assumed. Capital costs were either collected from literature or manufacturers. Both Rogers et al. (2014) and Fubara, Cecelja and Yang’s (2015) studies use the same energy prices for the whole calculated period. They do not assume an increase in energy prices.

Hammond and Hazeldine (2015) state that a lifecycle cost analysis is preferable but due to lack of data their economic analysis was based on current prices. Prices were collected from literature and normalised to US dollars per kWh to enable a comparison.

According to Woodward (1997), a crucial part of the life cycle costing concept is selecting an appropriate discount rate. A high discount rate (8-12 %) will favour options with low upfront costs, short lifetime and high operating costs. A low discount rate (2-4 %) will have the opposite effect. McKenna et al. (2013) used a discount factor of 4 %. Rogers et al (2015) compared two discount factors: one of 3 % based of the real rate of return the FIT scheme is based upon and one of 5.5 % based on the interest rate used in the RHI (7.5 %) subtracted with the inflation rate of 2 % set by the Bank of England. Pellegrini-Masini et al. (2010) used a discount rate of 3.5 % when calculating NPV of the life cycle costs of domestic energy demand reduction technologies from householders’ perspective.
3.5 GHG-emissions

When a household decreases or increases its use of a fuel or electricity, all the upstream impacts have to be considered to determine the total changes in GHG emissions (Allen and Hammond 2010). Allen and Hammond (2010) use the concept of the ‘marginal plant’ in their energy and GHG emission analysis of a few microgeneration technologies. When instantaneous demand is reduced it is the specific marginal plant that reduce its output rather than the average of all generators. In the UK today the marginal plants are coal and gas fired power plants while the base-load is nuclear plants. It is however difficult to quantify marginal GHG savings because they are influenced by a large and complex system. The argument for using marginal plants is supported by Dodds et al. (2015). According to Staffell et al. (2012) the marginal plants are combined cycle gas turbines (CCGTs) during winter months. This is due to peak heat demand driving up gas prices, resulting in gas-fired power plants being the most expensive to run during winter months. At these times a heat pump is therefore more likely to replace electricity produced from gas.

Dodds et al. (2015) argue that the GHG emissions during manufacturing of low carbon, microgeneration technologies are important as they offset the savings made during operation. Allen and Hammonds (2010) study shows that solar PV provides a net GHG benefit over its lifetime when the embodied GHG emissions from manufacturing the solar PV are taken into consideration.

Rogers et al. (2014) have used three different GHG emission factors for electricity representing recent grid emission factors and possible stages of grid decarbonisation. They have also included a 6 % leakage from ASHP systems, as the refrigerant R410-a used in such systems is a very potent greenhouse gas. Rogers et al. (2014) are calculating the embodied GHG emissions as well.

3.6 Chapter summary

This chapter has described the technical details regarding the microgeneration technologies included in the study; heat pumps, fuel cell mCHP and solar PV. The capacity of microgeneration technologies needs to be carefully matched with demand in order to have the best possible performance. The energy demand of a household is related to the behaviour of the occupants. Demand-side response is a term relating to energy use, behaviour and the added load microgeneration technologies infer on the electricity grid. Energy storage and smart meters are two technologies that will enable demand-side management. The concept of calculating the net present value of life cycle costs using a discount rate emerged as a promising method for evaluating the financial performance of microgeneration technologies. An environmental evaluation of microgeneration technologies should include the embodied emissions that occur during the manufacturing of the technologies as well as the emissions that occur from using gas and electricity during the operation of the technologies.

---

4 When demand is reduced on the electricity grid it is the marginal plant that reduces its output. Nuclear power plants are typical base load power plants, which means they run all the time since they are expensive to start up and shut down. Marginal plants, such as gas fired power plants, are cheap and quick to start up and shut down and can therefore be regulated according to instant demand on the grid.
4 Methodology

This chapter explains the approaches applied in the study and forms a connection between the theoretical framework in the previous chapter and the subsequent chapter where the results from the study are presented. The case study consisting of 6 case houses is presented here.

The Excel model Cambridge Housing Model (CHM) has been used throughout the study to obtain necessary data for each of the case houses. The CHM is an energy model covering the domestic sector in England and the UK, developed for DECC by Cambridge Architectural Research (Cambridge Architectural Research 2014). Based on building physics and climate data, outputs such as energy demand, heat loss, energy costs and GHG emissions can be calculated. Most of the calculations performed in the CHM are based on calculations used in “The Government’s Standard Assessment Procedure for Energy Rating of Dwellings”, also referred to as SAP (BRE 2011), see section 2.3.3. The CHM is only used in this study to calculate how the energy demand in the case houses changes and not to calculate influence on global GHG emissions or energy costs.

Based on the typical housing makeup in the UK presented in section 2.2, 6 case houses have been analysed. Detached, semi-detached and mid-terraced houses are the three most common dwelling types in the UK and were chosen as representatives in this study. The dwelling age shown in Table 6 was chosen based on the most common age for each of the three dwelling types. None of the houses have appropriate wall insulation and are heated with a condensing combination boiler connected to the central heating system of the dwelling. The average house in the UK has a floor area of 92 m$^2$, an energy rate of 164,1 kWh/m$^2\cdot$year and a heat loss of 297 W/°C (as a comparison to the information given in Table 6) (Prime 2014b, DECC 2015, Palmer and Cooper 2014). The demand for cooling is very low compared to the demand for heating and has therefore been assumed to be negligible.

Table 6: Case houses used based on typical housing situations in the UK. The data for area, energy rate and heat loss are collected from the Cambridge Housing Model (CHM) (Cambridge Architectural Research 2014).

<table>
<thead>
<tr>
<th>Case house</th>
<th>Dwelling type</th>
<th>Age</th>
<th>Area (m$^2$)</th>
<th>Window area (m$^2$)</th>
<th>Wall type</th>
<th>Energy rate (kWh/m$^2\cdot$yr)</th>
<th>Heat loss (W/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mid-terraced</td>
<td>1900-1929</td>
<td>88.36</td>
<td>12.83</td>
<td>Solid wall</td>
<td>188</td>
<td>281.6</td>
</tr>
<tr>
<td>2</td>
<td>Mid-terraced</td>
<td>1930-1949</td>
<td>87.50</td>
<td>5.12</td>
<td>Cavity wall</td>
<td>204</td>
<td>290.0</td>
</tr>
<tr>
<td>3</td>
<td>Semi-detached</td>
<td>1930-1949</td>
<td>111.1</td>
<td>49.85</td>
<td>Cavity wall</td>
<td>190</td>
<td>454.2</td>
</tr>
<tr>
<td>4</td>
<td>Semi-detached</td>
<td>1950-1966</td>
<td>79.80</td>
<td>17.19</td>
<td>Cavity wall</td>
<td>196</td>
<td>299.5</td>
</tr>
<tr>
<td>5</td>
<td>Detached</td>
<td>1967-1975</td>
<td>144.5</td>
<td>61.93</td>
<td>Cavity wall</td>
<td>173</td>
<td>598.1</td>
</tr>
<tr>
<td>6</td>
<td>Detached</td>
<td>1996-2002</td>
<td>166.5</td>
<td>51.72</td>
<td>Cavity wall</td>
<td>142</td>
<td>400.2</td>
</tr>
</tbody>
</table>

For each of the case houses a range of microgeneration technologies and energy efficiency measures have been evaluated, see below. The energy efficiency measures and

5 Appropriate wall insulation is dependent on wall type. The two most common types of wall insulation are cavity and solid wall insulation. Solid wall insulation can either be implemented onto external or internal walls of a house. A cavity wall is a brick wall with a filled or unfilled cavity in between. Cavity wall insulation fills the cavity. Solid wall is a solid brick wall and the insulation has to be put outside of the bricks either on the inside wall of the house (internal) or on the outside wall (external).
Microgeneration technologies were chosen because they contribute to a sustainable development according to section 1.4. Another criterion was that these measures and technologies are possible to install in the most common dwelling types in the UK. They are not restricted by access to land (such as a GSHP) and can be installed in urban areas. (Further details are given in section 3.1.4.)

The technologies and measures that have been evaluated are as follows:

- **Energy efficiency measures:**
  - Insulating cavity or solid walls, depending on wall type (see Table 6)
  - Installing, or extending existing, loft insulation
  - Installing LED lighting
  - Replacing existing appliances with more energy efficient models
- **Installing an air source heat pump (ASHP) and an ASHP in combination with solar PV**
- **Installing a solar assisted heat pump (SAHP) and a SAHP in combination with solar PV**
- **Installing a fuel cell mCHP and a fuel cell mCHP in combination with solar PV**

The above technologies and measures have been combined into eight different scenarios. The scenarios were created to be able to evaluate as many different combinations of the technologies and measures as possible. Scenario R is the reference scenario where no measures have been applied and no new technologies have been introduced. Energy efficiency measures were implemented in scenario 2-7 to lower the demand for heat and electricity before the respective microgeneration technologies were implemented. The eight scenarios (Table 7) have then been applied to each of the case houses (Table 6).

### Table 7: An overview of evaluated technologies and measures and in which scenario they were implemented. Scenario R is the reference scenario in which none of the technologies or measures was applied.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Measure / technology</th>
<th>Energy efficiency measures</th>
<th>ASHP</th>
<th>SAHP</th>
<th>Solar PV</th>
<th>Fuel cell mCHP</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
The process that was used for the case study consisted of four steps. Figure 8 shows an overview of each step and they are all described in detail below.

**Figure 8: The process that was used for the case study.**

4.1 **STEP 1: Calculating current annual energy demand (scenario R)**

Step 1 reviewed the current energy demand (scenario R). Monthly data for demand of hot water and space heating, heat loss coefficient, mean internal temperature and electricity use for lighting and appliances (including cooking) was obtained from the CHM.

4.2 **STEP 2: Implementing energy efficiency measures and calculating new annual energy demand (scenario 1)**

In step 2 the new energy demand was calculated based on the assumption that the described energy efficiency measures were implemented. The energy efficiency measures included in the study are described below.

4.2.1 **Insulation measures**

Solid wall insulation was applicable for house 1. As mentioned previously there are two types of solid wall insulation: internal and external. Both of them were implemented separately. Full loft insulation was already installed for this house therefore no changes were made to loft insulation. Of the total window area on house 1, 40 % were single glazed and 60 % were double glazed. Double glazing was implemented to replace the single glazed windows.

Cavity wall insulation was applicable and implemented for house 2. The house had 100mm of loft insulation that was increased to 300 mm. (300 mm is the thickest layer of loft insulation available to model in the CHM.) Of the total window area on house 2, 40 % were single glazed and 60 % double glazed. Double glazing was implemented on the single glazed windows.

House 3 had unfilled cavity walls and 100 mm loft insulation. Of the total window area on house 3, 14 % were single glazed and 86 % double glazed. The same measures were implemented for house 3 as for house 2.

House 4 had unfilled cavity walls and 50 mm loft insulation. Cavity wall insulation and 300 mm loft insulation were implemented. All windows on house 4 were double glazed therefore no changes were made to the windows.
Only cavity wall insulation was implemented in house 5. Double glazed windows and 300 mm loft insulation were already installed.

House 6 had no cavity wall insulation, 150 mm loft insulation and all windows were double glazed. Cavity wall insulation and 300 mm loft insulation were implemented.

After modelling the implementation of the insulation measures updated data for hot water and space heating demand, heat loss coefficient and mean internal temperature was collected.

