THE POTENTIAL IMPACTS OF MICRO-GENERATION AND LOW-CARBON HEATING ON DISTRIBUTION NETWORKS

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A thesis submitted for the degree of Master of Philosophy

University College London

March 2018

DECLARATION

I, Owain Jones, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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ABSTRACT

Micro-generation and low-carbon heat could potentially form part of the UK's decarbonisation strategy. This study examines the potential impacts of micro-CHP, solar PV and air-source heat pumps on distribution networks, using minute-scale electricity generation and demand data from field studies. These data are augmented by simulated data for a fuel cell micro-CHP profile, based on the heat demand of an average UK household. The value of using minute-scale rather than lower frequency data is more accurate information on peaks in household demand.

An analysis of the economic implications of micro-CHP concludes that micro-CHP would have to fall in price for it to be economically viable for the household. Moreover, emissions benefits are limited and prone to decline.

The supply and demand profiles of the various technologies were used with network design software (IPSA-Power), and models of real world distribution networks, to understand their potential impacts on distribution networks. Two sub-urban networks were analysed, with similar results, indicating the results can be generalised. For each minute of data, a steady state load flow analysis was performed in order to approximate a dynamic power system analysis.

Stirling engine micro-CHP has only minor impacts on the distribution network, principally through reducing power losses. Fuel cell micro-CHP can have considerable benefits through reducing losses and power flows, however one more than 60% of homes install fuel cell micro-CHP these benefits will be reduced. The other technologies tend to have greater detrimental impacts on networks through less frequent but greater voltage rise (solar PV), increased power flows (heat pumps) and increased losses (both solar PV and heat pumps). Micro-CHP can worsen the effects of solar PV and mitigate the effects of heat pumps if the technologies are deployed on the same network.

DEDICATION

This thesis is dedicated to my parents, for encouraging my curiosity and bookishness, and for all the support they have given me through the years.

ACKNOWLEDGEMENTS

I would first like to thank my supervisors, Paul Dodds and Paul Ekins, for their support. They have been there to provide me with advice and guidance throughout the process, and have provided me with much useful feedback on drafts of my thesis. As well as introducing me to contacts, and helping me to find useful data.

The thesis would not have been possible without the aid of colleagues at Durham University and Northern Powergrid, especially Robin Wardle and Peter Matthews. I spent three months at Durham University working with data from the CLNR project, which I was subsequently able to use in my thesis. Robin introduced me to, and provided me with guidance on, network modelling software, without which I could not have conducted much of the research in this thesis. They also provided me with the network models used within this thesis.

I would also like to thank TNEI for providing the IPSA-Power software, and for the training courses that they run on how to use it, both of which were of great aid to this thesis.

I would like to thank E.On for providing funding for this research.

Finally, I would like to thank my parents for providing me with support (and accommodation) through the final stages of this study.

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ABBREVIATIONS

Micro-CHP	Micro Combined Heat and Power
Solar PV	Solar Photo-voltaic
PU	Per Unit Voltage
FC	Fuel Cell(s)
DNO	Distribution Network Operator
CLNR	Consumer Led Network Revolution (Project)
ICE	Internal Combustion Engine
PCC	Pearson Correlation Coefficient
SOFC	Solid Oxide Fuel Cell
PEM(FC)	Polymer Electrolyte Membrane Fuel Cell
NPV	Net Present Value
ASHP	Air Source Heat Pump
GSHP	Ground Source Heat Pump
IPSA	Interactive power Systems Analysis

1 INTRODUCTION

The UK Parliament has legislated, through the Climate Change Act (2008), for an 80% reduction in CO_2 emissions from 1990 levels by 2050. It will be necessary to largely decarbonise domestic heating in order to meet this target (DECC, 2013). A commonly mentioned approach is to electrify heating, using low-carbon electricity (DECC, 2012, DECC, 2013, Staffell, 2014). However this approach could place a large and potentially costly additional burden on the electricity system (National Grid, 2011). Combined Heat and Power (CHP) potentially offers low-carbon distributed generation in communities, and smaller versions, named micro-CHP, have been developed for deployment within houses (Staffell, 2014, DECC, 2012). Combined Heat and Power is the cogeneration of both heat and electricity through the capture and usage of 'waste' heat from electricity generation processes. Other micro-generation or low-carbon heat technologies include solar PV and heat pumps.

Most installed CHP capacity provides energy to industries, and what little does serve domestic buildings is mostly in the form of large-scale CHP for district heating serving multiple residences, rather than in individual-dwelling micro-CHP (Hinnells, 2008). However, with the need to decarbonise heating, micro-CHP is a viable low carbon option, with its main competitors being District Heating (DH), heat pumps and boilers using low-carbon gas such as hydrogen or biogas. Micro-CHP has been in development for a number of years, with several field trials being carried out, especially in Japan, where full scale deployment has started (Staffell and Green, 2012, Staffell and Green, 2009).

The chapter will first provide background on: micro-CHP technologies (Section 1.1), solar PV and heat pumps (Section 2.2), and electricity distribution networks (Section 1.3). Then the thesis questions will be detailed in Section 1.4, and the novel contribution of the study will be summarised in Section 1.5. An outline of the rest of the thesis is provided in Section 1.6.

1.1 Background of micro-CHP

There are two primary groups of micro-CHP device. The first are those that generate electricity through combusting gas in engines. The second are those generate electricity in fuel cells. Of the former, the main technologies are Stirling engine and internal combustion engine devices, whereas of the latter, the main fuel cells used for stationary applications are Solid Oxide Fuel Cells (SOFCs) and Polymer Electrolyte Membrane Fuel Cells (PEMFCs or PEMs) (Hawkes et al., 2009).

1.1.1 Stirling engines

Stirling engines are a reasonably well established technology, using external combustion of fuel to drive a piston to produce electricity. A number of papers have claimed that Stirling engines will be the fastest growing micro-CHP device in the short term (Hawkes and Leach, 2005, Hudson et al., 2011, Alanne et al., 2010). The advantages of Stirling engines are: that they are more technically mature (Alanne et al., 2010); have a high overall efficiency (Hudson et al., 2011, Kuhn et al., 2008); can combust a variety of fuels, including petroleum and solid fuels (such as biomass) in addition to natural gas (Alanne et al., 2010, De Paepe et al., 2006); and that they can respond rapidly to load changes (Hawkes and Leach, 2005).

The main disadvantage is their low electrical efficiency (Staffell, 2009, De Paepe et al., 2006), however other papers have claimed that their low electrical efficiency is an advantage (Kuhn et al., 2008), as it leads to a high heat-to-power ratio more consistent with building demands, but other papers claim their high heat-to-power ratio (12:1) only makes them suitable for very large buildings (Carbon Trust, 2011), though other sources place the heat-to-power ratio as low as 5:1 (De Paepe et al., 2006). The emissions reduction of micro-CHP is claimed to be dependent on the amount of exported electricity (Hawkes and Leach, 2005), and Staffell (2009) has claimed that the low electrical efficiency of Stirling engines could increase emissions. A simulation of Stirling engine operation by Alanne et al. (2010) found no CO_2 mitigation, which would indicate that the low electrical efficiency is a disadvantage.

1.1.2 Internal Combustion Engines

Like Stirling engines, internal combustion engines also work on natural gas, but using internal rather than external combustion. While they have a higher electrical efficiency than Stirling engines, around 16-27% (Maalla and Kunsch, 2008, Possidente et al., 2006, Onovwiona et al., 2007), and consequently a better heat to power ratio, of around 3:1 (Cockroft and Kelly, 2006), leading to more exported electricity and thus better mitigation prospects, they also have a number of disadvantages. These disadvantages include noisy operation, regular maintenance of moving parts (Kuhn et al., 2008) and inflexibility of output, generally needing to operate at constant output (Staffell, 2009), and being unable to operate below half power (De Paepe et al., 2006). They also tend to have a higher power output, and are considered more applicable to larger buildings (Kuhn et al., 2008).

Despite the disadvantages, a number of papers include internal combustion engines in lists of potential domestic micro-CHP technologies (Maalla and Kunsch, 2008, Possidente et al., 2006, Onovwiona et al., 2007, De Paepe et al., 2006, Staffell, 2009, Kuhn et al., 2008). In fact, Onovwiona et al. (2007) consider them to be the prime mover of choice for micro-CHP applications, due to the well-proven technology, robust nature, reliability and reasonable cost, however many of these advantages could also apply to Stirling engines. Another advantage mentioned by Possidente et al. (2006) is their large electric power range; however, any output over $5kW_e$, with the heat-to-power ratios that ICEs have would produce more thermal energy than most UK homes need, making them only suitable for large buildings.

Their higher electrical efficiency compared with Stirling engines could be considered an advantage as mentioned earlier, but it is rarely listed as such in the literature. Also it is only when operating at full capacity that ICEs achieve electrical efficiencies greater than 20% (Onovwiona et al., 2007). Table 1.2 provides a summary and comparison of the efficiencies of Stirling engine, ICE and fuel cell micro-CHP. Due to their disadvantages, ICEs are not examined further in this study.

	Electrical efficiency	Thermal efficiency	Overall efficiency	Heat-to-power ratio
Internal Combustion	23%	58%	81%	2.5:1
Stirling	15%	75%	90%	5:1
Fuel cell	30-45%	55-45%	85-90%	1.8:1 to 1:1

Table 1.1 Overview of micro-CHP efficiencies in the literature. Data derived from values given in the literature (Staffell, 2009, Hawkes et al., 2009, De Paepe et al., 2006, Hawkes and Leach, 2005, Maalla and Kunsch, 2008, Kuhn et al., 2008, Possidente et al., 2006, Onovwiona et al., 2007, Spendelow et al., 2011).

1.1.3 Fuel cell micro-CHP

Unlike Stirling or internal combustion engines, fuel cells generate electricity through the chemical conversion of hydrogen, with waste heat being a by-product. Fuel cells have the advantage of having higher electrical efficiencies than gas fired micro-CHP, potentially as much as three times higher (Hawkes et al., 2009) which leads to lower heat to power ratios, of between 2:1 and 1:1 (Hawkes et al., 2011), noticeably lower than the ratio of heat-to-power demands in most properties (Staffell, 2009). But in the long term, the low heat-to-power ratios may be an advantage, as rises in insulation leads to lower heat demand, thus lowering the heat-to-power demand ratio in households and making them more suited to fuel cell micro-CHP (Hawkes et al., 2011).

Further advantages mentioned in the literature are the high overall efficiencies of fuel cells, which can reach 90% (Onovwiona and Ugursal, 2006). Fuel cells also have good part load characteristics, being able to maintain their high efficiencies at low power output (Hawkes et al., 2011, Onovwiona and Ugursal, 2006). Their lack of moving parts also makes fuel cells quieter than the mechanical, gas-fired, micro-CHP (Hawkes et al., 2009), while also lowering the maintenance costs, but the ancillary systems required by fuel cell micro-CHP would incur additional maintenance costs (Onovwiona and Ugursal, 2006).