4.2.2 Lighting and appliances
The CHM provides an option for low energy lighting. The low energy lighting option in the CHM is based on the calculations for lighting applied in SAP (BRE 2011) and results in a percentage of the total lighting installed. House 1 had 50 % energy efficient lighting installed, house 2 and house 3 had 12.5 %, house 4 and house 5 had 0 % and house 6 had 38 %. It is assumed that none of the case houses had any LED lighting installed in the reference scenario (scenario R). The energy efficient lighting option in the CHM uses 50 % less energy than conventional lighting, i.e. incandescent light bulbs. LED light bulbs use 15 % of the energy incandescent light bulbs use. Based on the current electricity used for lighting \( (E_{\text{Step 1}}) \), a new electricity use for lighting \( (E_{\text{Step 2}}) \) can be calculated according to equation 1:

\[
E_{\text{Step 2}} = \% \text{ of conventional lighting } \times E_{\text{Step 1}} \times 0.15 + \% \text{ of energy efficient lighting } \times E_{\text{Step 1}} \times 0.3
\]

The use of appliances is heavily connected to behaviour and therefore difficult to model. This will be further discussed in section 5.4. A few assumptions have been made to lower the energy used by appliances. Appliances are divided into a five categories based on Palmer and Terry (2014). The categories (along with its associated percentage of total electricity usage) are cold appliances (14 %), consumer electronics (18 %), cooking (11 %), washing appliances (11 %) and other (46 %). According to Palmer and Terry (2014) an average increase of 20 % in energy efficiency is possible for cold and washing appliances when replacing existing appliances with the most efficient ones currently on the market. This average was used as an assumption for cold and washing appliances. Consumer electronics were assumed to decrease 10 % mainly due to lowering standby power, according to The Energy Saving Trust (2012). According to Prime (2014b) the main appliance used for cooking is the kettle and on average a kettle uses 167 kWh per year. According to the Energy Saving Trust (2014a) 20 % of the energy used by a kettle can be saved by replacing a conventional kettle with an energy efficient ECO kettle. This assumption is used for the cooking category. In total for appliances an increase of energy efficiency by 8 % was achieved (reflected as a decrease of energy use by 8 %).

4.3 STEP 3: Matching microgeneration capacity with new energy usage from Step 2 (scenario 2-7)

In step 3 the microgeneration technologies were matched with the new heating and electricity demand of each case house.

4.3.1 Air source heat pump
Easy Renewable Software Solutions (Easy RSS), an online application developed by Qualitick™, was used to size the air source heat pumps (ASHP) (Qualitick™ 2015). The main input to the program is maximum heat loss of the house and annual energy demand for hot
water and space heating. The ASHP was sized to an outdoor temperature of -2°C (the average annual air temperature provided in the Easy RSS) and to an output temperature of 50 °C for space heating and 70 °C for hot water heating (based on the average temperatures of a domestic UK heating system). With these temperatures a low temperature heating system did not have to be installed. The heat pump was assumed to meet 100 % of the annual demand for space and hot water heating. The heat pump model used was a Vaillant aroTHERM 5kW or 8 kW, depending on the heat loss of the house. According to the Easy RSS calculations, the heat pump had an SPF of 2.7 for space heating and 2.5 for water heating. The economic lifetime of the ASHP was assumed to be 20 years (Greening and Azapagic 2012).

4.3.2 Solar assisted heat pump
In this study the solar assisted heat pump (SAHP) system Minus 7, described under section 3.1.1, was used. The SAHP had an output temperature of 35 °C, SPF of 3.9 and was assumed to provide 100 % of the annual demand of space and hot water heating (Hill 2015). The lower output temperature, compared to the ASHP, means the SAHP has a better efficiency but a low temperature heating system had to be installed alongside the SAHP system. The installed capacity of the heat pump was 6.5 kW. The economic lifetime of the SAHP system was assumed to be 20 years, according to Hill (2015).

4.3.3 Solar PV
PVGIS (a web-based tool provided by The European Commission Joint Research Centre) was used to calculate the required capacity and output of solar PV (European Commission 2015). The solar PV system had a peak power of 4, 5 or 6 kW depending on the annual electricity demand for lighting and appliances for each case house. The solar PV systems were calculated to cover the annual demand for household electricity. The solar PV systems were mono-crystalline silicon cells with an efficiency of 16 % according to Rogers et al. (2015). The economic lifetime of the solar PV was assumed to be 20 years (Allen and Hammond 2010).

4.3.4 Fuel cell mCHP
The fuel cell mCHP systems were assumed to have an overall efficiency of 95 % (39 % electrical efficiency and 56 % heating efficiency) according to Dodds et al. (2015). A PEMFC with an assumed economic lifetime of 14 years was used (Dodds and Hawkes 2014). The fuel processor converting natural gas into hydrogen (as described in section 3.1.3) was assumed to have an efficiency of 85 %, according to Dodds and Hawkes (2014). The fuel cell mCHP was assumed to have an installed heating capacity of 2 kW and an installed electricity capacity of 1.4 kW. According to Dodds and Hawkes (2014) that is the most common system available on the market today. The limited capacity meant the fuel cell mCHP could not always meet the heating demand of the dwelling. If necessary, a gas boiler was assumed to be used as a secondary heating system. Since the fuel cell mCHP was assumed to replace a gas boiler the running of the fuel cell mCHP was connected to the heat demand of the house. This resulted in more electricity being produced during winter when the heat demand is higher, and less electricity got produced in the summer months.

4.4 STEP 4: Calculating net present value of costs and income and influence on global GHG emissions
In this step, costs and GHG-emissions related to energy use in scenarios R and 1-7 were calculated and analysed for all case houses.
4.4.1 Financial appraisal

The financial appraisal was undertaken by calculating capital costs, operating costs (costs for energy and maintenance) and income from payments of governmental subsidies. The governmental subsidies included in the study were the domestic Renewable Heat Incentive (RHI) and Feed-In Tariffs (FIT) (a description of those subsidies is given in section 2.4). The net present value function in Excel combined with capital cost was used to calculate the net expenditure during the economic lifetime of the technologies; the net expenditure was defined as the total costs subtracted by total income. In scenario R and scenario 1 no technologies were installed, instead a calculation period of 20 years was used. For the net present value calculations a discount rate of 3% was assumed, according to Pellegrini-Massini et al. (2010). Table 8 and Table 9 below show investment and operating costs, income and references for the price details.

Table 8: Capital costs for the technologies and measures used in the study. The capital costs include costs for materials, installation and manufacturing.

<table>
<thead>
<tr>
<th>Technology/measure</th>
<th>Capital cost</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid wall – external insulation</td>
<td>£8 000</td>
<td>(The Energy Saving Trust 2014b)</td>
</tr>
<tr>
<td>Solid wall – internal insulation</td>
<td>£7 000</td>
<td>(The Energy Saving Trust 2014b)</td>
</tr>
<tr>
<td>Double glazed windows</td>
<td>£250/m²</td>
<td>(Homebuilding 2015)</td>
</tr>
<tr>
<td>Low temperature radiators</td>
<td>£1 500 – 2 000</td>
<td>(Jones 2015)</td>
</tr>
<tr>
<td>LED lights</td>
<td>£272⁶</td>
<td>(LED Planet 2015, Palmer and Cooper 2014)</td>
</tr>
<tr>
<td>ASHP</td>
<td>£6 500 for the 5 kW ASHP, £8 000 for the 8 kW</td>
<td>(The Energy Saving Trust 2014c)</td>
</tr>
<tr>
<td>SAHP</td>
<td>£30 000</td>
<td>(Hill 2015)</td>
</tr>
<tr>
<td>Solar PV</td>
<td>£1 640 per kW⁷</td>
<td>(DECC 2014e)</td>
</tr>
<tr>
<td>Fuel cell mCHP</td>
<td>£17 000</td>
<td>(Dodds and Hawkes 2014)</td>
</tr>
</tbody>
</table>

Standing charges were assumed to stay constant at £70/year for electricity and £88/year for gas. According to Rogers et al. (2015) the maintenance cost for ASHP can be assumed to £75/year. According to Hill (2015) the Minus 7 SAHP requires minimal maintenance and the author therefore assumed the maintenance cost for the SAHP to be £50/year. The maintenance cost for the fuel cell mCHP was calculated according to equation 2 (Rogers, et al. 2014):

\[
\text{maintenance cost} = 100 + 0.01 \cdot E_{\text{generated}} \, £/\text{year}
\]

The maintenance cost for solar PV is assumed to be negligible (Staffell, et al. 2010). The maintenance costs were assumed to stay constant throughout the lifetime of the technology.

⁶ According to Palmer and Cooper (2014) households have an average of 34 light bulbs. One light bulb was assumed to cost £8 and have an economic lifetime of 25 000 hours (LED Planet, 2015). This is the only cost used for lighting and energy efficient appliances.

⁷ The cost of solar PV is given in cost per kW installed by size band. The size bands are 0-4 kW, 4-10 kW and 10-50 kW. In this study the capacities for the solar PV installations are 4-6 kW, which means cost data for the size band 4-10 kW has been used.
Energy prices, Table 9, are projections modelled by DECC (2014d). The energy prices are given in £/kWh. The energy price projections used in the study are the “Reference Scenario” in the energy projections modelled by DECC (2014d). The “Reference Scenario” is based on central estimates of growth and fossil fuel prices. It also includes current as well as planned policies where decisions on policy design are sufficient enough to allow for robust estimates of impact.

Table 9: Prices for electricity and gas per year in £/kWh. The prices are projections modelled by DECC (2014d).

<table>
<thead>
<tr>
<th>Year</th>
<th>Electricity</th>
<th>Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>0.159</td>
<td>0.047</td>
</tr>
<tr>
<td>2016</td>
<td>0.169</td>
<td>0.050</td>
</tr>
<tr>
<td>2017</td>
<td>0.180</td>
<td>0.052</td>
</tr>
<tr>
<td>2018</td>
<td>0.181</td>
<td>0.051</td>
</tr>
<tr>
<td>2019</td>
<td>0.193</td>
<td>0.050</td>
</tr>
<tr>
<td>2020</td>
<td>0.193</td>
<td>0.050</td>
</tr>
<tr>
<td>2021</td>
<td>0.200</td>
<td>0.051</td>
</tr>
<tr>
<td>2022</td>
<td>0.203</td>
<td>0.052</td>
</tr>
<tr>
<td>2023</td>
<td>0.203</td>
<td>0.050</td>
</tr>
<tr>
<td>2024</td>
<td>0.207</td>
<td>0.051</td>
</tr>
<tr>
<td>2025</td>
<td>0.213</td>
<td>0.052</td>
</tr>
<tr>
<td>2026</td>
<td>0.217</td>
<td>0.053</td>
</tr>
<tr>
<td>2027</td>
<td>0.216</td>
<td>0.053</td>
</tr>
<tr>
<td>2028</td>
<td>0.216</td>
<td>0.053</td>
</tr>
<tr>
<td>2029</td>
<td>0.214</td>
<td>0.054</td>
</tr>
<tr>
<td>2030</td>
<td>0.217</td>
<td>0.054</td>
</tr>
<tr>
<td>2031</td>
<td>0.219</td>
<td>0.055</td>
</tr>
<tr>
<td>2032</td>
<td>0.220</td>
<td>0.055</td>
</tr>
<tr>
<td>2033</td>
<td>0.214</td>
<td>0.055</td>
</tr>
<tr>
<td>2034</td>
<td>0.210</td>
<td>0.055</td>
</tr>
</tbody>
</table>

The income from payments of governmental subsidies for the different technologies is shown in Table 10. The Minus 7 SAHP is currently not eligible for domestic RHI. It was assumed that 25 % of the solar electricity produced was consumed on site and 75 % exported (The Energy Saving Trust 2014f). The FIT subsidy automatically assumes an export of 50 %, therefore 50 % of the total electricity production was paid for and 25 % were given away for free (The Energy Saving Trust 2014e). It was assumed that 50 % of the electricity produced by a fuel cell mCHP was consumed on site and 50 % exported. This was an assumption made by the author based on the fact that the electricity production from a fuel cell mCHP is more evenly spread out over the year (and over the hours of the day) compared with solar PV.
Table 10: Income for the different microgeneration technologies. The price details are collected from The Energy Saving Trust (2014e) and Ofgem (2015b).

<table>
<thead>
<tr>
<th>Technology</th>
<th>Type of income</th>
<th>Payment period (years)</th>
<th>Income</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASHP</td>
<td>RHI</td>
<td>7</td>
<td>0.0742 £/kWh of renewable heat generated</td>
</tr>
<tr>
<td>Solar PV</td>
<td>FIT</td>
<td>20</td>
<td>Generation tariff: 0.1339 £/kWh of electricity generated Export tariff: 0.0485 £/kWh of electricity exported to the grid</td>
</tr>
<tr>
<td>Fuel cell mCHP</td>
<td>FIT</td>
<td>10</td>
<td>Generation tariff: 0.1445 £/kWh of electricity generated Export tariff: 0.0485 £/kWh of electricity exported to the grid</td>
</tr>
</tbody>
</table>

4.4.2 Environmental impact

GHG emission factors, given in the unit of carbon dioxide equivalents (CO$_2$e) per kWh, and embodied emissions from manufacturing of the technologies are presented in Table 11 and Table 12. The GHG included in the study are carbon dioxide (CO$_2$), methane (CH$_4$) and nitrous oxide (N$_2$O) according to DEFRA (2014). The ‘marginal power plant’ concept (section 3.5) was not used, since it is difficult to quantify the marginal emissions. The average GHG emission factor for electricity produced in the UK (DEFRA 2014) was used and instead GHG emissions levels were included in the sensitivity analysis, see section 5.2.2. The gas and electricity emissions include direct and indirect emissions (DEFRA 2014). Direct emissions are the emissions that occur at end-use, when producing electricity or using a gas boiler to produce heat. Indirect emissions are the emissions that occur ‘up-stream’ when transporting, refining, purifying and/or distributing the energy sources used for heating and electricity production.

Table 11: GHG emission factors for average UK electricity and natural gas. The emission factors include direct and indirect emission associated with the energy sources. (DEFRA 2014)

<table>
<thead>
<tr>
<th>Energy source</th>
<th>GHG emission factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0.533 kg CO$_2$e/kWh</td>
</tr>
<tr>
<td>Natural gas</td>
<td>0.33 kg CO$_2$e/kWh</td>
</tr>
</tbody>
</table>

There is no general formula to calculate embodied emissions, instead data for embodied emissions related to the microgeneration technologies were taken from previous lifecycle analyses for the respective technologies, as shown in Table 12. For the ASHP and SAHP a refrigerant leakage of 6% annually was assumed according to Rogers et al. (2015) (see section 3.5). Each heat pump was assumed to contain 4.5 kg of the refrigerant R410-a, which resulted in an annual influence of 466 kg CO$_2$e per heat pump (DEFRA 2014). GHG emissions offset by the electricity produced from solar PV was calculated with the emission factor for electricity presented in Table 11.

Table 12: Embodied emissions for the microgeneration technologies. (Greening and Azapagic 2012, Circular Ecology 2014, Allen and Hammond 2010)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Embodied emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASHP</td>
<td>0.0138 kg CO$_2$e/kWh electricity</td>
</tr>
<tr>
<td>SAHP</td>
<td>0.0138 kg CO$_2$e/kWh + 100 kg GHG/m$^2$ solar thermal collectors</td>
</tr>
<tr>
<td>Solar PV</td>
<td>242 kg CO$_2$e/m$^2$</td>
</tr>
<tr>
<td>Fuel cell mCHP</td>
<td>750 kg CO$_2$e per system</td>
</tr>
</tbody>
</table>
4.5 Sensitivity analysis

To analyse the results from the case study sensitivity analysis was performed. The sensitivity analysis was used to evaluate the influence from various different input factors used in the case study. The parameters that were included in the sensitivity analysis were energy prices (electricity and gas prices), discount rates, heat pump efficiency, capital costs, governmental subsidies and GHG emissions from electricity generation.

4.6 Chapter summary

This chapter presented the methodology used in the study. The case study compromising of six case houses was presented. A range of energy innovations available to homeowners, including energy efficiency measures and microgeneration technologies, were chosen to be evaluated. Eight scenarios, one reference scenario and seven scenarios based on the energy innovations, were evaluated for each case house. The process for the case study consisted of four steps that included calculating the current energy demand in the CHM, installing appropriate energy efficiency measures and calculating new energy demand, sizing the microgeneration technologies and calculating financial and environmental impacts. Sensitivity analysis was performed to evaluate how a few chosen parameters affect the results of the case study.
5 Results: Case study and sensitivity analysis

In this chapter the results from the study are presented for each separate case house. The aspects presented for each case house are; the energy use for the scenarios presented in Table 7, influence on GHG emissions for each scenario and the results from the financial analysis. The results are then compared and discussed.

In the latter part of this chapter the results from the sensitivity analysis are presented. The aspects that have been analysed are energy prices, discount rates, heat pump efficiency, capital costs, level of governmental subsidies and GHG emissions from electricity generation. The last part of the chapter is an analysis of demand-side response and behaviour in relation to different heating technologies and electricity prices.

5.1 Results from the case study

In this part the results from the case study are presented following the methodology presented in the previous chapter. In scenario 1 only energy efficiency measures are installed. In scenarios 2-7 energy efficiency measures are installed alongside a microgeneration technology. However for scenarios 2-7 only the installed microgeneration technologies in each scenario are referred to from hereon after.

5.1.1 Results relating to house 1

Calculations were made for external and internal solid wall insulation separately, resulting in the finding that both types of insulation had the same effect on lowering energy usage. It quickly became evident that solid wall insulation was not a financially feasible option, with a payback time above 20 years for both external and internal wall insulation. It was therefore decided to exclude solid wall from the calculations for house 1.

Table 13 shows data related to house 1; the gas and electricity usage, the amount of electricity exported to the grid (amount produced subtracted by the amount used on site based on assumptions in section 4.4.1) and the total energy used. In scenarios 4 and 5, where ASHP and SAHP are installed (see Table 7 section 4), the least amount of energy is used. In scenarios 6 and 7, where a fuel cell mCHP is used (see Table 7 section 4), the largest amount of electricity is exported. When a fuel cell mCHP is used (scenarios 6 and 7) gas is used to produce both heating and electricity for lighting, appliances and cooking. It is assumed that 50% of the electricity is used on site. A small amount of electricity from the grid is also used in scenarios 6 and 7 because the supply of electricity did not exactly match the demand. In scenarios 6 and 7 the total amount of energy used is larger than in any of the other scenarios. This is because the fuel cell mCHP cannot meet the full heat demand due to its limited capacity and a back-up gas boiler has to be used. An interesting aspect to point out is that despite the high energy use in scenarios 6 and 7, the operating costs (costs for gas and electricity) are lower in scenarios 6 and 7 than in the other scenarios, as Figure 10 shows, and the influence on global GHG emissions is also lower, as Figure 9 shows. These aspects are further discussed below.
Table 13: Energy use for house 1 apportioned to the end-use categories space and water heating and lighting, appliances and cooking. The amount of electricity exported to the grid is shown and total amount of energy used per year.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Energy use (kWh/year)</th>
<th>Space and water heating (kWh/year)</th>
<th>Lighting, appliances and cooking (kWh/year)</th>
<th>Amount of electricity exported to the grid (kWh/year)</th>
<th>Total energy used (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Gas 15 390 Electricity 0</td>
<td>Gas 0 Electricity 3 610</td>
<td></td>
<td>0</td>
<td>19 000</td>
</tr>
<tr>
<td>1</td>
<td>Gas 15 000 Electricity 0</td>
<td>Gas 0 Electricity 2 970</td>
<td></td>
<td>0</td>
<td>17 970</td>
</tr>
<tr>
<td>2</td>
<td>0 Electricity 4 493</td>
<td>Gas 0 Electricity 2 970</td>
<td></td>
<td>0</td>
<td>7 460</td>
</tr>
<tr>
<td>3</td>
<td>0 Electricity 4 493</td>
<td>Gas 0 Electricity 2 970</td>
<td></td>
<td>2 644</td>
<td>7 460</td>
</tr>
<tr>
<td>4</td>
<td>0 Electricity 3 068</td>
<td>Gas 0 Electricity 2 970</td>
<td></td>
<td>0</td>
<td>6 035</td>
</tr>
<tr>
<td>5</td>
<td>0 Electricity 3 068</td>
<td>Gas 0 Electricity 2 970</td>
<td></td>
<td>2 644</td>
<td>6 035</td>
</tr>
<tr>
<td>6</td>
<td>14 840 Electricity 0</td>
<td>Gas 8 987 Electricity 481</td>
<td></td>
<td>4 771</td>
<td>24 300</td>
</tr>
<tr>
<td>7</td>
<td>14 840 Electricity 0</td>
<td>Gas 8 987 Electricity 101</td>
<td></td>
<td>7 917</td>
<td>23 930</td>
</tr>
</tbody>
</table>

Figure 9 shows the influence on global GHG emissions within each scenario (an explanation of what is included in the calculations is given in section 4.4.2). If solar PV is not installed alongside heating technologies, installing a fuel cell mCHP (scenario 6) is the best environmental option. Despite the fact that fuel cell mCHP (scenarios 6 and 7) use the largest amount of energy it is still the most environmentally beneficial option. This is due to production of carbon intensive electricity being offset by production of electricity from the fuel cell mCHP. Installing solar PV alongside a heating technology, as in scenarios 3, 5 and 7, results in a large difference compared to when a heating technology alone is installed (scenarios 2, 4 and 6). This is due to the fact that solar electricity is offsetting production of carbon intensive grid electricity. The best overall solution from an environmental perspective is to install fuel cell mCHP alongside solar PV (scenario 7). In that scenario the influence on global GHG emissions are lowered with 98 % compared to the reference scenario where no measures were applied (scenario R in Table 7 section 4). Installing an ASHP alone (scenario 3) does not make as much difference on the influence on global GHG emissions. The influence on GHG emissions is lowered with 20 % in scenario 2 compared to scenario R. Fuel cell mCHP (scenario 6), SAHP with solar PV (scenario 5) or fuel cell mCHP with solar PV (scenario 7) are clearly much better options from an environmental perspective.

Figure 9: Influence on global GHG emissions per scenario for house 1.

Figure 10 shows the total income and costs as well as net expenditure for each scenario applied to house 1. The net expenditure is the net present value of the total cost subtracted by
the total income for the calculated period, section 4.4.1. If the net expenditure is lower (closer to 0) than the net expenditure for scenario R it means the scenario is profitable. The energy costs are costs for electricity and gas. The income in scenario 2 is domestic RHI payments for heat production from an ASHP. The income in scenario 3 is domestic RHI payments for heat production from an ASHP and FIT payments for solar PV. The income in scenario 5 is FIT payments for solar PV. The income in scenario 6 is FIT payments for electricity production from the fuel cell mCHP. The income in scenario 7 is FIT payments for fuel cell mCHP and solar PV. The only profitable scenarios for house 1 are installing energy efficiency measures (scenario 1) and installing an ASHP together with solar PV (scenario 3).

The financial details for the profitable scenarios are shown in Table 14. The payback time for installing energy efficiency measures (scenario 1) is 6.3 years, making it a reasonable investment. The payback time for installing an ASHP with solar PV (scenario 3) is 19.0 years, which is almost as long as the economic lifetime (20 years) of the ASHP and solar PV used in the scenario. This means it is an unreasonable investment. The payback time to install solar PV alone is 9.55 years. Simply installing an ASHP (scenario 2) is not profitable when compared to scenario R. It therefore seems to be the costs for the ASHP that need to be decreased (or the governmental subsidies need to be increased) rather than the costs or subsidies for solar PV. Capital costs for SAHP (scenarios 4 and 5) and fuel cell mCHP (scenarios 6 and 7) are significant. Those technologies are however the most environmentally friendly ones and should be the obvious choice for a homeowner that aims at making his or her home more sustainable. There are a few options to make ASHP, solar PV, SAHP and fuel cell mCHP technologies more profitable, which is discussed in more detail in the latter part of this chapter.

Table 14: Financial details for the profitable scenarios for house 1. The total savings and average savings are in reference to the costs in scenario R.

<table>
<thead>
<tr>
<th>Profitable scenarios</th>
<th>Capital cost</th>
<th>Total savings</th>
<th>Average savings per year</th>
<th>Payback time (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-£1555</td>
<td>£4115</td>
<td>£205.8</td>
<td>6.3</td>
</tr>
<tr>
<td>3</td>
<td>-£14620</td>
<td>£14630</td>
<td>£731.4</td>
<td>19.0</td>
</tr>
</tbody>
</table>
As can be seen in Table 13, installation of LED lighting and the more efficient use of appliances mean 643 kWh less electricity is used for lighting and appliances each year. The payback time for LED lighting and energy efficient appliances is 2.34 years. If the cost for a new A+++ fridge or dishwasher were included the payback time would be longer. Installing LED lighting make up the dominating part of the reduction in electricity usage and the payback time can therefore be assumed to be valid for the assumptions that has been made (see section 4.2.2 and 4.4.1 for further details).