The hydrogen fuel is normally produced from natural gas by a built-in reformer. Some fuel cells can run directly on natural gas, though this could reduce their lifetime (Staffell, 2009). The principal fuel cells used in stationary applications are Solid Oxide Fuel Cells (SOFCs) and Polymer Electrolyte Fuel Cells (PEMFCs), though others can potentially be used, such as Phosphoric Acid Fuel Cells (PAFCs), Molten Carbonate Fuel Cells (MCFCs), and Alkaline Fuel Cells (AFCs).

1.1.3.1 Solid Oxide Fuel Cells (SOFCs)

Of the various fuel cell types SOFCs are considered the best for stationary applications such as micro-CHP. The majority of the literature on fuel cell micro-CHP tends to mention both SOFCs and PEMFCs as potential micro-CHP prime movers, before going on to explain the advantages SOFCs have over PEMFCs, and focusing their research on SOFCs, but there are a few studies which claim PEMFCs are better suited to micro-CHP applications.

Advantages of SOFCs are their ability to internally reform hydrogen and higher tolerance of fuel impurities. This leads to lower fuel processing costs (Hawkes et al., 2009, Hawkes et al., 2011). The high operating temperature is also an advantage, leading to higher grade heat and more efficient heat transfers (Hawkes et al., 2009, Hawkes et al., 2011, Cockroft and Kelly, 2006). However, this higher temperature operation leads to more expensive material requirements, and greater sensitivity to thermal cycling, but this can be overcome by the increasing development of low temperature SOFCs (though still higher than other fuel cells, retaining the high grade heat benefits); such SOFCs could use a wider range of (cheaper) materials and are more resilient to cycling (Hawkes et al., 2011). Finally SOFCs tend to have higher electrical efficiencies than other fuel cells, theoretically up to 50% (Barelli et al., 2011, Aki, 2007, Cockroft and Kelly, 2006), but this could lead to a lower heat-to-power output, and the problems mentioned earlier as a result.

The main disadvantages are largely due to their high operating temperature, being unable to cope with rapid cycling, and the high cost of materials (Hinnells, 2008), however as mentioned above, these could be overcome by developments in low temperature SOFCs.

1.1.3.2 Polymer Electrolyte Membrane fuel cells (PEMs)

Despite much of the literature favouring SOFCs, PEMFCs are still a strong contender for a micro-CHP technology, with at least one major Japanese company using them in their ENE-FARM range of home fuel cell products (including micro-CHP) (Tokyo Gas, 2013), and, like SOFCs, they are the subject of intense commercial research (Staffell, 2009). PEMFCs have been demonstrated to have higher overall efficiencies than SOFCs, and under ideal conditions can match SOFCs in electrical efficiency levels (Barelli et al., 2011) (however it is doubtful these conditions would be found in most domestic residences). PEMFCs also have the advantage of being more resilient to thermal cycling than SOFCs.

However, PEMFCs also have significant drawbacks. First, they are much more sensitive to impurities than SOFCs, requiring more complex reforming and control systems to avoid fuel cell degradation, increasing the cost (P.Moçotéguy et al., 2009), further increasing the cost is the use of precious metal electro-catalysts, normally platinum, necessary to ensure high power output (Hawkes et al., 2011). Second, their lower operating temperature requires more complicated (and thus more expensive) heat recovery systems (P.Moçotéguy et al., 2009).

Some of these problems could be overcome through the development of high temperature PEMFCs, making them more tolerant to impurities and giving better heat outputs. But developments in this direction are less advanced than those towards low temperature SOFCs, and high temperature operation could bring other problems which can reduce output and hasten degradation (P.Moçotéguy et al., 2009).

1.1.3.3 Other fuel cells

In addition to SOFCs and PEMFCs, other devices such as PAFCs and AFCs could eventually see use in micro-CHP applications. Historically, there has been little interest in these technologies due to difficulties in overcoming the high manufacturing costs of PAFCs and the low lifetimes of AFCs (Staffell, 2009). However they potentially have higher tolerance for fuel impurities than SOFCs, and operate at temperatures that are higher than PEMFCs and lower than SOFCs (Staffell, 2009), which could make them well suited for micro-CHP applications if their difficulties could be overcome. MCFCs have been used for CHP, but only for large scale installations to date.

1.2 Other micro-generation or low-carbon heat technologies

1.2.1 Solar PV

Solar PV is another micro-generation technology. It generates electricity through the excitation of electrons by sunlight in semi-conductive materials (typically silicon). Solar PV installations will generate at least some electricity as long as there is sunlight, even if it is cloudy; though they will only generate their peak output in full sunlight, i.e. in the middle of a summer day.

Solar PV has seen significant uptake in the UK (and internationally). It benefited from strong feed-in-tariff support, though growth has continued even after reductions in FiTs. As of late 2017, the total installed capacity in the UK is over 12 GW (Staffell et al., 2017b), and 5.5 GW of this is domestic installations (Ofgem, 2017).

1.2.2 Heat pumps

Heat pumps are an alternative low-carbon single dwelling heat provider, they work by using electrical energy to move heat energy from a colder external environment into the dwelling. They are able to achieve effective efficiencies (or Coefficients of Performance, CoP) greater than 1, as the electrical energy is not converted into heat but rather used to tap external heat sources. Typical CoPs are in the range of 2-4 (DECC, 2013). There are two main types of heat pumps: air-source (ASHP), which take heat energy from the outside air; and ground-source (GSHP), which take heat energy from the ground.

The DECC Future of Heating report (2013) indicates that large scale replacement of gas boilers with heat pumps is likely to be the way forward; though it acknowledges that there are uncertainties over the future of heating, specifically over the extent of electrification of heating and the future role of the gas networks.

1.3 Electricity distribution networks

In the UK currently there is a transmission network that delivers electricity to 14 regional networks managed by 14 Distribution Network Operators (DNOs) owned by six companies (DECC, 2013). There are also six independent DNOs that run smaller networks within these, often for new housing developments. The regional networks are further divided into smaller distribution networks, with high-voltage transmission lines feeding into medium-voltage lines, which then feed into low-voltage distribution lines. Eventually these distribution lines will feed into a small low-voltage network of a few hundred homes fed by a single network transformer, which can have a rated capacity of 200 kVA to over 1 MVA (Lakervi and Holmes, 2003). It is networks such as this that are the focus of this thesis. These networks are currently designed for unidirectional power flows, and are optimised for current household demands. They are not optimised for the connection of large additional demands, such as heat pumps, or domestic micro-generation; either of these could cause disruptions to the network, such as voltage rise, increased losses or transformer overload (Infield et al., 2007, Thomson and Infield, 2007, Ackermann and Knyazkin, 2002, Castro et al., 2014, Rogers et al., 2013).

1.4 Research questions

One issue surrounding the deployment of micro-CHP are the uncertainties over price and economic viability (Staffell and Green, 2012, Tokyo Gas Co. Ltd. and Panasonic Corporation, 2011, Alanne et al., 2010, Ren and Gao, 2010), which in turn will lead to uncertainties over uptake and penetration rates. Another is that the deployment of micro-CHP could have significant impacts on electricity distribution networks (Ackermann and Knyazkin, 2002, Acha et al., 2009, Aki et al., 2006, Thomson and Infield, 2007, Rogers et al., 2013), due to the export of electricity from properties with micro-CHP installed. This impact could vary considerably, not only due to the uncertainty over micro-CHP uptake, but also due to a variety of different operating profiles for micro-CHP. Further to this it’s possible that micro-CHP could help alleviate the extra burden placed on the electricity networks by the electrification of heating.

The research questions that have been developed are:

- How might micro-CHP affect the cost of heating and greenhouse gas emissions from households?
- What impacts might micro-CHP have on distribution networks?
- How are these impacts likely to compare with those of solar PV and heat pumps?

- What are the consequences of deploying combinations of both micro-CHP and other technologies on the same distribution network?

The research questions are important because, to date, much of the studies into micro-CHP have largely focused on the impacts for a single household, generally in terms of carbon emissions or energy bill savings, and few have looked into the potential impacts on the energy system as a whole.

However, any impact is dependant primarily on the future uptake of micro-generation in the UK, hence the need for the first question on the list. As mentioned earlier there is still considerable uncertainty over how much of a role (if any) micro-CHP will play in the UK's energy mix. It is probable that uptake will depend primarily on two factors. First, the energy bill savings and overall economic benefit to the household; this will determine its future economic viability, which is especially vital if uptake depends solely on householder choice and economics. Second, on the extent to which it reduces carbon emissions, as this will make it more (or less) likely to be subsidised and will determine if it is a valid low-carbon technology.

The second question is concerned with the impacts that micro-CHP could have on distribution networks, which will manifest through reductions in demand from, and even exports of electricity to, the network(s) from those homes with micro-CHP installed. If significant amounts of electricity are exported, it could force distribution network operators to both change the way they operate, and to upgrade their existing distribution networks. The impacts will naturally be dependent on the uptake of micro-CHP examined in the first question. But there will also be other factors involved, including the heat profile of the homes with micro-CHP, operating profiles of micro-CHP, the heat-to-power ratio of micro-CHP (dependent on the type of micro-CHP used, and the future development of micro-CHP) and the heat-to-power ratio of the house. The heat-to-power ratio of micro-CHP, is known for existing micro-CHP devices that have been developed, and the heat-to-power ratios of future devices are largely predictable. The current heat profile of UK houses varies but these variations are predictable through gas consumption statistics. The operating profiles of micro-CHP are technology-specific. Engine-based micro-CHP would operate like existing boilers, causing large peaks in usage, potentially leading to large amounts of electricity being exported at these times. Fuel cell micro-CHP would operate at a constant low level of output, while a backup boiler would be used to satisfy peaks in heat demand from the household, leading to a constant low level of electricity output, which would in theory have much less impact on the distribution networks.

Once the potential export of electricity from homes with micro-CHP and the number of such homes is known this information would then have to be examined in the context of how distribution networks operate in order to determine the impacts upon them.

The third question is concerned with how the impacts of micro-CHP compare to those of other technologies. Solar PV, also being a micro-generation technology, would have similar impacts to micro-CHP on distribution networks; though its impacts would be felt most on summer days rather than at peak heating times. Heat pumps would place additional demand on distribution networks, which may also cause disruption.

The final question is concerned with how combinations of micro-generation technologies would impact a distribution network. It is expected that micro-CHP and solar PV could complement each other, as the former generates electricity primarily in winter, while the latter generates electricity on summer days. It is also expected that as micro-CHP is generating at times of peak demand, it could offset the additional demand of heat pumps.

1.5 Novel contribution of this study

The key novelties of this study are an examination of the effects of micro-CHP on distribution networks and the use of high-resolution minute-scale field trial data.