5.1.2 Results relating to house 2

Table 15 shows data related to house 2; the gas and electricity usage, the amount of electricity exported to the grid and the total energy used. Similar to house 1 it is in scenarios 4 and 5 (SAHP and SAHP with solar PV is installed, respectively) that the least amount of energy is used, and in scenarios 6 and 7 (fuel cell mCHP and fuel cell mCHP with solar PV is installed, respectively) that the largest amount of electricity is exported. The energy used for heating in scenarios 1-7 differ more compared to scenario R for house 2 than for house 1 since more insulation measures were installed for house 2. In scenarios 6 and 7 less electricity from the grid is used which means the electricity production from the fuel cell mCHP is better matched with the demand than in house 1.

Table 15: Energy used in house 2 apportioned to the categories space and water heating and lighting, appliances and cooking. The amount of electricity exported to the grid and the total amount of energy used per year is presented as well.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Space heating and water heating (kWh/year)</th>
<th>Lighting, appliances and cooking (kWh/year)</th>
<th>Amount of electricity exported to the grid (kWh/year)</th>
<th>Total energy used (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>Gas</td>
<td>Electricity</td>
<td>Gas</td>
<td>Electricity</td>
</tr>
<tr>
<td>R</td>
<td>16 850</td>
<td>0</td>
<td>0</td>
<td>3 551</td>
</tr>
<tr>
<td>1</td>
<td>12 440</td>
<td>0</td>
<td>0</td>
<td>2 636</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>3 720</td>
<td>0</td>
<td>2 636</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>3 720</td>
<td>0</td>
<td>2 636</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>2 533</td>
<td>0</td>
<td>2 636</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>2 533</td>
<td>0</td>
<td>2 636</td>
</tr>
<tr>
<td>6</td>
<td>12 240</td>
<td>0</td>
<td>8 381</td>
<td>369.5</td>
</tr>
<tr>
<td>7</td>
<td>12 240</td>
<td>0</td>
<td>8 381</td>
<td>20.52</td>
</tr>
</tbody>
</table>

Figure 11 shows the influence on global GHG emissions for each scenario for house 2. Installing only energy efficiency measures (scenario 1) and installing an ASHP (scenario 2) lead to almost the same influence of global GHG emissions. Installing a fuel cell mCHP (scenarios 6 and 7) is the best option from an environmental perspective since electricity production from the fuel cell mCHP offset production of carbon-intensive electricity. This is especially true for scenario 7 where low-carbon electricity is produced from both fuel cell mCHP and solar PV, of which a large amount is exported to the grid. The electricity used on site was also included in the calculations of the influence on global GHG emissions. So much carbon-intensive electricity is offset in scenario 7 that the influence on GHG emissions has a negative value. Installing a SAHP with solar PV (scenario 5) is as good environmental option as installing only a fuel cell mCHP (scenario 6). The influence on global GHG emissions in scenario 7 are lowered by 109 % compared to scenario R. In the second best options influence in global GHG emissions are reduced by 80 % compared to scenario R.
Figure 11: The influence on global GHG emissions per scenario for house 2.

Figure 12 shows the total cost and income as well as net expenditure for each scenario. Energy costs in scenarios 6 and 7, where a fuel cell mCHP is used, are lower than in any other scenario, similar to house 1. The net expenditure in scenarios 6 and 7 are lower than in scenario R, which makes them profitable. In scenario 2 where an ASHP is installed, the electricity costs are quite high. The capital costs in scenario 2 are not as high as in scenarios 3-7 therefore it is most likely the high energy costs that prevent scenario 2 from being profitable. The scenarios where FIT payments are made (scenarios 3, 5, 6 and 7) have a higher level of income than in the scenarios where no FIT payments are made. Figure 12 shows that it is profitable to install energy efficiency measures (scenario 1), an ASHP with solar PV (scenario 3), a fuel cell mCHP (scenario 6) and fuel cell mCHP with solar PV (scenario 7).

Figure 12: Total income and costs during the calculated period for each scenario. For each scenario the net expenditure is showed as total cost minus total income. A scenario is profitable if the net expenditure is lower (closer to 0) than scenario R, i.e. income is positive and costs are negative. The income in scenario 2 is domestic RHI payments. The income in scenario 3 is domestic RHI and FIT payments. The income in scenario 5 is FIT payments. The income in scenarios 6 and 7 is FIT payments.

The payback time for installing energy efficiency measures (scenario 1) is 3 years, which makes it a reasonable investment. The payback time for installing an ASHP with solar PVs (scenario 3) is 13.4 years, which is a better investment opportunity than for the same technologies in house 1. The net expenditure for fuel cell mCHP (scenario 6) and fuel cell mCHP with solar PV (scenario 7) are lower than the net expenditure in scenario R. The payback time is still above 14 years, exceeding the economic lifetime of the technology. The
two scenarios with a fuel cell mCHP could become profitable with a reasonable payback time if the lifetime of the technology gets extended or if the net expenditure decreased. (This will be further discussed later on in this chapter). If only solar PV was installed (without any of the heating technologies), the payback time would be 8.9 years.

Table 16: Financial details for the profitable scenarios for house 2. The total savings and average savings are in reference to the costs for scenario R.

<table>
<thead>
<tr>
<th>Profitable scenarios</th>
<th>Capital cost</th>
<th>Total savings</th>
<th>Average savings per year</th>
<th>Payback time (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-£1 395</td>
<td>£6 113</td>
<td>£305.7</td>
<td>3.02</td>
</tr>
<tr>
<td>3</td>
<td>-£14 450</td>
<td>£18 610</td>
<td>£930.8</td>
<td>13.40</td>
</tr>
<tr>
<td>6</td>
<td>-£18 390</td>
<td>£14 460</td>
<td>£1 032</td>
<td>&gt;14</td>
</tr>
<tr>
<td>7</td>
<td>-£24 950</td>
<td>£20 760</td>
<td>£1 482</td>
<td>&gt;14</td>
</tr>
</tbody>
</table>

The payback time for replacing old lighting with LED light bulbs and utilising energy efficient appliances is 1.68 years, and lead to a 915 kWh decrease in electricity usage.

5.1.3 Results relating to house 3

Table 17 shows data for house 3: the electricity and gas used, the amount of electricity exported to the grid and the total amount of energy used. Scenarios 4 and 5 use the least amount of energy and scenarios 6 and 7 export the largest amount of electricity, similar to previous houses. In scenarios 4 and 5 less energy is used for space and water heating than for lighting, appliances and cooking. This is similar for the previous houses. In house 3, different from houses 1 and 2, more gas is used for space and water heating in scenarios 6 and 7. This is because the energy demand of house 3 is higher and the back-up gas boiler used in scenarios 6 and 7 is used more than in houses 2 and 3.

Table 17: Energy used in house 3 apportioned in the categories space and water heating and lighting, appliances and cooking. The amount of electricity exported to the grid and the total amount of energy used is also presented.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Energy use</th>
<th>Space heating and water heating (kWh/year)</th>
<th>Lighting, appliances and cooking (kWh/year)</th>
<th>Amount of electricity exported to the grid (kWh/year)</th>
<th>Total energy used (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gas</td>
<td>Electricity</td>
<td>Gas</td>
<td>Electricity</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>18 900</td>
<td>0</td>
<td>0</td>
<td>4 437</td>
<td>23 340</td>
</tr>
<tr>
<td>1</td>
<td>14 870</td>
<td>0</td>
<td>0</td>
<td>3 471</td>
<td>18 340</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>4 655</td>
<td>0</td>
<td>3 471</td>
<td>8 126</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>4 655</td>
<td>0</td>
<td>3 471</td>
<td>8 126</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>3 170</td>
<td>0</td>
<td>3 471</td>
<td>6 640</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>3 170</td>
<td>0</td>
<td>3 471</td>
<td>6 640</td>
</tr>
<tr>
<td>6</td>
<td>15 190</td>
<td>0</td>
<td>8 583</td>
<td>957.7</td>
<td>24 730</td>
</tr>
<tr>
<td>7</td>
<td>15 190</td>
<td>0</td>
<td>8 583</td>
<td>197.1</td>
<td>23 970</td>
</tr>
</tbody>
</table>

Figure 13 shows the influence on global GHG emissions for each scenario. Installing energy efficiency measures (scenario 1) have almost the same impact on global GHG emissions as installing an ASHP (scenario 2). The ASHP needs to be installed with solar PV (scenario 3) to lead to a significant environmental improvement. Installing a fuel cell mCHP with solar PV (scenario 7) is the best option for house 3 with a 102% reduction of the influence on global GHG emission compared to scenario R, similar to the other houses. The second best option is installing a SAHP with solar PV (scenario 5), which is similar to house 1.
Figure 13: The influence on global GHG emissions per scenario for house 3.

Figure 14 shows the total cost and income as well as net expenditure for each scenario. For this house, similar to house 2, it is profitable to install energy efficiency measures (scenario 1), an ASHP with solar PV (scenario 3), a fuel cell mCHP (scenario 6) and a fuel cell mCHP with solar PV (scenario 7).

Financial details for the profitable scenarios are showed in Table 18. The payback time for the energy efficiency measures (scenario 1) is approximately 7 years, which makes it a reasonable investment. The payback time for scenario 1 is longer compared to scenario 1 for house 2 due to the increased capital cost of double glazing and the other insulation measures. House 3 is a bigger house than house 2 and therefore the energy efficiency measures are more expensive. The payback time for an ASHP with solar PV (scenario 3) is 14.32 years, which is slightly longer compared to the same technologies for house 2. Again the reason is the costs of the energy efficiency measures (the cost for the ASHP and the solar PV are the same for both houses). The payback time for scenario 3 is shorter compared to house 1 because more energy efficiency measures was installed which lowered the energy demand and the amount spent on expensive electricity. Installing fuel cell mCHP has a lower net expenditure than scenario R.
but the payback time is longer than the lifetime of the technology. The lifetime of the technology needs to be extended or the net expenditure lowered in order to make them financially viable options. The savings made by installing a fuel cell mCHP (scenarios 6 and 7) are lower for house 3 than for house 2. The payback time to install only solar PV is 9.9 years.

Table 18: Financial details for the profitable scenarios of house 3. The total savings and average savings are in reference to the costs for scenario R.

<table>
<thead>
<tr>
<th>Profitable scenarios</th>
<th>Capital cost</th>
<th>Total savings</th>
<th>Average savings per year</th>
<th>Payback time (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-£2 585</td>
<td>£3 393</td>
<td>£169.7</td>
<td>7.270</td>
</tr>
<tr>
<td>3</td>
<td>-£17 280</td>
<td>£3 730</td>
<td>£186.5</td>
<td>14.32</td>
</tr>
<tr>
<td>6</td>
<td>-£19 580</td>
<td>£3 903</td>
<td>£278.8</td>
<td>&gt;14</td>
</tr>
<tr>
<td>7</td>
<td>-£27 780</td>
<td>£3 574</td>
<td>£255.3</td>
<td>&gt;14</td>
</tr>
</tbody>
</table>

The payback time for installing LED light bulbs and energy efficient appliances is 1.2 years and (as showed in Table 17) lead to a 966 kWh decrease in electricity usage.

5.1.4 Results relating to house 4

Table 19 shows data related to house 4; the electricity and gas used, the amount of electricity exported to the grid and the total amount of energy used. Similar to previous houses scenarios 4 and 5 use the least energy, while scenarios 6 and 7 export the largest amount of electricity to the grid. A difference can be identified compared to house 3 (which is the same house type but older and has a larger area according to Table 6). House 4 uses less gas for space and water heating in scenarios 6 and 7 than in scenario 1. House 3 used more gas in scenarios 6 and 7 than in scenario 1. The reason is that house 4 has a lower energy demand than house 3 which means the fuel cell mCHP used in scenarios 6 and 7 cover a larger part of the heat demand and the back-up boiler is not used as much. The same reason is valid when observing that house 4 uses less total amount of energy in scenarios 6 and 7 compared to scenario R, which is not the case for house 3. Since the heat demand in house 4 is much lower than in previous houses the heat pumps scenarios (scenarios 2-5) use significantly less electricity than in previous houses.

Table 19: Energy used in house 4 apportioned in the categories space and water heating and lighting, appliances and cooking. The amount of electricity exported and the total amount of energy used are also presented.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Space and water heating (kWh/year)</th>
<th>Lighting, appliances and cooking (kWh/year)</th>
<th>Amount of electricity exported to the grid (kWh/year)</th>
<th>Total energy used (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>15 320</td>
<td>0</td>
<td>0</td>
<td>19 220</td>
</tr>
<tr>
<td>1</td>
<td>11 096</td>
<td>0</td>
<td>0</td>
<td>14 030</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>3 299</td>
<td>0</td>
<td>6 234</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>3 299</td>
<td>2 934</td>
<td>6 234</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>2 231</td>
<td>0</td>
<td>5 166</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>2 231</td>
<td>3 304</td>
<td>5 166</td>
</tr>
<tr>
<td>6</td>
<td>10 780</td>
<td>7 402</td>
<td>3 808</td>
<td>18 950</td>
</tr>
<tr>
<td>7</td>
<td>10 780</td>
<td>7 402</td>
<td>6 293</td>
<td>18 240</td>
</tr>
</tbody>
</table>
Figure 15 shows influence on global GHG emissions for each scenario. For house 4 installing energy efficiency measures (scenario 1) is equally environmentally beneficial as installing an ASHP (scenario 2). In previous houses installing an ASHP (scenario 2) was slightly better than installing energy efficiency measures alone (scenario 1). Both scenarios 1 and 2 are significant improvements compared to scenario R. If an ASHP is installed alongside solar PV (scenario 3) the influence on global GHG emissions decreases significantly compared to only installing an ASHP. The same is applicable to SAHP (scenarios 4 and 5). Overall the measures taken in scenarios 1-7 lead to bigger improvements compared to previous cases. This is because more loft insulation was applied in house 4 (in houses 1-3 a thicker layer of loft insulation was applied already in the reference scenario). The best option from an environmental perspective is installing a fuel cell mCHP with solar PV (scenario 7), similar to previous houses. The influence on global GHG emissions in scenario 7 is 118 % lower than in scenario R, which is the largest decrease so far. This is because more energy efficiency measures are installed in house 4 leading to a greater change in heat demand and therefore a greater difference in the amount of gas that is needed to supply the heat demand. ASHP with solar PV (scenario 3), SAHP with solar PV (scenario 5) and only fuel cell mCHP (scenario 6) lower the influence on global GHG emissions with 75 %, 85 % and 79 % respectively.

![House 4: influence on global GHG emissions](image)

Figure 15: The influence on global GHG emissions per scenario for house 4.

Figure 16 shows the total cost and income as well as net expenditure for each scenario. Installing energy efficiency measures (scenario 1), an ASHP with solar PV (scenario 3), a fuel cell mCHP (scenario 6) and a fuel cell mCHP with solar PV (scenario 7) are the technologies and measures for house 4 that have lower net expenditure than scenario R.
Figure 16: Total income and costs during the calculated period for each scenario. For each scenario the net expenditure is showed as total cost minus total income. A scenario is profitable if the net expenditure is lower (closer to 0) than scenario R, i.e. income is positive and costs are negative. The income in scenario 2 is domestic RHI payments. The income in scenario 3 is domestic RHI and FIT payments. The income in scenario 5 is FIT payments. The income in scenarios 6 and 7 is FIT payments.

Table 20 shows the financial details for the profitable scenarios for house 4. The reason the payback time for scenario 3 is longer than for example for the same scenario in house 2 is the extra capital cost the extra insulation infer. The payback time to install fuel cell mCHP (scenario 6 and 7) exceed the economic lifetime of the technology. The payback time for only solar PV is 9.9 years.

Table 20: Financial details for the profitable scenarios for house 4. The total savings and average savings are in reference to the costs for scenario R.

<table>
<thead>
<tr>
<th>Profitable scenarios</th>
<th>Capital cost</th>
<th>Total savings</th>
<th>Average savings per year</th>
<th>Payback time (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-£1 047</td>
<td>£2 830</td>
<td>£141.5</td>
<td>4.40</td>
</tr>
<tr>
<td>3</td>
<td>-£18 047</td>
<td>£3 219</td>
<td>£160.9</td>
<td>15.9</td>
</tr>
<tr>
<td>6</td>
<td>-£18 050</td>
<td>£1 514</td>
<td>£108.1</td>
<td>&gt;14</td>
</tr>
<tr>
<td>7</td>
<td>-£26 250</td>
<td>£462.6</td>
<td>£33.04</td>
<td>&gt;14</td>
</tr>
</tbody>
</table>

The payback time to install LED lighting and energy efficient appliances is 1.2 years and result in a 967 kWh decrease of electricity usage.

5.1.5 Results relating to house 5

Table 21 shows results related to house 5; the electricity and gas used, the amount of electricity exported to the grid and the amount of total energy used. Similar to previous houses the least amount of energy is used in scenarios 4 and 5 and in scenarios 6 and 7 the largest amount of electricity is exported. House 5 has a high energy demand, similarly to house 3. Therefore the capacity of the fuel cell mCHP in scenarios 6 and 7 is not enough to meet the heat demand. More gas is used in scenarios 6 and 7 than in scenario 1, because a back-up boiler needs to be used due to the high heat demand. House 5 exports more electricity in scenarios 6 and 7 compared to the previous houses. House 5 is the only case house where the total energy used in scenarios 6 and 7 is significantly higher than even the total energy used in scenario R.
Table 21: Energy used in house 5 apportioned in the categories space and water heating and lighting, appliances and cooking. The amount of electricity exported and the total amount of energy used are also presented.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Energy use</th>
<th>Space and water heating (kWh/year)</th>
<th>Lighting, appliances and cooking (kWh/year)</th>
<th>Amount of electricity exported to the grid (kWh/year)</th>
<th>Total energy used (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Gas</td>
<td>21 840</td>
<td>0</td>
<td>5 732</td>
<td>27 570</td>
</tr>
<tr>
<td>1</td>
<td>Electricity</td>
<td>17 460</td>
<td>0</td>
<td>4 416</td>
<td>21 880</td>
</tr>
<tr>
<td>2</td>
<td>Gas</td>
<td>0</td>
<td>5 878</td>
<td>0</td>
<td>10 290</td>
</tr>
<tr>
<td>3</td>
<td>Electricity</td>
<td>0</td>
<td>5 878</td>
<td>4 416</td>
<td>10 290</td>
</tr>
<tr>
<td>4</td>
<td>Gas</td>
<td>0</td>
<td>4 008</td>
<td>0</td>
<td>8 424</td>
</tr>
<tr>
<td>5</td>
<td>Electricity</td>
<td>0</td>
<td>4 008</td>
<td>4 416</td>
<td>8 424</td>
</tr>
<tr>
<td>6</td>
<td>Gas</td>
<td>18 880</td>
<td>0</td>
<td>10 660</td>
<td>30 830</td>
</tr>
<tr>
<td>7</td>
<td>Electricity</td>
<td>0</td>
<td>10 660</td>
<td>333.9</td>
<td>29 880</td>
</tr>
</tbody>
</table>

Figure 17 shows the influence on global GHG emissions for each scenario. In Case 5 the impact on global GHG emissions in the scenarios 1-7 compared to scenario R are not lowered as much as in previous cases. This is due to the fact that full loft insulation and double glazing were already installed, so there was less reductions to be gained compared to scenario R. The most compelling environmental option for house 5 is installing fuel cell mCHP with solar PV (scenario 7), where the influence to global GHG emissions is 102 % lower than in scenario R.

![House 5: influence on global GHG emissions](image)

Figure 17: The total influence on global GHG emissions per scenario for house 5.

Figure 18 shows the total cost and income as well as net expenditure for each scenario. For house 5 it is profitable to install energy efficiency measures (scenario 1), an ASHP with solar PV (scenario 3), a fuel cell mCHP (scenario 6) and a fuel cell mCHP with solar PV (scenario 7). The financial details for those scenarios are showed in Table 22.
The payback time for installing energy efficiency measures (scenario 1) is approximately 2.6 years, which makes it a very reasonable investment. The total savings are larger than house 3 (house 3 has a payback time of 3.02 years for scenario 1). The reason the payback time is so favourable for house 5 is because no loft insulation or double glazing had to be installed and the cavity wall insulation that was applied is a cheap measure followed by significant energy savings. The payback time to install an ASHP with solar PV (scenario 3) is 13.8 years. The reason the payback time is more favourable (despite house 5 having a much higher heating demand than for example house 4) is the capital costs for the energy efficiency measures and the income from solar PV. The payback time for only solar PV is 8.2 years. The payback time to install fuel cell mCHP (scenarios 6 and 7) exceed the economic lifetime of the fuel cell mCHP.

The payback time for installing LED lighting and energy efficient appliances is 1.67 years and lead to a decrease in electricity usage of 1316 kWh. The decrease in electricity usage is significantly more than in the previous houses and the payback time is therefore better.

### 5.1.6 Results relating to house 6

Table 23 shows the results related to house 6; electricity and gas used, the amount of electricity exported to the grid and the amount of total energy used. Similar to the previous houses the least amount of energy is used in scenarios 4 and 5 and the largest amount of electricity is exported in scenarios 6 and 7. For house 6 the gas used in scenarios 6 and 7 is less than the gas used in scenario R and 1 because the efficiency of the gas boiler in house 6 is
only 66%. The efficiency of the gas boilers used in previous houses is between 85-90%. The fuel cell mCHP has an overall efficiency of 81% (the fuel cell unit has an efficiency of 95% and the fuel processor an efficiency of 85%), which means a definite improvement compared to a gas boiler with an efficiency of 66%. About the same amount of electricity are exported in house 6 as house 5 (they are the same house type, have the same fuel cell mCHP and solar PV capacity installed and can therefore be compared).

Table 23: Energy used in house 6 apportioned in the categories space and water heating and lighting, appliances and cooking. The amount of electricity exported and the total amount of energy used are also presented.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>R</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy use</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td>22 470</td>
<td>0</td>
<td>0</td>
<td>5 581</td>
<td>0</td>
<td>28 060</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>0</td>
<td>0</td>
<td>4 488</td>
<td>0</td>
<td>24 730</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td>0</td>
<td>0</td>
<td>4 488</td>
<td>0</td>
<td>9 582</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>0</td>
<td>0</td>
<td>4 488</td>
<td>3 963</td>
<td>9 582</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td>0</td>
<td>3 466</td>
<td>0</td>
<td>4 488</td>
<td>0</td>
<td>7 954</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>0</td>
<td>3 466</td>
<td>0</td>
<td>4 488</td>
<td>3 963</td>
<td>7 954</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td>17 280</td>
<td>0</td>
<td>10 090</td>
<td>1 441</td>
<td>5 097</td>
<td>28 800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>0</td>
<td>10 090</td>
<td>456.0</td>
<td>9 396</td>
<td>27 820</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 19 shows influence on global GHG emissions for each scenario. Compared to house 5 the difference between scenario R and scenario 1-7 is bigger. This is due to more insulation measures being installed in house 6. Particularly the difference between scenarios 1 and 2 is larger than for previous houses. This is because the ASHP in scenario 2 replaces a gas boiler with a low efficiency. The best environmental option for house 6 is to install a fuel cell mCHP with solar PV (scenario 7), where the influence to global GHG emissions is 107% lower than in scenario R.

Figure 20 shows the total cost and income as well as net expenditure for each scenario. For house 6 it is profitable to install energy efficiency measures (scenario 1), an ASHP with solar PV (scenario 3), a fuel cell mCHP (scenario 6) and a fuel cell mCHP with solar PV (scenario 7). The financial details for those scenarios are showed in Table 24. House 6 is the first house where the energy costs in scenario 2 is lower than in scenario 1. For all the other houses the
energy costs in scenario 2 was higher or about the same as in scenario 1. Once again this is due to the low efficiency of the gas boiler used in scenario 1.

The payback time for installing energy efficiency measures (scenario 1) is 4.3 years, which means it is a reasonable investment. The payback time to install an ASHP with solar PV (scenario 3) is 12.15 years, which makes it the shortest payback time for scenario 3 compared to the previous houses. The payback time for solar PV is 9.9 years alone. The payback time for fuel cell mCHP (scenarios 6 and 7) exceeds the lifetime of the technology.

The payback time for installing LED lighting and energy efficient appliances is 1.4 years and reduces electricity usage with 1093 kWh.

5.2 Sensitivity analysis

A sensitivity analysis has been performed to evaluate how a few chosen aspects affect the results presented above. The aspects that were included in the sensitivity analysis were energy prices, discount rates, heat pump efficiency, implications from individual conditions of each case house, capital costs, level of governmental subsidies and GHG emissions from electricity generation.