While there have been previous studies of the impacts on electricity networks of all three technologies mentioned here, they have all been either limited in scope, have used only simulated data or have used lower resolution data than used here. There have been studies that used minute scale data to analyse network impacts (Rogers et al., 2013, Thomson and Infield, 2007); however, the data was simulated, rather than taken from field trials as the data in this research is. The studies also only examined engine-based micro-CHP (alongside either heat pumps or solar PV). Castro et al. (2014) examined the impacts of solar PV using half-hourly field trial data, but only on the summer day of lowest load. To date the impacts of fuel cell micro-CHP on UK distribution networks have not been examined.

1.6 Thesis Outline

Chapter 2 examines the literature and existing research surrounding micro-CHP and distribution networks, providing a critical assessment of the literature and identifying gaps in the existing knowledge. Chapter 3 gives an overview of the data used in the research and provides the initial analysis into the economic and emissions reduction potential of micro-CHP; thus answering the first research question: 'How might micro-CHP affect the cost of heating and greenhouse gas emissions from households?' Chapter 4 details the methodology used in the examination of the impacts of micro-CHP on electricity distribution networks, giving an overview of the modelling software and how it was used to generate the results. Chapter 5 gives an analysis of these results, detailing the impacts that micro-CHP has on distribution networks; and thus answers the second research question: 'What impacts might micro-CHP have on distribution networks?' Chapter 6 gives further analysis of the results, examining how solar PV and heat pumps can impact networks, both on their own and in combination with micro-CHP; thus answering the final two research questions: 'How are these impacts likely to compare with those of solar PV and heat pumps?' and 'What are the consequences of deploying combinations of both micro-CHP and other technologies on the same distribution network?' Chapter 7 provides a summary of the research.

2 LITERATURE REVIEW

In this chapter, the current scientific knowledge surrounding micro-CHP is summarised and analysed. The contribution micro-CHP can make to decarbonisation is examined in Section 2.1 and the economic benefits for households that install micro-CHP in Section 2.2. Other micro-generation and low-carbon heating options are summarised in Section 2.3. The challenges micro-CHP, and other micro-generation or heating technologies, can pose for electricity distribution networks and previous research on the subject is discussed in Section 2.4. A summary and an outline of the research questions is given in Section 2.5.

2.1 Fuel sources for micro-CHP and its contributions to decarbonisation

This section examines the current state of three potential fuel sources for micro-CHP: natural gas; biomass/biogas; and hydrogen. It also looks at the potential contribution micro-CHP can make to decarbonisation of the energy sector.

2.1.1 Natural Gas

Almost all micro-CHP installed to date runs on natural gas. Despite this micro-CHP can still contribute to decarbonisation by avoiding the use of more carbon intensive grid electricity. Stirling engines appear to offer the poorest carbon savings, with both Carbon Trust (2011) and Staffell and Green (2012) estimating them at -4% to 12%, for a typical house, based on field trials, meaning it's possible that they could increase carbon emissions. Other figures for the carbon reductions of Stirling engines are within this range, but tend towards the higher end, such as in Peacock and Newborough (2005) with 10% carbon savings. However, this result is based on the modelling of Stirling micro-CHP, rather than household trials like the other papers. Internal combustion engines tend to have higher carbon savings, of around 12-21% (Carbon Trust, 2011), and fuel cells are higher still with a 16-40% reduction in carbon emissions (Peacock and Newborough, 2005). The large variance in the results is mainly due to the fact that micro-CHP can produce different carbon savings for different houses, depending on their heat consumption. The carbon savings of micro-CHP come from offsetting grid electricity through the generation of onsite electricity. The amount of electricity generated is dependent on the amount by which the micro-CHP is used, which is in turn dependant on the heat demand of the property. Thus large houses with high heat demand produce large carbon savings, while smaller houses produce fewer carbon savings.

However, many of the emissions reductions mentioned above are assuming current grid carbon levels, and as the carbon intensity of grid electricity falls, the carbon savings of micro-CHP will also fall, and eventually become negative. Hawkes et al. (2011) examined how emissions savings of SOFC micro-CHP and heat pumps are affected by grid carbon intensity, and produced the graph shown in Figure 2.1. They deduce that micro-CHP will provide better carbon savings than heat pumps until the marginal emissions factor of grid electricity is below 0.45 kgCO_2/kWh, and that it will provide at least some savings as long as the marginal emissions factor is above 0.2 kgCO_2/kWh. They go on to claim that the marginal emissions factor will remain above 0.45 kgCO_2/kWh until 2025, which seems likely, as the UK will probably still be using at least some natural gas. Peacock and Newborough (2005) also examine this and conclude that as long as the marginal emissions factor is above 0.33 kgCO_2/kWh, fuel cell micro-CHP will generate carbon savings. But the use of the marginal, rather than average, emissions factor in this case assumes that all of the grid carbon that is offset by the use of micro-CHP comes from natural gas (or coal), which may only be the case if it is generating electricity at peak times; this is particularly dubious for fuel cell micro-CHP which is better suited to providing baseload heat than to meeting peak heating demands (Hawkes et al., 2009).

Image not available in online version

Figure 2.1 Sensitivity of average CO2 reduction to the marginal emissions factor of grid electricity (Hawkes et al., 2011).

As Hawkes et al. (2011) only examined SOFCs, there is no indication in the literature of how Stirling and internal combustion engine micro-CHP is affected by the decarbonisation of the grid. Of course, this problem could be avoided if alternative carbon-neutral fuels were used by micro-CHP.

2.1.2 Bioenergy

Of the micro-CHP technologies mentioned in chapter 1 (Section 1.2), only Stirling engines can directly combust biomass, with both other technologies requiring gasification of biomass into biogas before utilisation (Dong et al., 2009). Biogas is a suitable fuel for SOFC micro-CHP, requiring only a reformer (similarly to natural gas) before it can be used, and could even be internally reformed (Farhad et al., 2010).

The supply of bioenergy, however, is by no means certain. One study suggests that bioenergy plays an important role across all sectors, but sets an import limit of 350 TWh, with the majority of this used in the transport sector, and just 5.5 TWh used for residential/service sector heat (Winskel et al., 2009). Another estimates that just 35 TWh of biomass could be produced domestically using unused arable land (with no mention of how much would go to meet heat demand) (Martınez-Perez et al., 2007). Compare these values with the annual gas use for domestic heating of 300 TWh (BEIS, 2016), and it implies that bioenergy can meet only a few percent of heat demand.

Meanwhile studies into conversion of the gas network provide differing information. One claims that bio-methane will be the main competitor to hydrogen in the long term, and will supply around a quarter of heat, even if the gas network is reconfigured to deliver hydrogen (Demoullin, 2012). Another study, which looks at the possibility of bio-methane injection into the gas network, suggests that long term only 6% of the gas supply could come from bio-methane, and that almost all of it would be used in industry (Dodds and McDowall, 2013).

Hence while bioenergy is a potential carbon-neutral fuel for micro-CHP, the literature throws considerable doubt the role it could play in meeting future heat demand.

2.1.3 Hydrogen

As mentioned in the discussion of fuel cells in chapter one (Section 1.1.3), they work by converting hydrogen to electricity and heat through chemical processes. Most fuel cell micro-CHP systems require a reformer to convert natural gas to hydrogen. If hydrogen were available directly, fuel cell micro-CHP could potentially be manufactured more cheaply as a reformer would not be required if the hydrogen purity were sufficiently high (Staffell and Green, 2012).

While hydrogen is widely used in industry, studies examining the future of the hydrogen, anticipate large scale production and distribution of hydrogen taking off from around 2035 or later (McDowall and Eames, 2007, Barreto et al., 2003, WETO-H2, 2006), it could start earlier if the price of carbon were high enough to justify it. Staffell et al. (2017a) outline several future energy scenarios, a number of which included widespread hydrogen use. They found that the use of hydrogen could be a more cost effective way of decarbonising heating than full electrification.

Hydrogen itself is not a primary fuel. Rather, it is an energy carrier that needs to be manufactured and is only low-carbon if the manufacturing lifecycle emissions are low. The most common methods are reforming or gasifying hydrocarbons, and electrolysis of water. The emissions from reforming and gasifying depend on the presence and efficiency of any carbon capture and storage (CCS), while the lifecycle emissions from electrolysis depend on the carbon intensity of the electricity supply. CCS systems will always emit some CO_2 while electrolysis is potentially near zero-carbon if the electricity is produced from renewable or nuclear generation.

Electrolysis is a mature technology, having been used for decades, and is currently supplying 4% of global hydrogen demand (Fuel Cell Today, 2012).

In most scenarios, the most common hydrogen production method is steam methane reforming of natural gas with CCS. Nuclear and renewables (generally large scale offshore wind) also play an important role, especially if hydrogen use is envisioned to be more widespread (WETO-H2, 2006, Dodds and Demoullin, 2012, McDowall and Eames, 2007, UKCCC, 2016, Staffell et al., 2017a).

Research has been done examining the potential of fully converting the UK gas network to carry hydrogen, using the UK MARKAL energy systems model. This research suggests that such conversion could take place from 2045 onwards, with replacement of the transmission network and upgrading of the distribution network (Dodds and Demoullin, 2012, Dodds and McDowall, 2013). In such a scenario, a substantial proportion of domestic heating (approximately 25%) is supplied by fuel cell micro-CHP, with much of the rest coming from heat pumps and some hydrogen boilers. This is one of the few future heating scenarios in the literature where micro-CHP would appear to play a major long term heating role.

2.1.4 Areas of uncertainty

From the literature examined in this section, it would appear there is still uncertainty over the household emissions savings resulting from the installation of micro-CHP, with most papers indicating a range of savings and limited field trial data. There is also uncertainty over how emissions savings will change as the gird is decarbonised. It may be beneficial for this thesis to conduct further research into the emissions reduction potential of micro-CHP. This leads to the latter part of the first research question: ‘How might micro-CHP affect the cost of heating and greenhouse gas emissions from households?’

2.2 Economics of micro-CHP

2.2.1 Broad factors affecting the economics and expected energy cost savings of micro-CHP

Installation of micro-CHP has the potential to reduce the costs of household energy bills. These savings occur as the result of energy efficiency improvements and the use of cheaper fuels in place of expensive grid electricity (Alanne et al., 2010). The most important driver of economic performance is the relative price of electricity to the fuel used (commonly known as the ‘spark gap’ for natural gas fuel) (Hawkes et al., 2011). These savings, like the decarbonisation contributions, can vary considerably, from €200 (£165) per annum (Alanne et al., 2010) to \$7900 (£4800) (Greene et al., 2011) (though the latter figure seems very optimistic, it also takes into account gas savings as well as electricity savings, while in theory gas use should increase with use of micro-CHP, also, in the UK a typical energy bill, even for a larger house, is £1500-3000). In the UK a study by Staffell and Green (2009) suggested that use of micro-CHP could increase household energy bills in 30%, due to the low value of exported electricity; but, that savings of £600-750 per annum were possible with a Feed in Tariff of 10 p/kWh, indicating a potential reliance on FiTs. In addition to FiTs, other factors affecting bill savings include the heat demand of the house (higher heat demand means more electricity generated) and the type of micro-CHP, with better electrical efficiency producing more savings (as these devices will produce more electricity).

In order to be economically feasible the capital investment in the micro-CHP system should be equal to (or lower) the cumulated savings during a suitable payback period (Alanne et al., 2010):

$$C_{I,\mu CHP} = \frac{(1+r)^n - 1}{r(1+r)^n} S_{\mu CHP} \qquad \textbf{3-1}$$

Where $C_{I,\mu CHP}$ is the maximum capital investment (or break-even price), $S_{\mu CHP}$ is the annual savings r is the real interest rate and n is the payback period. Most of the literature assumes a payback period of ten years, and a real interest rate of 2-5%. This combined with the range of savings above, gives us a range of ideal micro-CHP prices, from £1,300 to £37,000, using the initial range mentioned above (£165 to £4800). However, as has been mentioned, the upper value for savings might be unrealistically high. Some preliminary calculations, based on typical UK demands (DECC, 2011) suggest that the savings should be in the area of a few hundred pounds. Assuming an upper limit on savings of £750 as suggested by Staffell and Green (2009) (with a FiT of 10p/kWh), this gives us a smaller range of micro-CHP prices from £1,300 to £5,700, with Stirling engines towards the lower end of the scale and fuel cells towards the upper end.

2.2.2 Current and future costs of micro-CHP

Greene et al. (2011) provide a summary of costs in the US. Stirling and internal combustion engines are priced at $13,000 (£8,000) and $35,000 (£21,000) respectively, and fuel cell micro-CHP at $50,000 (£30,000). Dodds and Hawkes (2014) state that the cost of a 1 kW fuel cell micro-CHP device in Japan is between £13,000 and £17,000. All these figures are outside the cost range established earlier, which implies that for micro-CHP to be economically viable, costs will have to fall. However, lower costs have been estimated by the Sweett Group (2013), on behalf of DECC, who claim the cost of engine-based micro-CHP to be between £1,445 and £6,182 per kW, with an average of £3,258 per kW. Though these figures are for micro-CHP in the 10-20 kW size range, and from a limited amount of data. They also estimate a cost of £4,500 for fuel cell micro-CHP, though again from limited data.

Most of the literature on future costs focuses on fuel cell micro-CHP devices. This is presumably due to the fact that Stirling and internal combustion engines are mature technologies. Learning curves for fuel cell stacks can be difficult to estimate, due to the lack of historical data, and the inaccessibility of data on manufacturing costs due to the privacy of the companies producing them (Neij, 2008). Thus most studies assume a learning rate by basing it on historical price data. Two studies, both instigated by the US Department of Energy have attempted to predict and set targets for future fuel cell micro-CHP prices. One, conducted by Spendelow et al. (2011) based its projections comments from both stakeholders and the research community, it set a 2015 target of $1,200 for a 2kWe fuel cell micro-CHP system, and a 2020 target of $1,000. The other by Maru et al. (2010) based its conclusions on data from a panel of experts, and was independent of stakeholder predictions, it predicted that a 1 kW SOFC micro-CHP system would cost $1,000-3,000 in 2015, and $1,000-2,000 in 2020. Both sets of results are within the previously estimated cost range; however, given that fuel cell costs in Japan were still over £13,000 in 2014 (Dodds and Hawkes, 2014), it would seem these targets and predictions were inaccurate.

Staffell and Green, over two reports, use historical data for fuel cell micro-CHP prices, taken mostly from deployment in Japan under the Large Scale Residential Fuel Cell Demonstration Project (2005-2009) (Staffell and Green, 2009). They estimate, in their first report (Staffell and Green, 2009), that based on historic data that fuel cell micro-CHP has a learning rate of 17.5%, and that for targets to fall below £2,000 by 2025, a learning rate of at least 19% would be needed, which is unlikely to be achieved. Their subsequent report (Staffell and Green, 2012) was somewhat more detailed analysing both the fall in prices of individual fuel cell stacks and micro-CHP devices as a whole, giving a better indication of the driving factors of micro-CHP prices. They suggest that other optimistic price forecasts fail to take into account the full cost. This is due to them being based primarily on the falling prices of the fuel cells themselves and fail to account for the fact that the rest of the micro-CHP system (referred to as 'Balance of Plant') is a major cost which is unlikely to fall substantially in price as it is comprised of components that are technologically mature. The report suggests a realistic long term target of £2,300 /kW. A subsequent analysis by Staffell et al. (2017a) estimated the cost of fuel cell micro-CHP in Japan in 2020 to be £4,500 to £9,000. One final interesting suggestion that comes out of Staffell and Green (2012) is that 80% of the 'Balance of Plant' cost is due to the gas-to-hydrogen reformer, and that removing this could halve the total system cost.

Assuming annual savings of £750 and a ten year payback period, the break-even price of fuel cell micro-CHP would be £6,700. Subtracting each of the estimated, predicted or actual micro-CHP costs from this price would give a range of Net Present Values (NPVs) for micro-CHP, summarised in Table 2.1.

Source	Type of price	Micro-CHP price (£)	Net Present Value (£)
Greene et.al. (2011)	US prices at the time	30,000	-23,300
Dodds and Hawkes (2014)	Japanese prices at the time	15,000	-8,300
Sweett Group (2013)	Estimate of cost in the UK	4,500	2,200
Spendelow et. al. (2011)	US target for 2020 price	700	6,000
Maru et. al. (2010)	US prediction for 2020 price	1000	5,700
Staffell and Green (2012)	Realistic long term price target	2,300	4,400
Staffell et. al. (2017)	Prediction for Japan 2020 price	6,750	50

Table 2.1 Summary of prices for fuel cell micro-CHP. Listing the prices in the literature, and the resulting NPV assuming annual savings of £750 and a 10-year payback period.

2.2.3 Areas of uncertainty

The examination of the literature in this section indicates there is still uncertainty over the annual energy cost savings of micro-CHP technologies and over the future costs of micro-CHP. The thesis may be able to add to the existing body of research by further examining the economic savings of micro-CHP, and potentially estimating the required break-even price of micro-CHP technologies. This leads to the first part of the first research question: 'How might micro-CHP affect the cost of heating and greenhouse gas emissions from households?'

2.3 Other low-carbon heating and micro-generation options

2.3.1 Heat Pumps

GSHPs have been in use throughout North America and Europe for several years (Omer, 2008), and make up the majority of existing UK installations (Singh et al., 2010). They have an advantage over ASHPs in that the ground that they draw their heat from areas which are at an (approximately) constant temperature of 10 ^{o}C all year round, giving them a better performance in winter than the ASHPs which draw their heat from colder air. They are considered to be the most efficient form of heat generation, having a CoP of 3-4, with the greatest potential for carbon reduction (even before decarbonisation of the electricity supply) (Cockroft and Kelly, 2006). However, they are difficult to install, due to having to bury the pipes in the ground, and consequently have high installation costs of \$10,000-20,000 (£6,000-12,000) (Omer, 2008) and have, to date, been mostly restricted to new-build properties (Hewitt et al., 2011). A study of heat pumps in Germany indicated that GSHPs would have a CoP of around 4 (Miara et al., 2010). In UK field trials, GSHPs have performed poorly, with efficiencies of 2-3, and average efficiencies of 2.54 (Energy Saving Trust, 2013a) and 2.74 (after improvements in operation strategies) (DECC, 2014); a more recent field trial saw GSHPs achieve average CoPs of 2.77 in winter and 2.93 in summer (Love et al., 2017).

ASHPs have seen increasing uptake in recent years likely due to their lower price and ease of retrofit (Singh et al., 2010). However, they have a more variable CoP, which depends on the changing air temperature, and thus have the problem of low efficiency in the winter, when demand is at a maximum. It has been suggested that they are suitable for mild and moderate regions, including European maritime climates (which includes much of the UK), where the temperature seldom drops below 0 ^{o}C. Again, evidence from Germany indicates CoPs of around 3 (Miara et al., 2010). But, as with GSHPs, UK field trials produced poorer results, with CoPs between 1.5 and 2.5, with a mean of 2.16 (Energy Saving Trust, 2013a), 2.34 (after improvements in operation strategies) (DECC, 2014), and 2.41 in winter and 2.64 in summer (Love et al., 2017).

2.3.2 Solar PV

Solar PV is a well established distributed generation technology in the UK (and internationally). Despite this there is still variation in their estimated savings across different sources. Energy Saving Trust (2017) estimate economic savings between £260 and £305 per annum for a 4 kWp system, depending on location; while UK Power (2013) estimates £460 per annum for a 3.5 kWp system, and Which? (2018) estimate £292 per annum for a 4 kWp system. All of these are lower than some of the potential savings of fuel cell micro-CHP.

2.4 Challenges and opportunities facing electricity networks

Currently, distribution networks are not well suited for the connection of generation devices, largely due to the fact that the power-flow is radial and unidirectional, with no redundancy (Ackermann and Knyazkin, 2002). The networks are designed to supply energy to homes, not take it from them. But distributed generation can still be implemented, with the main advantage being that it reduces losses in the system. The optimal loss reduction scenarios involve situating distributed generation in ideal locations in the network (Acharya et al., 2006). However, as it is homeowners and not DNOs that decide if distributed generation is installed, there is no guarantee of it being situated in the best location.

Soroudi et al. (2011) propose a list of objectives for distributed generation: investment deferral in network capacity, loss reduction, reliability improvement, reducing cost, increasing investment incentives, reducing cost of energy not supplied, and emission reduction. Micro-CHP may be capable of fulfilling many of these objectives.

In addition to the above objectives for distributed generation, changes will have to be made in the operation of distribution networks in order to accommodate distributed generation. Distribution networks are currently managed passively, if distributed generation is to be incorporated without large overhead costs, it may be necessary for DNOs to switch to more active management of distribution networks (Currie et al., 2004). There was an EU project underway in Germany, DISPOWER, which aimed to develop an active management scheme. A paper on the project raises several issues of note (Donkelaar and Scheepers, 2004). It recognises that distributed generation can achieve some of the objectives mentioned in the last paragraph. But, it also states that the current passive network approach will provide major challenges in the future, and that there is need to look for more cost effective methods of network management, where distributed generation and distribution networks are more integrated. The paper also claims that the UK's ambitious distributed generation targets could incur substantial additional costs for reserve and balancing.

2.4.1 The challenge of electrifying heat provision

One of the most important areas where changes will occur as a result of a shifting energy paradigm is in the electricity networks themselves. The UK electricity system has rapidly varying dispatchable capacity that is capable of meeting demand. Current electricity demand has higher intraday variations than interseasonal variations. If heating is electrified, a large interseasonal peak demand will develop in winter, as heat demand is much higher than electricity demand, as shown in Figure 2.3. Even accounting for the fact that heat pumps generate 2 to 4 times as much heat as the electricity they use, this could lead to the overloading of the electricity network unless major upgrade works are initiated.