5.2.1 Financial factors

To analyse how energy prices affect the result the “Low Prices” and “High Prices” projections from DECC (2014d) have been used to evaluate the impact on the results. The “Low Prices”
scenario has the same assumptions as the “Reference Scenario” but with lower projected fossil fuel prices. The “High Prices” scenario has the same assumptions but with higher projected fossil fuel prices (for a further explanation of energy prices and the assumptions see section 4.4.1.).

A sensitivity analysis of the discount rate has been performed by increasing the discount rate to 5 % and 8 % respectively. The two discount rates use the same energy prices as in the study (“Reference Scenario”). Figure 21 shows the percentage change in net expenditure for house 5 when the energy prices and the discount rates are changed (new net expenditure with different energy prices or discount rates compared to the net expenditure presented in section 5.1.5). Only the percentage change for house 5 is presented here but the other case houses followed the same trend. The change in energy prices and discount rates are shown in the same figure to show which of the two economic factors that has the biggest impact on net expenditure.

The heat pump scenarios (scenarios 2, 3, 4 and 5) are less sensitive to changes in energy prices compared to the scenarios that have gas based heating systems (scenarios R, 1, 6 and 7). This is because less amount of energy is used in the heat pump scenarios (scenarios 2, 3, 4 and 5), which makes them less sensitive to changes in energy prices. An ASHP (scenarios 2 and 3) use more electricity than an SAHP (scenarios 4 and 5) due to the slightly lower efficiency of the ASHP, which results in a higher sensitivity for varying energy prices for the ASHP compared to the SAHP. As can be seen, a higher discount rate favours the scenarios with zero capital cost (scenario R) or low capital cost (scenarios 1 and 2). According to Woodward (1997) technologies with a low capital cost and high operating cost are favoured by a high discount rate, which is supported by the results in Figure 21.

![Figure 21](image)

**Figure 21:** The percentage change of the net expenditure when the energy prices and discount rates are changed. The two categories “Low Prices” and “High Prices” are two different energy price projections made by DECC (2014d), reflecting lower and higher projected fossil fuel prices respectively. This graph is the specific percentage changes for house 5 but the other cases follow the same trend.

### 5.2.2 GHG emissions from electricity generation

Section 3.5 describes how previous studies have evaluated how different microgeneration technologies are affected by the GHG emissions from electricity production. In this study a value of 533 g CO$_2$e/kWh have been used. The results show that SAHP (scenarios 4 and 5) and fuel cell mCHP (scenarios 6 and 7) are the two best options from an environmental perspective for all 6 case houses. However, as the GHG emissions from electricity production decreases these results may look different and therefore sensitivity analysis of GHG emission factors for electricity have been undertaken. The two GHG emission factors included in the
sensitivity analysis are 233 g CO$_2$e /kWh (half of today’s levels) and 100 g CO$_2$e/kWh (based on the Carbon Plan (HM Government 2011) assuming that level can be a reality by 2030).

When the GHG emission factor for electricity is 233 g CO$_2$e/kWh, scenarios 6 and 7 (when fuel cell mCHP is installed) are still more environmentally beneficial options than scenario R and scenario 1 for all case houses. Scenarios 6 and 7 are however no longer the best option. Scenarios 4 and 5 where a SAHP is installed is the best option followed by scenarios 2 and 3 where an ASHP is installed.

When the GHG emission factor for electricity is 100 g CO$_2$e/kWh, the scenarios where fuel cell mCHPs are installed (scenarios 6 and 7) are the worst option from an environmental perspective. Scenarios 6 and 7 now have higher GHG emissions than any other scenario for house 1, 3 and 5. For houses 2, 4 and 6, fuel cell mCHP (scenarios 6 and 7) have about the same GHG emissions as the gas boiler (scenario R). Combining fuel cell mCHP with solar PV does not lead to any major improvements, the GHG emission levels are about the same as without solar PV.

For ASHP and SAHP however the levels keep decreasing, both with and without solar PV, and for all case houses. This shows that ASHP and SAHP become better heating options from an environmental perspective the more the electricity production decarbonises. When the GHG emissions from electricity production decreases the fuel cell mCHP technology need to produce hydrogen from a renewable source (not natural gas like today) in order to stay a sustainable option. It is possible to produce hydrogen from electrolysis but the costs are currently higher than producing hydrogen from natural gas (Dodds and Hawkes 2014). If fuel cell mCHP would become a commercial heating option the costs for electrolysis would most likely reduce, alongside the development of zero carbon electricity. It could however take 15-20 years (or longer) before the emissions from electricity generation are on such low levels that fuel cell mCHP no longer is an environmentally beneficial option compared to a gas boiler (DECC 2014d).

5.2.3 Solar assisted heat pumps

The SAHP system that is evaluated in this study is currently not eligible for the domestic RHI subsidy (section 4.4.1). It is eligible for the non-domestic RHI, which is a similar incentive but for non-domestic installations. The first step in evaluating how this technology can become more commercially viable was a sensitivity analysis of the payback time if the Minus7 SAHP system was eligible for the domestic RHI. The installation would then receive a subsidy of 19.2 p/kWh of renewable heat produced.

The SAHP remained having higher net expenditure than a gas boiler (scenario R) for all case houses except house 2 where the SAHP had lower net expenditure over the calculated period than a gas boiler (scenario R). For house 2 the SAHP had a payback time of 14.06 years without solar PV (scenario 4) and 14.85 years with solar PV (scenario 5).

According to the manufacturer the Minus 7 SAHP system is a good solution for 2-4 dwellings (Minus7 2015). When installed for 2-4 dwellings the system has the better performance and shorter payback time. If installing the system for 2 dwellings the capital costs would be around £15000 per house. Table 25 shows the profitable SAHP scenarios for each case house and their respective payback times when assuming an installation cost of £15000 per house and a domestic RHI grant of 19.2 p/kWh.
Table 25: Profitable SAHP scenarios and payback time when assuming a cost for SAHP of £15000 and a domestic RHI grant of 19.2 p/kWh.

<table>
<thead>
<tr>
<th>Case house</th>
<th>Profitable scenario</th>
<th>Payback time (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>14.6</td>
</tr>
<tr>
<td>2</td>
<td>4 and 5</td>
<td>10.6 and 10.4</td>
</tr>
<tr>
<td>3</td>
<td>4 and 5</td>
<td>8.4 and 9</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>15.4</td>
</tr>
<tr>
<td>5</td>
<td>4 and 5</td>
<td>6.83 and 7.11</td>
</tr>
<tr>
<td>6</td>
<td>4 and 5</td>
<td>15.7 and 11.2</td>
</tr>
</tbody>
</table>

Since the Minus 7 SAHP system is currently only eligible under the non-domestic RHI it might be a suitable heating option to install on several houses. Table 26 shows the financial details for a SAHP system installed on three terraced houses. A local energy company, a council or landlords could own the installation.

Table 26: Financial details for a non-domestic Minus 7 SAHP system installed on three terraced houses. Local energy companies, councils, landlords or housing associations could be interested such installation. All the costs, except maintenance costs, are given as a net present value for the costs occurring during the financial calculation period of 20 years.

| Operating costs: Electricity | £16 370 |
| Maintenance                  | £50 / year |
| Total savings                | £68 930 |
| Total RHI payments           | £41 130 |
| Capital costs                | £48 600 |
| Payback time                 | 8.44 years |

According to Gupta, Barnfield and Hipwood (2014) the Government supports community-led energy initiatives. In the last 4 years two government-funded programmes, the Low Carbon Communities Challenge and Local Energy Assessment Fund, have sponsored communities with capital funding for physical interventions to the buildings and provided funding to behaviour change campaigns and low carbon living activities. The Minus 7 SAHP system would be ideal for that type of funding. Combining community initiatives with the non-domestic RHI grant would make SAHP a promising technology. As stated by HM Government and DECC (2015) non-traditional players (such as community led projects) will become a part of the energy system in the future and a solution such as the Minus 7 SAHP system enables non-traditional players to join the energy system.

### 5.2.4 Air source heat pumps

The performance of an ASHP can be improved by installing low temperature radiators or under floor heating. According to Easy RSS (Qualitick™ 2015) the SPF would increase to 3.4 for both space and water heating if the heat pump outlet temperature can be lowered to 40 °C. An electric immersion heater would be used to meet the difference between the outlet of the heat pump and the hot water temperature required (domestic hot water must periodically be raised to 60 °C to limit the risk of Legionnaires disease).

Increasing the SPF from 2.7 to 3.4 means the heat pump will use 26 % less electricity and still provide the same amount of heat. Table 27 shows the payback time and change in net expenditure for the scenarios where an ASHP was considered (scenarios 2 and 3), for all case houses. The net expenditure is slightly increased or staying about the same for all case houses. The reason is the capital cost of the low temperature radiators that has to be installed in order to be able to raise the efficiency of the heat pump. The payback time is longer than the period
used in the calculations (<20), except for houses 2, 3, 4 and 5 when an ASHP installed together with solar PV (scenario 3).

Table 27: New payback time and change in net expenditure when the SPF was raised from 2.7 to 3.4, for the scenarios where ASHP was considered (scenarios 2 and 3).

<table>
<thead>
<tr>
<th>Case house</th>
<th>Scenarios 2</th>
<th>Change in net expenditure (%)</th>
<th>Scenarios 3</th>
<th>Change in net expenditure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Payback time (years)</td>
<td></td>
<td>Payback time (years)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>&gt;20</td>
<td>-</td>
<td>&gt;20</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>&gt;20</td>
<td>-</td>
<td>14.9</td>
<td>+0.023</td>
</tr>
<tr>
<td>3</td>
<td>&gt;20</td>
<td>-</td>
<td>15.4</td>
<td>+0.7</td>
</tr>
<tr>
<td>4</td>
<td>&gt;20</td>
<td>-</td>
<td>&gt;20</td>
<td>+0.075</td>
</tr>
<tr>
<td>5</td>
<td>&gt;20</td>
<td>-</td>
<td>13.64</td>
<td>-1.5</td>
</tr>
<tr>
<td>6</td>
<td>&gt;20</td>
<td>-</td>
<td>13.6</td>
<td>+0.04</td>
</tr>
</tbody>
</table>

Since improving the SPF from 2.7 to 3.4 alone did not make the scenarios where an ASHP was considered a financially viable option, the tariff for the RHI was changed as well, with the result of that amendment seen in Table 28. If the SPF is raised from 2.7 to 3.4 and the RHI tariff is doubled from 7.45 pence/kWh to 14.8 pence/kWh installing an ASHP (scenarios 2 and 3) becomes a reasonable investment for all case houses except house 1 and house 4. This shows that the governmental subsidy given for heat pumps could be considered to be too low at the moment. It can however be assumed that such an increase in governmental subsidies is not likely. It is probably more likely that the capital costs of the ASHP will decrease as its market share increases resulting in lower payback times.

Table 28: New payback time and change in net expenditure when raising the SPF from 2.7 to 3.4 and the tariff of RHI given for an ASHP is doubled.

<table>
<thead>
<tr>
<th>Case house</th>
<th>Scenarios 2</th>
<th>Change in net expenditure (%)</th>
<th>Scenarios 3</th>
<th>Change in net expenditure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Payback time (years)</td>
<td></td>
<td>Payback time (years)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>18.0</td>
<td>-15</td>
<td>&gt;20</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>9.85</td>
<td>-12</td>
<td>10.8</td>
<td>-16</td>
</tr>
<tr>
<td>3</td>
<td>11.7</td>
<td>-11</td>
<td>10.1</td>
<td>-14</td>
</tr>
<tr>
<td>4</td>
<td>&gt;20</td>
<td>-</td>
<td>16.5</td>
<td>-8</td>
</tr>
<tr>
<td>5</td>
<td>6.8</td>
<td>-14</td>
<td>8.33</td>
<td>-17</td>
</tr>
<tr>
<td>6</td>
<td>6.03</td>
<td>-11</td>
<td>9.38</td>
<td>-13</td>
</tr>
</tbody>
</table>

5.3 Individual conditions for the case houses

The implications of the individual conditions of the case houses are discussed below.