Image not available in online version

Figure 2.2 Daily UK Heat Profile (DECC, 2012).

UKCCC (2016) have suggested that the full electrification of heating may not be cost-effective, even with the reduction in energy requirements brought on by heat pumps with a high Coefficient of Performance. Some studies, such as Rogers et al. (2013), have suggested that the additional generation from micro-CHP could be used to support the operation of heat pumps. The electrification of transport, also examined by UKCCC, could cause further problems for the electricity network.

2.4.2 Advantages and issues of micro-CHP

A potential advantage of using micro-CHP is that it can work well in conjunction with heat pumps (Rogers et al., 2013). If micro-CHP operation is heat-led, then it should generate electricity at the same time that heat pumps are drawing electricity from the network. Therefore, when there is a large peak in electricity demand due to heat pumps, there will be a peak in the electricity being supplied by micro-CHP. This will help alleviate the need for additional reserve capacity in the network, while also, depending on where the micro-CHP is located in relation to the heat pumps, reducing the need to upgrade the network to provide additional heat capacity.

Another possible advantage of micro-CHP (and other distribution technologies, such as solar PV) is in reduction of losses on the network (Acha et al., 2009, Ackermann and Knyazkin, 2002). Generation of energy locally means less electricity needs to travel through the wires of the network, where losses can occur.

One potential drawback of micro-CHP (and other micro-generation technologies) is that large amounts of locally generated electricity could lead to instances of voltage rise on the network (Infield et al., 2007, Thomson and Infield, 2007). Voltage rise is defined as voltages on the network rising to levels outside of legal limits.

2.4.3 Previous studies involving micro-generation and networks

Acha et al. (2009) examine the impacts of including micro-CHP and charging of hybrid vehicles on a network. They used an optimal power flow tool, which coupled the gas and electricity networks via the micro-CHP, to analyse the network on an hourly timescale, using simulated data. The study examined two scenarios, a ‘plug and forget’ scenario where use of CHP and charging of vehicles happened whenever the owners wished, and ‘loss minimisation’ which provided incentives for operating CHP and charging vehicles at optimal times. In both scenarios operation of micro-

CHP was heat led, and the paper concluded that the CHP power injections were substantial in reducing peak load.

Another paper looked at the use of micro-CHP plants to support the local operation of electric heat pumps, studying a housing development of 128 dwellings supplied by a 200 kVA transformer, using simulated minute-scale data (Rogers et al., 2013). It identified the problem of heat pumps adding 3-6 kW of demand per house for distribution transformers designed to handle 1.4-9.8 kW per house, thus there was a distinct possibility of overloading the supply transformer, and the results showed that if more than 16 dwellings installed heat pumps (with no CHP), the transformer would overload. The technologies used were air source heat pumps, Stirling engine micro-CHP and large and small internal combustion micro-CHP. The study did not examine fuel cell micro-CHP. The results of the study showed that the best combination of technologies was small IC micro-CHP and heat pumps, with 48 of the former and 80 of the latter, thus supplying all the homes and achieving a carbon saving of 38.6%; however, this was assuming 2012 grid carbon emissions.

Several studies look at the optimum placement of distributed generation (both micro-CHP and other technologies) on the network in order to minimise losses or to best affect voltage levels (Acharya et al., 2006, Quezada et al., 2006, Acha et al., 2009, Rao et al., 2013). The issue with this focus on placement is that there is no real mechanism by which either DNOs or government can dictate where on a network micro-CHP (or other micro-generation) may be placed.

Some papers (Ackermann and Knyazkin, 2002, Acha et al., 2009) indicate that one of the main ways that micro-generation can affect distribution network operations is through reducing network losses. Both papers focus on developing equations relating distributed generation and total network load to network losses, and estimating the loss reduction at times of peak generation and demand.

Other papers such as Infield et al. (2007) and Thomson and Infield (2007) suggest the impacts on voltage levels will be a key concern of micro-generation, particularly voltage rise (i.e. where voltage levels rise above regulation limits). UK regulations stipulate that voltage levels should remain within 94% and 106% of the rated voltage (National Grid, 2004); though there is some leeway (as long as the network does not spend more than 10 minutes at a time above outside these limits there is no cause for concern).

Ocha et al. (2006) used a multi-objective index to examine network impacts. this index consisted of four parameters: real and reactive power losses, instances of voltage drop (and rise), the current capacity of conductors, and instances of short circuit. Each parameter was weighted according to its potential impact, with losses receiving the highest weighting, followed by instances of voltage drop/rise. The network was examined at maximum and minimum periods of demand.

A subsequent paper (Ocha and Harrison, 2011), examining how to minimise network losses, asserted that simply examining power losses at times of maximum and minimum demand fails to account for the impact of variable distributed generation output. They demonstrate that such an approach can both over- and under-estimate overall energy losses depending on the size of the distributed generation. In order to get a full picture of how variable distributed generation affects energy losses it is necessary to undertake a multi-period optimal power flow analysis, in this case of hourly periods over the course of a year. In this paper the distributed generation under consideration was micro-wind turbines.

Thomson and Infield (2007) used minute-scale simulated data of Stirling engine micro-CHP and solar PV to estimate their impacts on the network through load flow analysis. They find that two scenarios, where 100% of homes have micro-CHP and where 50% of homes have solar PV give rise to voltages in excess of regulations.

Castro et al. (2014) used half-hourly field trial data to examine the impacts of solar PV on electricity voltage levels. They did this by using load flow analysis to examine the impact of solar PV on maximum voltage levels during the summer day of lowest demand. They found that more than 30% of the network having solar PV would cause voltage rise issues.

2.4.4 Areas of uncertainty

While there have been a number of studies that have investigated the potential impacts of micro-generation and low-carbon heating on electricity distribution networks, to date there have been few that have used real world field trial data. The only study listed here that did limited its examination to solar PV, and used only half-hourly data, rather than the minute-scale data, utilised in several of the studies that used simulated data. Most studies referenced here also only examined one part of the potential impacts, either voltage levels, network losses, or transformer power flows. One study did examine both voltage levels and network losses, but there is still a lack of a comprehensive analysis of all the potential impacts of micro-CHP on distribution networks. All the studies here that did examine the impacts of micro-CHP only examined the impacts of engine-based micro-CHP, none have examined the impacts of fuel cell micro-CHP. There is clear need for further study into all the impacts of micro-CHP on distribution networks, along with those of solar PV and heat pumps, using high-resolution real world data. This drives the choice of the last three research questions: 'What impacts might micro-CHP have on distribution networks?', 'How are these impacts likely to compare with those of solar PV and heat pumps?' and 'What are the consequences of deploying combinations of both micro-CHP and other technologies on the same distribution network?'

2.5 Chapter Summary

This chapter has examined the literature around micro-generation, low carbon heat, and distribution networks. It has found that there is uncertainty over the economic benefits of micro-CHP, and the emissions reduction potential of micro-CHP. It is possible that further research in the area will contribute to the body of scientific knowledge on these issues.

There are a number of ways in which micro-generation and low carbon heat can impact electricity distribution networks. Heat pumps may place a considerable additional electrical burden on electricity networks, which may be mitigated by the presence of local generation from micro-CHP devices. Both micro-CHP and solar PV could benefit the network through reducing losses; however, both could cause problems to the network through raising voltage levels.

To date there have been a few studies examining the impacts of micro-generation and low-carbon heat on distribution networks, though all but one have used simulated data, and looked at a limited range of technologies and impacts. The one study that did use field trial data used only half-hourly data, rather than high frequency minute-scale data, and only examined solar PV and its impacts on voltage levels. None of the studies have examined the impacts of fuel cell micro-CHP.

There is still some uncertainty over the economic and emissions reduction potential of micro-CHP, and considerable uncertainty over the distribution network impacts of micro-generation and low-carbon heat. To address these uncertainties, four research questions were devised:

- How might micro-CHP affect the cost of heating and greenhouse gas emissions from households?
- What impacts might micro-CHP have on distribution networks?
- How are these impacts likely to compare with those of solar PV and heat pumps?
- What are the consequences of deploying combinations of both micro-CHP and other technologies on the same distribution network?

3 INITIAL DATA ANALYSIS

This chapter contains the details of the field trial data used throughout the thesis. It also contains: an examination of the benefits of using high frequency minute-scale data, an analysis of the correlation between micro-CHP generation and household demand, and an analysis of the economic and emissions reduction benefits of micro-CHP.

3.1 Chapter Introduction

The aims of this chapter are to present the data that will be used throughout the thesis, and perform some initial analysis on that data. The analysis will have four purposes: first, to demonstrate the higher information value of minute-scale data over ten-minute or half-hourly data; second, to examine how well micro-CHP generation correlates to household demand, as the more likely it is that micro-CHP will be generating at peak times, the more useful it is (from an economic, emissions, and network perspective); third, to examine the emissions reductions that occur as a result of micro-CHP; and fourth, to examine the economic benefit, to the household, of installing micro-CHP. The last three of these will contribute to answering the first research question: 'How might micro-CHP affect the cost of heating and greenhouse gas emissions from households?'. There will also be a brief examination of the economic and emissions reduction benefits of installing solar PV and heat pumps in the household, in order to compare micro-CHP against those technologies.

The methodologies used in this chapter are outlined in Section 3.2, while the data being used throughout the thesis is summarised in Section 3.3. A comparison of one-minute data with lower frequency data is presented in Section 3.4. The correlation of micro-CHP generation to household demand is analysed in Section 3.5, the emissions savings of micro-CHP in Section 3.6, and the economic savings in Section 3.7. Section 3.8 compares the results with those in the literature, and Section 3.9 provides a summary of the chapter.

3.2 Chapter methodologies

3.2.1 Comparing different resolution data

The data used in this analysis (summarised in Section 3.3) was high-resolution minute-scale data. In order to demonstrate the benefit of using high-resolution data, it is compared against lower resolution data; specifically ten-minute and half-hourly data. The lower resolution data was generated by aggregating the one-minute data. Two simple Python scripts were developed that went through the data and provided an average generation or demand value for every half-hour and ten-minute period. This data was then compared against the one-minute data in order to determine the amount of information lost when aggregating the data. The data was compared for a random day in each month, on order to test if there were significant differences in the effects of aggregation throughout the year.

3.2.2 Correlation of generation to demand

The correlation of generation to demand is examined using the Pearson correlation coefficient, defined as:

$$\rho_{X,Y} = \frac{cov(X,Y)}{\sigma_X \sigma_Y} \qquad \textbf{3-1}$$

The coefficient gives an indication of the correlation between two sets of data. The coefficient is a value between -1 and +1; with +1 being perfect positive correlation, -1 being perfect negative correlation and 0 being no correlation. In addition, there is an examination the proportion of generated electricity that is exported instead of being used in the household, and how micro-CHP changes the household's grid electricity demand profile. This is shown through frequency histograms of generation, export and adjusted grid demand (i.e. how much electricity households take from the grid after taking micro-CHP generation into account, also referred to as household electricity import) are produced. This is to show how micro-CHP reduces the number of high demand periods, and how often the use of micro-CHP results in high levels of export. Also examined is the average daily demand and generation profiles for the winter and summer months, to get an idea of how well micro-CHP matches household demand and by how much it reduces peak demand.