The higher the energy demand of a house is, the higher the energy costs will be and since electricity is three times more expensive than gas, houses with a high heat demand will be less suitable for electrified heating options such as heat pumps. It is impossible to know how energy prices will develop in the future but according to the projections of energy prices used in this study electricity prices will keep rising and keep being significantly higher than gas prices (DECC 2014d). For the same reason case houses with higher energy demand are more suitable for fuel cell mCHP since more heat and electricity can be produced on site using cheap gas.
For house 1 major limitation exists to lower the energy demand by installing insulation measures. Both internal and external solid wall insulation cause great disruption to the building and are very expensive to install (cavity wall insulation is both cheaper and easier to install). The operating costs for biomass boilers are nearing the operating costs for gas boilers (Staffell, et al. 2010) and could therefore be a better option for house 1 than the heating options considered in this study. Further research could diversify the case study by including more specific technology options based on the conditions of the building.

Installing double glazed windows are the most expensive of the energy efficiency measures. As a result of this the payback time for energy efficiency measures are lowest in the case houses where double glazing were installed already in the reference scenario.

5.4 Behavioural aspects and demand-side response

Below a few aspects of behaviour and demand-side response in relation to heating technologies, energy prices and energy use are analysed and discussed.

5.4.1 Different electricity tariffs

As part of managing energy demand, electricity tariffs that vary over time of day can be implemented (section 3.3). A sensitivity analysis has been performed to evaluate how fluctuating electricity tariffs impact the scenarios where the heating is electrified (scenarios 2, 3, 4 and 5). Table 29 shows the result of different electricity tariffs for the scenarios where an ASHP is considered (scenarios 2 and 3) and Table 30 shows the result for the scenarios when a SAHP is considered (scenarios 4 and 5). When comparing Table 29 and Table 27 it can be seen that fluctuating electricity tariffs lead to a greater change in net expenditure for scenario 2 and 3 than the increase of the efficiency of the ASHP did.

Table 29: Payback time and change in net expenditure for scenario 2 and 3 assuming fluctuating electricity tariffs.

<table>
<thead>
<tr>
<th>Case house</th>
<th>Scenario 2</th>
<th></th>
<th>Scenario 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Payback time (years)</td>
<td>Change in net expenditure (%)</td>
<td>Payback time (years)</td>
<td>Change in net expenditure (%)</td>
</tr>
<tr>
<td>1</td>
<td>&gt;20</td>
<td>-</td>
<td>17.6</td>
<td>-11.8</td>
</tr>
<tr>
<td>2</td>
<td>&gt;20</td>
<td>-10.9</td>
<td>12.3</td>
<td>-11.3</td>
</tr>
<tr>
<td>3</td>
<td>&gt;20</td>
<td>-</td>
<td>13.41</td>
<td>-11.9</td>
</tr>
<tr>
<td>4</td>
<td>&gt;20</td>
<td>-</td>
<td>17.4</td>
<td>-11.8</td>
</tr>
<tr>
<td>5</td>
<td>15.84</td>
<td>-12.4</td>
<td>12.9</td>
<td>-13.1</td>
</tr>
<tr>
<td>6</td>
<td>14.7</td>
<td>-11.7</td>
<td>12.9</td>
<td>-10.6</td>
</tr>
</tbody>
</table>

A fluctuating electricity tariff did not make the SAHP systems a profitable investment when the capital costs were £31,000 and no RHI (domestic or non-domestic) payments were received (according to the original assumptions made in section 4.4.1). A sensitivity analysis was therefore performed when the capital costs for the system was assumed to be £15,000 and a domestic RHI subsidy of 19.2 pence/kWh. Table 30 should be compared to Table 25 where the same assumptions were made. The changes in net expenditure in Table 30 are the percentage changes compared to the results showed in Table 25. The net expenditure for scenario 4 is lower in Table 30. The payback time for the investment in scenario 4 (SAHP alone) is shorter as well. For scenario 5 however the net expenditure is lower in Table 30 than in Table 25 but the payback time for the scenario (installing SAHP with solar PV) stays about the same. This is because the savings from producing your own electricity is less when the electricity tariffs are lower. The savings made from lower electricity tariffs are not large enough to make the payback time shorter.
Implementing electricity tariffs that reflect at what time of day the electricity is cheap versus when it is expensive enable for demand-side management. If it is cheaper to use electricity at night or during the middle of the day, the heat pump can be set to be on during those times. That would however require thermal storage to guarantee that space and hot water heating can be provided when demanded (thermal storage is further discussed in section 5.4.3 below).

### 5.4.2 Amount of electricity produced and used on site

The assumption used in this study regarding solar PV is that 75 % of the electricity is exported to the grid. The payback time for solar PV is 9-10 years for all case houses, as showed in the previous chapter (section 5.1.1 - 5.1.6). If more electricity could be used on site instead of being exported to the grid, it would mean less pressure on the grid and be more beneficial for the homeowner. If 50 % of the electricity were used on site instead of 25 %, the payback time would be lowered with around 2 years for each case house. This shows that there are economic benefits to exporting less electricity to the grid and instead use more electricity on site.

Tesla Motors (2015) recently released a domestic battery created to store solar electricity. Their battery costs around £2 000-£2 500 plus installation costs and can store 7-10 kWh. Hot water thermal stores are another possibility. According to Thygesen and Karlsson (2014) a thermal store is a more cost-effective option than batteries. Thermal stores are available for around £1 000 (Gas Appliance Guide 2015). Thermal stores can also help making heat pumps more efficient by minimising load cycles (Staffell, Brett, et al. 2012).

### 5.4.3 Low carbon heating technologies and demand-side response

The hot store in the Minus7 SAHP system used in this study is set to always maintain a temperature of at least 38 °C (an immersion heater periodically raises the domestic hot water to 60 °C to avoid the risk of Legionnaires disease). The heat pump operates based on the temperature of the hot store and not on the direct heating system settings chosen by the occupants of the house. This means that the heat pump in the Minus7 system is not driven by the demand of the house but rather by the temperature of the hot store. The solar thermal panels are also connected to the hot store so that they can provide heat directly to the hot store on warm days. Therefore the heat pump does not always have to operate for the hot store to maintain its temperature. The heat pump in the Minus7 system can operate during hours of the day when electricity prices are low to drive the thermal store up to the right temperature and be switched off when electricity prices are high and the demand on the grid is at its top.

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Table 30: Payback time and change in net expenditure for scenarios 4 and 5 assuming fluctuating electricity tariffs.

<table>
<thead>
<tr>
<th>Case house</th>
<th>Scenario 4</th>
<th>Change in net expenditure (%)</th>
<th>Scenario 5</th>
<th>Change in net expenditure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Payback time (years)</td>
<td></td>
<td>Payback time (years)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>18.9</td>
<td>-10.5</td>
<td>13.3</td>
<td>-10.8</td>
</tr>
<tr>
<td>2</td>
<td>9.5</td>
<td>-10.3</td>
<td>10.6</td>
<td>-10.7</td>
</tr>
<tr>
<td>3</td>
<td>7.3</td>
<td>-11.4</td>
<td>9.3</td>
<td>-12.2</td>
</tr>
<tr>
<td>4</td>
<td>&gt;20</td>
<td>-</td>
<td>15.8</td>
<td>-9.0</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>-13.0</td>
<td>7.3</td>
<td>-14.1</td>
</tr>
<tr>
<td>6</td>
<td>13.3</td>
<td>-11.5</td>
<td>11.4</td>
<td>-11.0</td>
</tr>
</tbody>
</table>
An ASHP operates based on a fluctuating outside air temperature and on the direct heating demand of the house. During cold winter days it can mean that the ASHP has to operate during all hours of the day to meet the demand. If the ASHP is not connected to a thermal store it means it will have to run during hours when demand and electricity prices are at their peak. According to Staffell et al. (2012) the fabric of a house and its heating system can be used as a thermal buffer (or storage), which means the ASHP would be set to be on during night time and certain hours of the day when the demand and electricity prices are lower. As Table 29 shows there is a clear economic incentive to have “time-of-day” electricity tariffs when using heat pumps (both ASHP and SAHP).

Temperature management (as described in section 3.2) has been identified as an area where human behaviour has a large influence on energy use. If the heating system is easily managed it will lower the impact behaviour has on energy use (according to Staffell et al. (2010) the way microgeneration technologies are managed have a significant impact on their efficiency and therefore the amount of energy used). The SAHP system used in this study operates when the hot store is below 38 °C and the only settings the occupants of the dwelling will be able to change is the indoor temperature. This means that the SAHP system distance the operation of the heating system from the user and by doing that also makes the system easier for the user. This should limit the impact behaviour has on the energy used by the SAHP system. If the SAHP system is installed by a landlord or a local energy company and connected to several dwellings it would be more reliable compared to an ASHP, since the only setting the occupants of the dwelling can change is the indoor temperature and the heat pump operates on the demand of the hot store (not directly on the demand of the house). According to Hill (2015) this has been an important reason for landlords and similar players when choosing to install the Minus7 SAHP system.

According to the results showed in this chapter a fuel cell mCHP (scenarios 6 and 7) has significant environmental benefits compared to a gas boiler (scenario R). However, as the GHG emissions from electricity generation is decreasing the environmental benefits from fuel cell mCHP fuelled by natural gas, decreases. Implementing fuel cell mCHPs in the energy system does have other benefits. It fulfils the sustainability criteria defined in the first chapter (section 1.4) by making the use of resources more efficient. A fuel cell mCHP fuelled by natural gas provide a stepping stone towards a more sustainable energy system. If a fuel cell mCHP is installed today it is more environmentally friendly than either of the heat pump systems included in the study. As mentioned previously, renewable electricity can be used to produce hydrogen and if that becomes a reality fuel cell mCHP will remain an environmentally friendly heating option.

Another advantage of the fuel cell mCHP is the joint production of heat and electricity. A fuel cell mCHP takes pressure off the grid during peak load and unlike solar PV it produces more electricity during the winter peak when it is needed the most. Fuel cell mCHP can therefore become a good complement to solar PV and heat pumps.

### 5.5 Chapter summary

In the first part of the chapter the results from the study were presented. In scenarios 4 and 5 (installing a SAHP and SAHP with solar PV) the least amount of energy is used across all of the case houses. Using a fuel cell mCHP together with solar PV (scenario 7) was the most environmentally beneficial option for all case houses, mainly due to the electricity produced
on-site offsetting carbon-intensive grid electricity. Using fuel cell mCHP (scenarios 6 and 7) meant a very small amount of grid electricity was used and instead quite a large amount of electricity was exported each year. Using a SAHP system, with and without solar PV (scenarios 5 and 6), was also a good option from an environmental perspective. For house 1 only scenario 1 (installing energy efficiency measures) was a good option financially. For house 2 scenarios 1, 3, 6 and 7 all had lower net expenditure over the calculated financial period than scenario R but only the energy efficiency measures used in scenario 1 had a reasonable payback time. The same trend is valid for house 3-5 as well. For house 6 installing an ASHP with solar PV (scenario 3), installing a fuel cell mCHP (scenario 6) and installing a fuel cell mCHP with solar PV (scenario 7) had similar payback times, however none of the payback times were short enough to provide a good financial option. For all of the case houses the payback time for LED was very favourable. The payback time for solar PV was better than any of the other microgeneration technologies but unfortunately still around 9 years, which is considered to be too long.

In the second half of this chapter sensitivity analysis was performed for several different aspects. Of the two financial factors analysed, discount rates affected the results the most and especially the scenarios where technologies and measures with low capital costs were used. Sensitivity analysis of GHG emissions from electricity generation showed that SAHP and ASHP would become stronger environmental options as the GHG emissions from electricity generation decreases. Fuel cell mCHP on the other hand will become less environmental beneficial as GHG emissions from electricity generation decreases. For ASHP and SAHP to become more financially viable options the domestic RHI needs to be increased and the capital costs of the SAHP need to be decreased. Installing the SAHP system for several dwellings can bring down the capital costs significantly which leads to reasonable payback times for all of the case houses.

In the last part of this chapter a few aspects of behaviour in relation to energy use were discussed. Using fluctuating electricity tariffs would be financially beneficial for both SAHP and ASHP. Thermal storage would gain both SAHP and ASHP as well, especially in combination with fluctuating electricity tariffs.
6 Discussion

In this chapter the wider context of the study is discussed. The methodology used is discussed as well as the impacts from the limitations applied to the study.

6.1 Heating technologies excluded from the study

There are other microgeneration technologies available on the market as presented in section 3.1. Biomass boilers and ground source heat pumps (GSHPs) are two of the most mentioned microgeneration technologies in the literature. Those two technologies were however excluded from the study since biomass is projected to have limited growth and GSHPs require access to land that is most likely not available in densely populated, urban areas. The Minus7 SAHP system is a better option than a GSHP, since the SPF is roughly the same but less land is required. Even though the capital cost for a Minus7 system is higher for a single dwelling it has a reasonable capital cost when installed for several dwellings.

Since individual gas boilers is the most common way to heat your house in the UK today the research and public discussion tend to be focused on finding other individual replacements for gas boilers. As the results from this study have shown, it is very difficult for sustainable microgeneration technologies to compete with cheap gas boilers. An interesting aspect for further research could be to look into communal or council driven heating system such as district heating networks. As the results have shown a SAHP system are very efficient and environmentally beneficial, but it is not a financially viable option for single households.

According to Hill (2015) the Minus7 SAHP system is a heating solution that is not optimised for individual use but rather should be used as a “miniature” district heating system for 2-4 dwellings. Such communal solutions could be the way forward to make the UK energy system sustainable. In this study only small scale, “micro” CHP plants have been considered (as in the fuel cell mCHP). Large-scale CHP plants could be another option to make the UK energy system sustainable. In a large-scale CHP plant electricity and heat is generated and the heat is distributed locally in a district-heating network. A large-scale CHP plant can have total efficiencies of up to 95% compared to the 30 - 40% efficiency of the power plants currently in use. Building the infrastructure for district-heating networks could however become extremely expensive in the UK where virtually no district-heating networks currently exist.

The UK has had availability to an abundance of natural gas resources leading to the construction of the national gas grid, which is a likely reason why district heating networks have not been developed.

There are other heating technologies in use in the UK today besides individual gas boilers. Oil and electricity are also used for heating and in those cases the microgeneration technologies evaluated in the study might be more financially viable. Since electricity prices are around three times higher than gas prices, a more efficient electrified heating system such as a heat pump would be more economically beneficial for homeowners currently using a direct electric heating system. Oil has high GHG emissions and high operating costs and replacing oil based heating systems with heat pumps or fuel cell mCHP would be both environmentally and financially beneficial. But as 80% of the dwellings in the UK use gas boilers for production of heat the problem remains to be solved on how to be able to replace cheap gas boiler with a more sustainable alternative.
6.2 Limitations of the electricity grid

As can be seen from the results in the previous chapter there are environmental benefits to be gained if homeowners produce electricity from solar PV and mCHP plants (supply-driven electricity sources). But there are limits to how much supply-driven electricity the grid can handle. The current premise is that the electricity grid can handle 20 - 30 % supply-driven electricity without any major changes in infrastructure or management practices (Singer 2011). By combining supply-driven electricity sources with heat storage and heat pumps the amount of supply-driven sources the grid can handle can be increased (Lund and Münster 2006). Fuel cell mCHP is also a type of supply-driven electricity source since it is not centrally controlled and it can lead to an excess amount of electricity being produced at certain hours (more electricity is produced in the winter than in the summer and more during evenings and nights because the electricity production correlates with the heat demand).

6.3 Impact of assumptions made in the study

The energy demand used for calculations in this study is based on a model. The results from the study would have been more accurate if calculations were made based on energy demand in an actual house. The energy demand modelled in the CHM is however considered to be accurate enough to give trustworthy results, since it is based on the English Housing Survey. The English Housing Survey provides data for 14 951 representative dwellings and forms the base for the calculations in the CHM (Cambridge Architectural Research 2014). For a deeper understanding of the energy implications for different types of houses the case study could have included for example flats and social housing as well.

The microgeneration technologies included in the study use less energy than a gas boiler in all of the case houses and they are more environmentally friendly than a gas boiler. The running energy costs are lower as well. The capital costs are therefore main implication. The capital costs for microgeneration technologies highly depend on the conditions of the dwelling where they are installed and it is difficult to make accurate assumptions. The assumptions used in the study can be seen as rough estimates. The author does not believe that more accurate estimations of capital costs would have changed the results significantly. A gas boiler would have remained the cheapest option. However as microgeneration technologies mature and become more commercial and therefore cheaper they might be able to compete with a gas boiler. It is difficult to forecast how capital costs for microgeneration technologies will develop. They are expected to become lower in the future (according to the learning curve theory) but how much (and how quickly) the capital costs decrease will have a large impact on the financial viability of the technologies.

The financial calculations are based on the economic lifetime of the microgeneration technologies. Fuel cell mCHP currently has an expected economic lifetime of 14 years, compared to 20 years for the other technologies included in the study. Fuel cell mCHP is an emerging technology and as the lifetime increases fuel cell mCHP will become more financially viable. It is also assumed that a fuel cell mCHP needs a back-up gas boiler since

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8 The electricity production is determined based on the supply, i.e. when it is windy or when the sun is shining. Demand-driven electricity production is determined based on demand, i.e. the coal power plant runs during peak power when most people demands electricity for cooking, washing their clothes etc.
the capacity not yet is great enough to cover the energy demand of the houses. It is assumed that an existing gas boiler is used as back-up heating and therefore the cost for a new gas boiler is not included. As the technology develops the capacity of the fuel cell mCHP will increase and the need for a back up heating system such as a gas boiler will then be diminished.

The only costs included for lighting and energy efficient appliances were the cost for LED light bulbs. A suggestion for further research is to evaluate the costs for replacing existing appliances with the most energy efficient models available on the market, to review the payback time of replacing existing appliances.

An annual total amount of 75.6 TWh is used by appliances and cooking in the UK domestic sector, which accounts for 15 % of the total energy used in the UK domestic sector. Lighting accounts for 3 % of the total energy used in the UK domestic sector. The measures for lowering the energy used by appliances in this study is largely based on estimates and the potential to lower energy used by appliances is most likely far bigger than what is stated in this report. Previous studies, such as Palmer and Cooper (2014) and Palmer and Terry (2014), have tried to measure the energy used by appliances in English households and from that statistical data estimate potential savings in that area.

6.4 The methodology used

6.4.1 Literature review
The references used in this study consist of books, articles, information gathered from websites and reports from governmental establishments, organisations and research institutes. To back up an argument several references have been used in order to validate the argument made. The author believes the references used are trustworthy since they are either peer-reviewed articles or reports published by well-known, acknowledged institutions. The main implication of the references used is that the research regarding the UK energy system was often undertaken by the same researchers. The author would have wished to have a wider variety of studies available undertaken by different researchers.

6.4.2 Case study
The results of the study are heavily dependent on the specific data used in the case study. If different case houses were chosen the results would have been different. The author have been trying to make the case study as general as possible by only choosing microgeneration technologies that can be widely used in all of the UK and by choosing case houses based on the most common dwelling types in the UK. The author has consciously chosen case houses that had a small amount of energy efficiency measures installed to be able to calculate the impact energy efficiency measures had on the energy use in the case houses. The reason for using six case houses instead of only one is because the microgeneration technologies are heavily dependant on the specific conditions of an individual house. By choosing six different case houses it was possible to see the performance of the microgeneration technologies for several different situations.

6.5 Generalizability of the study
As mentioned previously the results of the study are heavily dependent on the type of case houses used. The results are also dependent on the situation in the UK. Several aspects, including energy prices and type of reference scenario, would be different if the study was performed in another country. The author however believes that the methodology used in the
case study, specifically the four steps described in Figure 8, are generalizable to other type of buildings in the UK domestic sector as well as non-domestic buildings and other countries.
7 Conclusions and recommendations

In this chapter conclusions will be made to see if the aim was achieved and the four research questions answered. Recommendations to ASC Renewables regarding business opportunities are made.

What energy innovations (technologies and measures) exist today that would help make individual homeowners use and supply energy in a sustainable manner without compromising their standard of living?

Two key areas have been identified where homeowners can be more sustainable without compromising their standard of living.

The first key area is applying energy efficiency measures. The UK housing stock is poorly insulated. Wall insulation (cavity and solid wall insulation) and loft insulation are the major improvements that can be made to a house to make it more energy efficient. Installing LED lighting, replacing existing appliances with energy efficient appliances and reducing standby power are three actions aimed at lowering the amount of energy used for lighting and appliances.

The second key area is microgeneration of heat and electricity. Solar assisted and air source heat pumps, fuel cell micro combined heat and power and solar photovoltaic (solar PV) are the microgeneration technologies available to homeowners today. All of those technologies are eligible for urban areas. Solar assisted heat pumps and air source heat pumps use the least amount of energy out of the heating technologies included in the study. Fuel cell micro combined heat and power (fuel cell mCHP) can be a good complement to heat pumps and enable demand-side management since it produces both heat and electricity. Solar PV is another option for microgeneration of electricity.

What are the environmental benefits and the economic feasibility of introducing the identified energy innovations (technologies and measures)?

Solar assisted heat pumps have the strongest environmental benefits, especially as greenhouse gas emissions from electricity production decreases. The environmental benefits of an air source heat pump is not as great as for a solar assisted heat pump but becomes greater as the greenhouse gas emissions from electricity production decreases. The capital costs for solar assisted heat pumps are too high at the moment unless it can be shared between several properties. Air source heat pumps have lower capital costs then the solar assisted heat pumps but use slightly more electricity than the solar assisted heat pump systems due to lower efficiency. The savings made are not enough to give a reasonable payback time for air source heat pumps at the moment. The Renewable Heat Incentive subsidy given for air source heat pumps is not enough to make it a profitable replacement for a gas boiler. Fuel cell mCHP has very high environmental benefits because electricity production from the fuel cell micro combined heat and power offset production of carbon intensive grid electricity. As the greenhouse gas emissions from grid electricity production decreases the environmental benefits from the fuel cell mCHP. The lifetime of the fuel cell mCHP technology needs to be extended before it becomes a realistic financial option.
Even greater environmental benefits can be gained by combining heat pumps and fuel cell mCHP with solar PV. Since production of grid electricity is carbon intensive, utilising solar PV can offset a lot of greenhouse gas emissions from electricity production, just like the fuel cell mCHP does. The payback time for solar PV alone is better than for the heating technologies because of the high levels of governmental support given.

Installing energy efficiency measures save energy, lower the influence on global greenhouse gas emissions (although not as much as when a sustainable heating technology is installed as well) and they have a reasonable payback time.

Despite the fact that the energy usage and greenhouse gas emissions decrease when using microgeneration technologies (scenarios 2-7) instead of using a gas boiler (scenario R) for all case houses, using a gas boiler is a more financially viable option. Installing energy efficiency measures and using a gas boiler (scenario 1) is the best option when energy usage, environmental impact and financial viability are all taken into consideration.

**How do governmental policies and human behaviour affect the environmental benefits and economic feasibility of the identified energy innovations?**

Governmental subsidies are essential to make the microgeneration technologies included in the study financially viable. The existing subsidies are not enough to make any of the heating technologies cheaper than a gas boiler. Great environmental gains can be made from all of the technologies and the numbers of sustainable heating technologies need to be increased if the UK is going to reach realise its vision of establishing a low carbon energy system. Affordability is a high priority for the Government when establishing a low carbon energy system, as mentioned already in chapter 1 of this report. However, as the results of this study show, energy efficiency measures such as installing LED lighting and loft insulation are the only affordable energy innovations available to homeowners today. The governmental support therefore needs to be increased to make the sustainable microgeneration options an affordable reality for UK homeowners.

It has been established that human behaviour has an impact on the amount of energy used. Demand-side management such as smart meter will enable people to get a better understanding of their energy usage and how to decrease it. Fluctuating electricity tariffs are financially beneficial for the heating technologies and would give incentive for homeowners to shift their gas and electricity usage away from peak times.

**Can any possible business opportunities be identified among the energy innovations for ASC Renewables to investigate further?**

Heating is the key area to address to create more sustainable homes since 65 % of the total energy used in the UK domestic sector is used for heating. The fuel cell mCHP technology has great environmental benefits but need more research and development before it will become a commercial technology. A communal solution such as the Minus7 solar assisted heat pump has major environmental benefits and low operating costs due to low energy usage but the capital costs are too high for a single dwelling. ASC Renewables should further investigate solar assisted heat pump systems as a potential business opportunity.
8 References


DECC. *Updated energy and emissions projections.* Department for Energy and Climate Change, 2014d.