3.2.3 Calculation of economic and emissions savings

To calculate the economic and emissions savings of micro-CHP, it is necessary to compare the cost and benefits (either monetarily or emissions-wise) of micro-CHP to the cost of generating an equivalent amount of heat and electricity from a standard boiler and the electricity grid. The most straightforward way to calculate this is to compare the heat output and the gas used by the micro-CHP unit to a counterfactual regular boiler (with a heat efficiency of 0.9). The heat output is calculated by multiplying the generated electricity by the heat to power ratio (6:1 in the case of the Stirling engine, 1:1 in the case of the fuel cell):

$$\begin{aligned} &Heat\ Generated\ by\ microCHP\ (kWh) \\ &\quad = Electricity\ Generated\ by\ microCHP\ (kWh) \\ &\quad * Heat\ to\ Power\ ratio\ of\ microCHP \end{aligned} \qquad \textbf{3-2}$$

The gas used is calculated by dividing the heat output by the thermal efficiency (0.77 for the Stirling engine, 0.45 for the fuel cell):

$$Gas\ used\ by\ microCHP\ (kWh) = \frac{Electricity\ Generated\ by\ microCHP\ (kWh)}{Electical\ efficiency\ of\ microCHP} \qquad \textbf{3-3}$$

The micro-CHP unit will use more gas than the boiler but also generates electricity; this extra gas consumption is effectively used to generate the electricity output:

$$\begin{aligned} &Effecitve\ gas\ used\ to\ generate\ microCHP\ electrical\ output\ (kWh) \\ &\quad = Total\ gas\ used\ by\ microCHP\ (kWh) - Gas\ used\ by\ boiler\ (kWh) \end{aligned} \qquad \textbf{3-4}$$

Where the gas used by the boiler is simply the heat output divided by the boiler efficiency of 0.9.

The emissions associated with the generated electricity can be calculated by finding the emissions caused by the extra gas used. These emissions can then be compared to the emissions associated with generating the same amount of grid electricity, to find the overall emissions savings resulting from micro-CHP:

$$\begin{aligned} &Emission\ savings\ (gCO2) \\ &\quad = microCHP\ Electricity\ Generation\ (kWh) \\ &\quad * Grid\ Carbon\ Level\ (gCO2/kWh) - Extra\ Gas\ Used\ (kWh) \\ &\quad * Carbon\ intensity\ of\ gas\ (gCO2/kWh) \end{aligned} \tag{3-5}$$

For the purposes of calculating the economic benefit, the electricity used by the household is separated from that exported (as these have different economic values). This is done comparing the electrical output against the household demand for each minute of the year. Any time the generated electricity is greater than the household demand the excess is exported, and the total exported electricity is the sum of the exported electricity for each minute of the year. The electricity used in the house will be the total electricity generated less the electricity exported, and the economic benefits will be the economic gain (from avoided imports of grid electricity and tariff income) minus the cost of the extra gas used, like so:

$$\begin{aligned} &Annual\ Monetary\ gain\ (£) \\ &\quad = Avoided\ grid\ import\ (kWh) * Price\ of\ gird\ electricity\ (£/kWh) \\ &\quad +\ Total\ electricity\ generated\ (kWh) * Generation\ tariff\ (£/kWh) \\ &\quad + ELectricity\ exported\ to\ grid\ (kWh) * Export\ tariff\ (£/kWh) \\ &\quad - Extra\ Gas\ Used\ (kWh) * Price\ of\ gas\ \ (£/kWh) \end{aligned} \tag{3-6}$$

3.3 Summary of the Data

The generation profiles of Stirling engines and the demand profiles of households have been taken from in-house measurements, from a field trial conducted by the Consumer Led Network Revolution project, which was co-funded by Ofgem’s Low Carbon Network Fund and by an electricity distribution network operator, Northern Powergrid. British Gas, EA Technology, Durham University and Newcastle University were also involved (CLNR, 2014).

The CLNR project conducted separate field trials (referred to in the project as 'test cells') of a number of technologies, including Stirling engine micro-CHP, solar PV and heat pumps. Test cell 4 trialled micro-CHP, while test cells 3 and 5 trialled heat pumps and solar PV respectively.

Test Cell 4 of the CLNR project was comprised of 11 domestic locations where micro-CHP units have been installed. The micro-CHP unit is a Baxi Ecogen Stirling engine, with a maximum heat output of 6 kW, a maximum electrical output of 1kW, and an overall efficiency of 90% (Baxi, 2010), producing a heat to power ratio of 6:1, an electric efficiency of 13%, and a heat efficiency of 77%. The homes also contained a secondary boiler to provide additional heat output if required.

For test cell 4, trial monitoring began in December 2012 and ended in March 2014. The trial monitoring data was collected by British Gas. At each location, two parameters were measured: the electrical consumption and generation of the micro-CHP engine, and the amount of electricity imported (or exported) from the grid by the house as a whole. These parameters were measured in average Watts generated, or consumed, for each minute.

Data completeness varied across the 11 locations, which included 8 semi-detatched homes, 2 detached homes and 1 terraced home. Figure 3.1 summarises the data completeness of each location over the monitoring period.

It can be seen that one of the locations (1) does not have any household import data. Most of the other locations have data for varying periods between November 2012 and March 2014. Some locations have notably less data than others, such as 3 and 10, and on closer inspection, a substantial amount of the data is missing, with data for these locations being 79% and 33% complete respectively, location 8 also only has six months of whole house import data; because of the incompleteness of the data these locations have been excluded from the analysis.

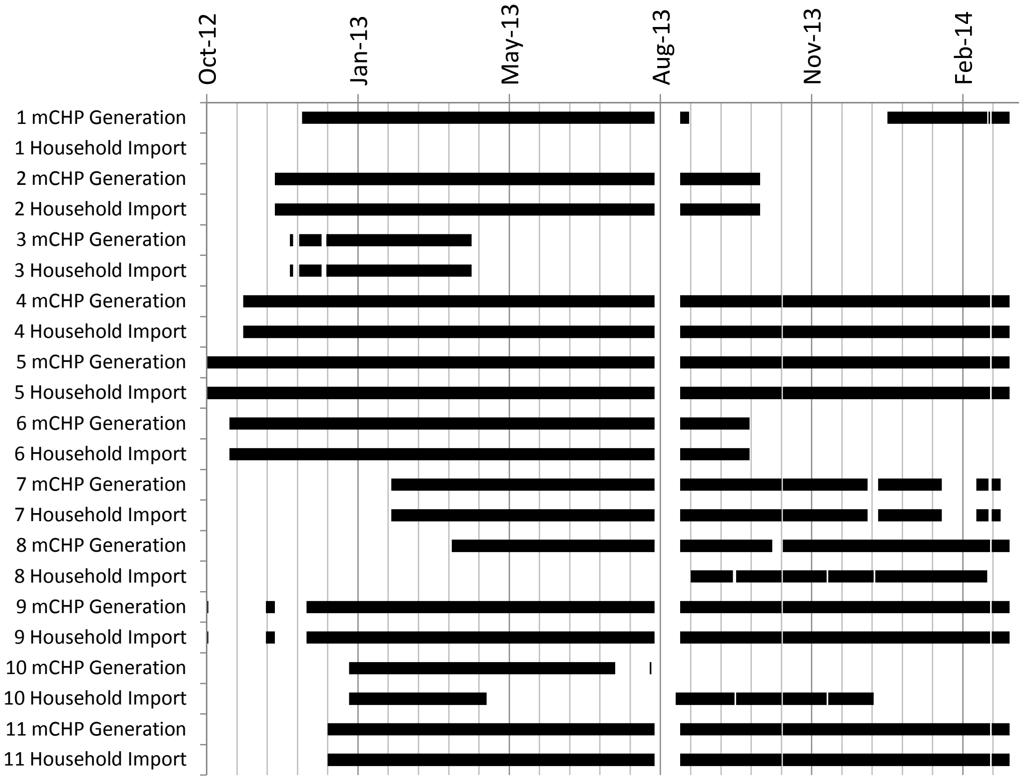

Figure 3.1 Availability of field trial data over time. The black bars show the periods for which data is available.

A total of seven locations were available to be studied, summarised in Table 3.1

Trial Participant Reference	Data Availability
2	November 2012 – October 2013
4	December 2012 – March 2014
5	November 2012 – March 2014
6	November 2012 – October 2013
7	February 2013 – March 2014
9	December 2012 – March 2014
11	January 2013 – March 2014

Table 3.1 Trial locations used in the analysis, and the dates for which data is available.

In each data set there were occasional minutes where data was missing. In these cases the data was estimated by taking the average over the data for that time period for every other day in the month. For example, if data for Wednesday 19th June, at 20:04 was missing, the data would be estimated by averaging over the data at 20:04 on every other weekday in June. If the missing data point had occured on a Saturday or Sunday, the data for all other weekend days in the month would be averaged over. It was felt that other weekdays or weekends in the month would have the most similar daily demand or generation profile, and thus would provide the best estimate.

Every data set was missing six days of data in August. These were estimated by averaging over the existing August data, in the same way as outlined above.

For privacy purposes, it was not possible to use or show the individual household profiles in this research, therefore only the average data over all loactions is used. This data is shown in full in Figure 3.2.

The experimental data was compared against the demand data for an average house, in order to test its validity. Figure 3.3 shows (for January only, but the similarity holds for other months), that the average heat generation profile of the Stirling engine micro-CHP in the trial is similar to that of an average house, though with lower values. This would be due to the fact that the Stirling engine is not providing all the heat for the homes in the trial, some is provided by a backup boiler.

The overall electricity demand was also compared against the national average. the average total annual household demand of homes in the trial was 4,400kWh. According to government statistics, the average household demand in 2013 (the year of the trial) was 4,300kWh (in subsequent years the demand has declined slightly to just under 4,000kWh) (BEIS, 2017). Given that the national average of household demand is similar to that in the trial, it would be reasonable to assume that the homes in the trial represent the national average.

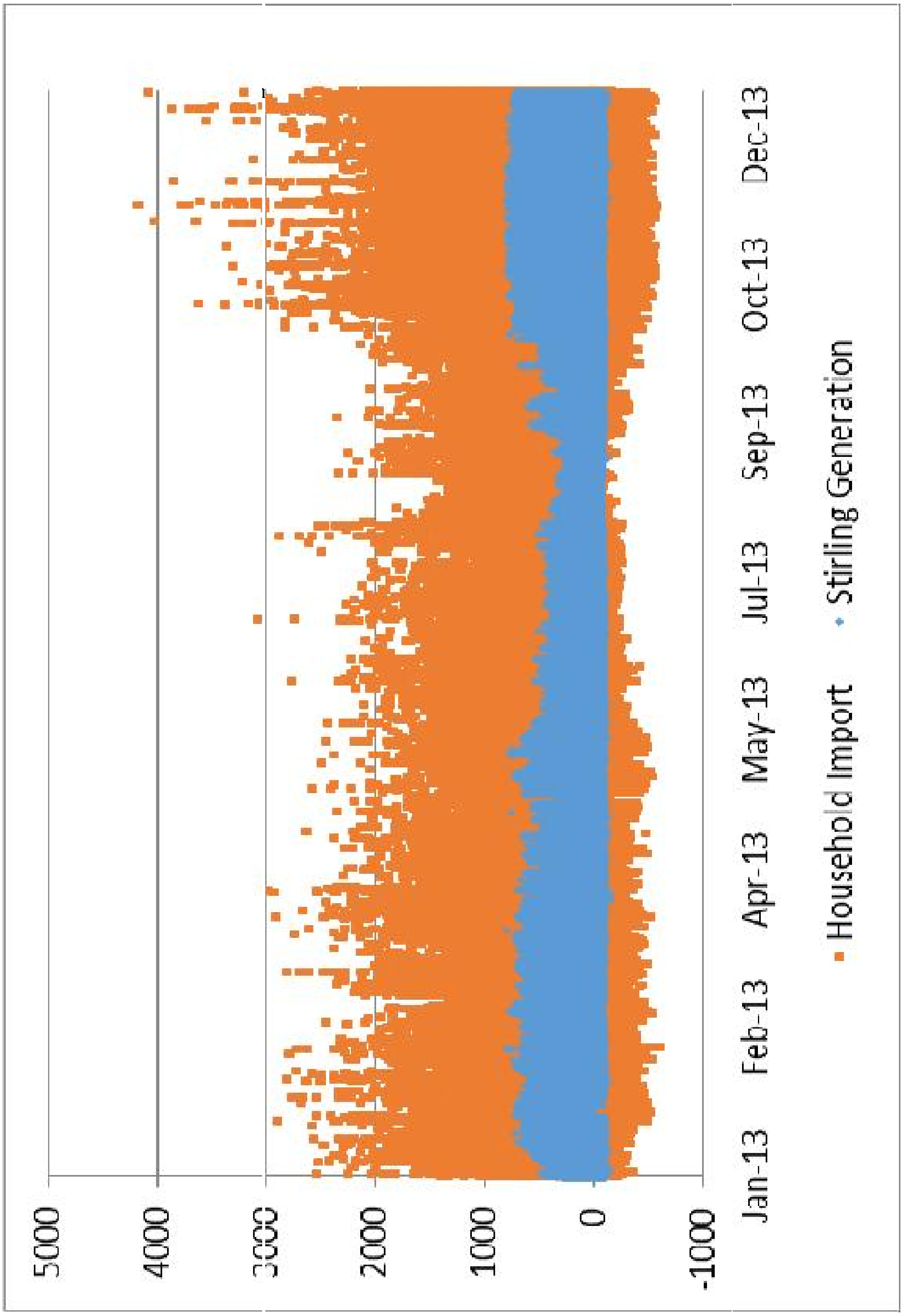

Figure 3.2 Stirling engine generation and household import, averaged over all locations in the field trial, for each minute of 2013.

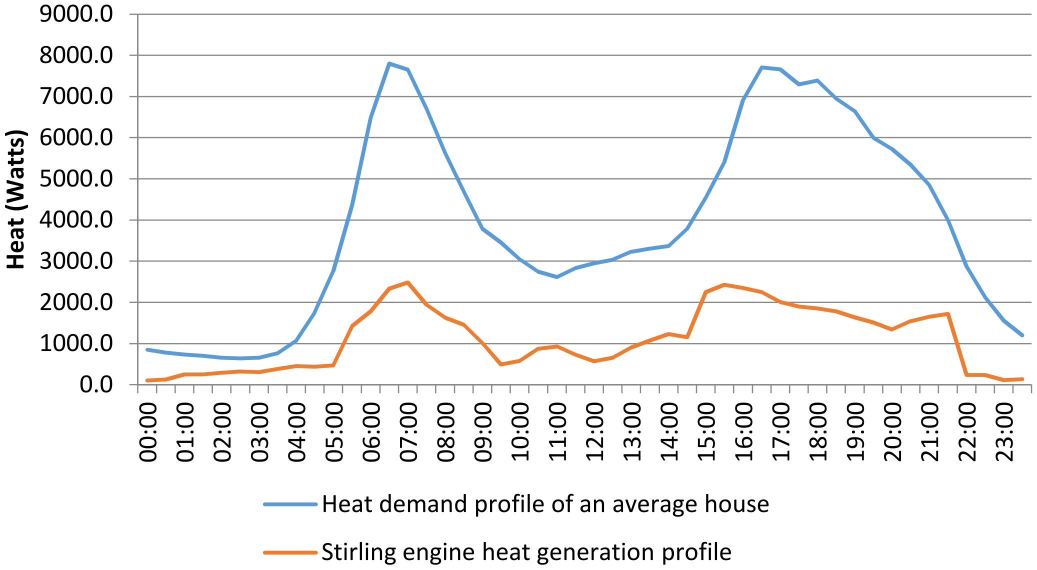

Figure 3.3 Comparison of Stirling engine generation against average heat demand. Here the heat output of the Stirling engines in the trial is compared against that of a typical UK house (Summerfield et al., 2015), for an average January day.

Test cell 3 trialled heat pumps in 89 homes, and test cell 5 trialled solar PV in 155 homes (CLNR, 2015). As with test cell 4, these trials measured generation and demand data minutely, and the average data over all homes is used in this research.

3.3.1 Development of fuel cell micro-CHP profiles

While the field trial was limited to Stirling engine micro-CHP, it is possible to estimate the profile of other micro-CHP technologies. Fuel cells will operate rather differently from Stirling engines, as frequent on/off cycling, as seen in the Stirling engine profiles will cause degradation and reduce the operational lifespan. Therefore, their operational profile will need to be one that stays on for long periods in order to meet baseload heat demand. In this research it is assumed that fuel cell micro-CHP would operate continuously for long periods of time, several hours per day, if not all day, in order to provide base-load heat.

Using a profile of UK heat demand in average homes (Summerfield et al., 2015), is it possible to estimate the demand profile for a 1 kW fuel cell micro-CHP device (see Figures 3.4 and 3.5). The fuel cell runs at full power (1 kW) during the months of January to April, and October to December. Between May and September, the fuel cell operates in essentially two modes. Between 03:50 and 21:40 the fuel cell generates at full capacity (1 kW) or half capacity (0.5 kW) in July and August, and between 22:20 and 03:10 it produces no output. There are two transitionary periods (03.10-03.50, and 21.40-22.20) separating the on/off phases. These operational profiles are such in order to best match the heat demand profile. The generation profile used for the fuel cell does result in some excess heat production, though it is assumed that the houses in question would have water tanks in which hot water can be stored, and then used at peak times. The amount of storage needed to accommodate the excess heat was calculated to be equivalent to a 30-litre hot water tank, which is considerably smaller than most domestic hot water tanks. The electricity demands of a house with fuel cell micro-CHP were assumed to be the same as those in the Stirling engine field trial (where the electrical demand is the sum of the measured micro-CHP generation and electricity imported from the grid).

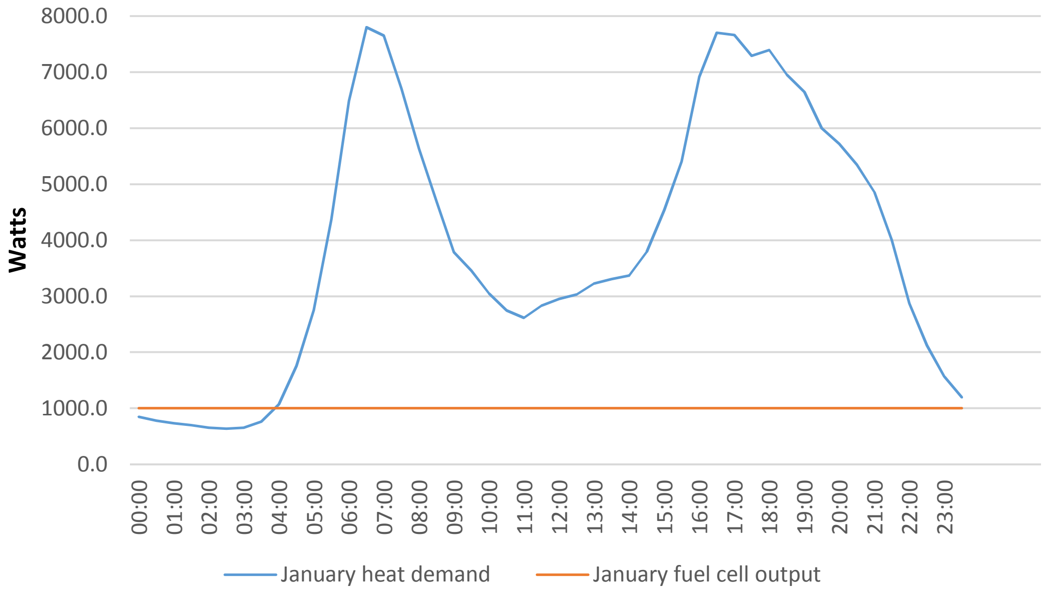

Figure 3.4 January fuel cell heat generation compared with average daily heat demand.

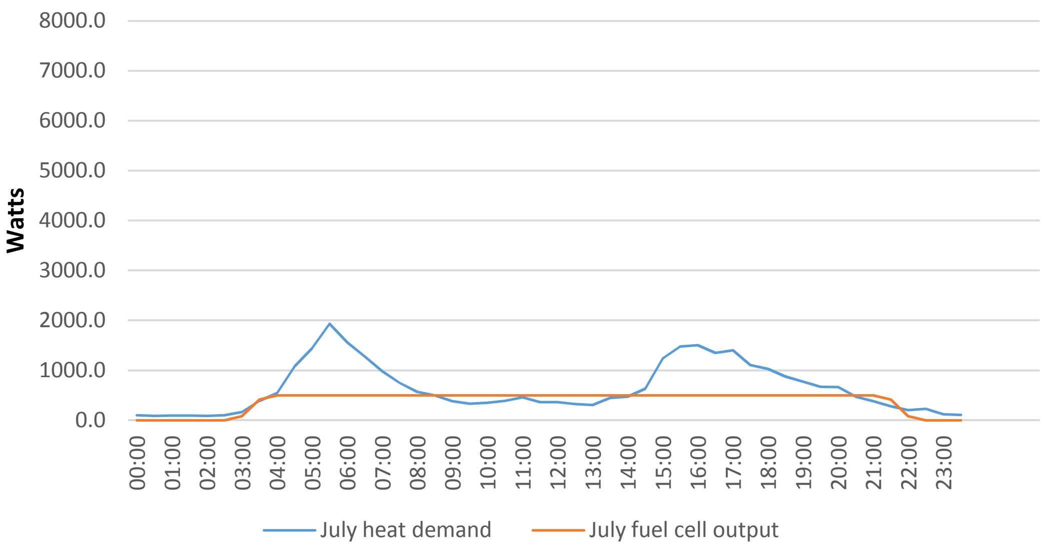

Figure 3.5 June fuel cell heat generation compared with average daily heat demand.

3.4 The benefits of using minute-scale data

It is expected that minute-scale data will provide more accurate information than lower resolution data. In order to test this, the minute-scale data will be compared against ten minute and half-hourly data.

The ways in which the data changes when aggregating to lower resolutions was examined for various sections of the data. Figures 3.6 and 3.7 demonstrate different resolutions of household demand and Stirling engine generation, respectively, using a day in October as an example. Both figures show that there is slightly more variation in the ten-minute data than in the half-hourly data. Figure 3.6 demonstrates that there are considerably higher peaks and troughs in the one-minute data than either the ten-minute or half-hourly data. Throughout the daytime the one-minute data is often over 500 W higher than the ten-minute or half-hourly data. From a grid perspective, where peaks in data are more important than the overall demand, this should be of interest. Figure 3.7 shows that there is less difference in variation between data resolutions for Stirling engine generation. Though there can at times be close to 100 W difference in the generation between the one-minute and lower resolution data. The lower variation is not unexpected, the output of a single generator would vary less than a household containing various electrical devices. Analysis of days in other months provided similar results.

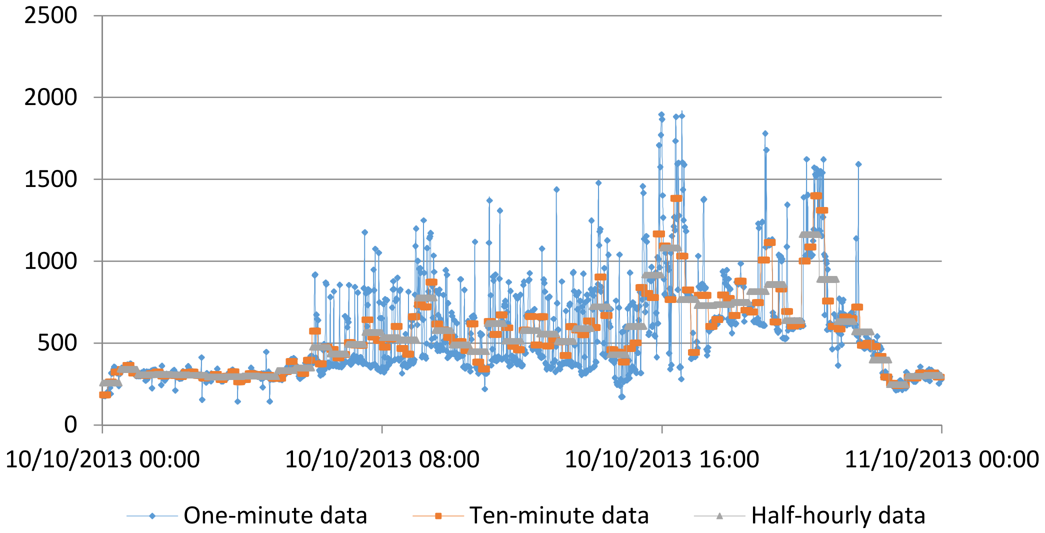

Figure 3.6 Household demand for different data resolutions. Demonstration of how the household demand data is affected by changing between one-minute, ten-minute and half-hourly data, for a typical day in October.

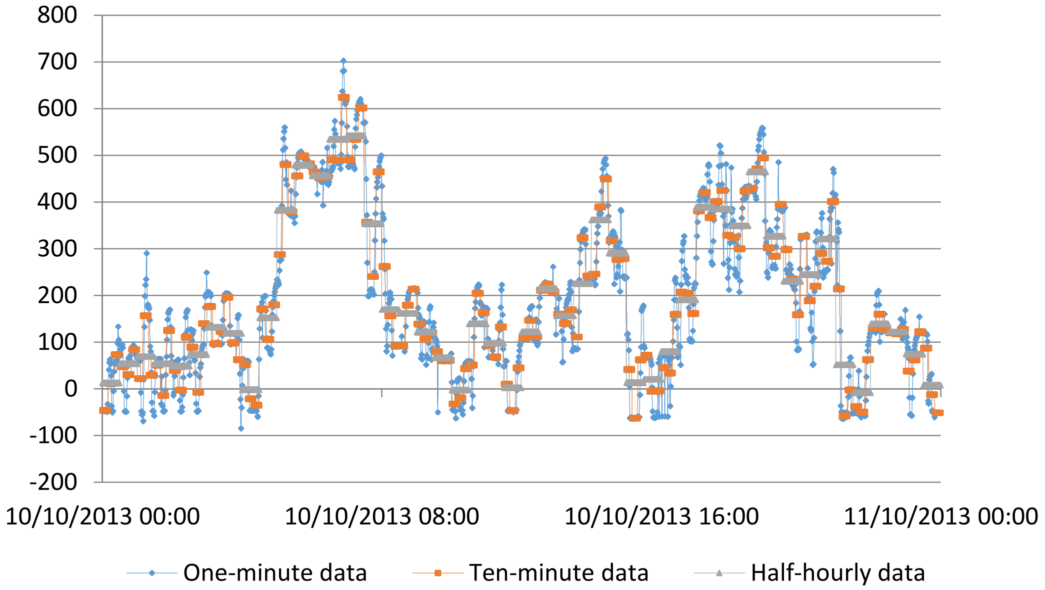

Figure 3.7 Stirling engine generation for different data resolutions. Demonstration of how the Stirling engine generation data is affected by changing between one-minute, ten-minute and half-hourly data, for a typical day in October.

The changes to the annual peak demand and generation can be considerable. Table 3.2 shows how the peak demand or generation changes as the data is aggregated. Household demand is particularly affected, with the peak being over 1kW higher when using one-minute data rather than lower frequency data; also when aggregating to half-hourly data, the peak shifts to a different day of the year. The peaks in solar PV generation and heat pump demand also change by a few hundred Watts, while the peak in Stirling engine micro-CHP generation changes only slightly. Again, as grid operation is particularly concerned with peaks in demand, such differences could have an effect when observing the impacts of micro-generation and low-carbon heat on the electricity network.

	Household demand	Stirling Engine generation	Solar PV generation	Heat Pump demand
One-minute Peak value (kW)	4.7	0.81	3.7	1.4
Time of peak	23/11/2013 17:01	13/02/2013 06:41	30/03/2013 11:17	19/11/2013 18:42
Ten-minute Peak value (kW)	3.6	0.78	3.5	1.3
Time of peak	23/11/2013 17:00	11/11/2013 06:40	30/03/2013 11:10	19/11/2013 18:40
Half-hourly Peak value (kW)	3	0.76	3.4	1.2
Time of peak	26/12/2013 17:00	11/11/2013 06:30	30/03/2013 11:00	19/11/2013 18:30

Table 3.2 Changes to the demand and generation peaks when using high frequency data.

3.5 Correlation and export

Table 3.3 shows the main results of the analysis of the generation and export of micro-CHP, and the Pearson Correlation Coefficient (PCC). This shows that both Stirling engine and fuel cell generation has weak positive correlation to household demand, meaning that while it is more likely that the micro-CHP will be generating at times of high demand, it cannot be relied upon to do so. Also of concern from a network perspective is the amount of generation being exported. While for Stirling engines this is reasonably low, for fuel cells more than half of the generated electricity is exported. Given that the data is averaged over several houses, it is reasonable to assume that much of the exported electricity is being exported to the grid at times of low demand across the electricity network, which is not ideal.

Type	Total Annual Generation (kWh)	Total Annual Export (kWh)	Percentage of Generation Exported	Demand-to-Generation (PCC)
Stirling Engine	1040	118	11%	0.224
Fuel Cell	6700	3310	49%	0.339

Table 3.3 Summary of the generation, export and correlation to demand of Stirling engine and fuel cell micro-CHP.

The generation and export profiles of both micro-CHP technologies can be analysed using frequency histograms. Figure 3.8 shows that the Stirling engines, on average, spend over a third of the year generating no electricity, and less than 5% of the year generating more than 500 W. Figures 3.9 and 3.10 show how the presence of micro-CHP changes the demand profile of the household, comparing how much electricity is taken from the grid in a normal household with no micro-CHP, to how much is imported from (or exported to) the grid with each micro-CHP technology.

In Figure 3.9, the “Stirling engine” histogram and the “no micro-CHP” histogram are quite similar in appearance. The biggest differences between the two are that the “Stirling engine” histogram shows a reduction in demand across the import side of the graph; while also showing added export, although export occurs for only around 10% of the year, with half of that time spent exporting small amounts of electricity (<200 W). Figure 3.10 shows that Stirling engine homes also spend less time importing large amounts of electricity from the grid (i.e. amounts over 1000 W).

Fuel cells produce a more dramatic change, exporting electricity to the grid 78% of the time. At the other end of the demand spectrum, fuel cells almost eliminate high demand periods, with the house now spending less than 1% of the year taking more than 1000 W from the grid, and no time taking more than 1400 W.

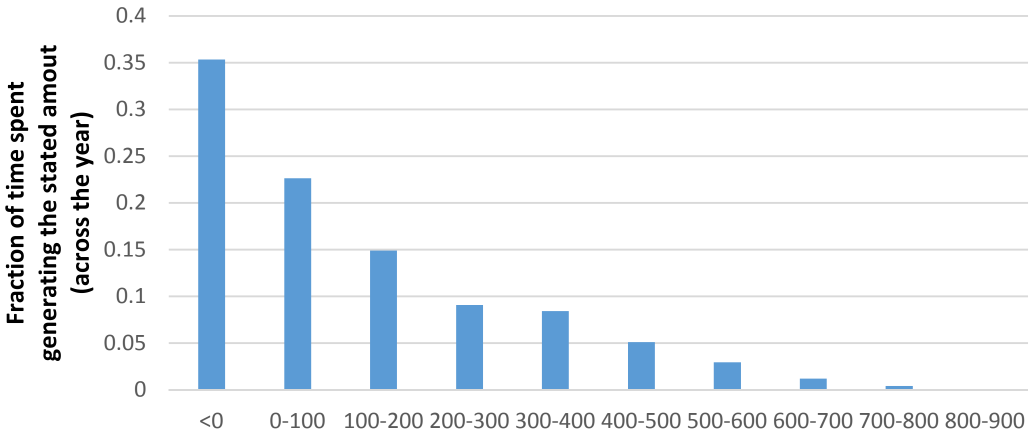

Figure 3.8 Histogram of Stirling engine generation frequency, note when the engine is not generating it has negative output due to parasitic power loss, thus the <0 column effectively indicates no generation.

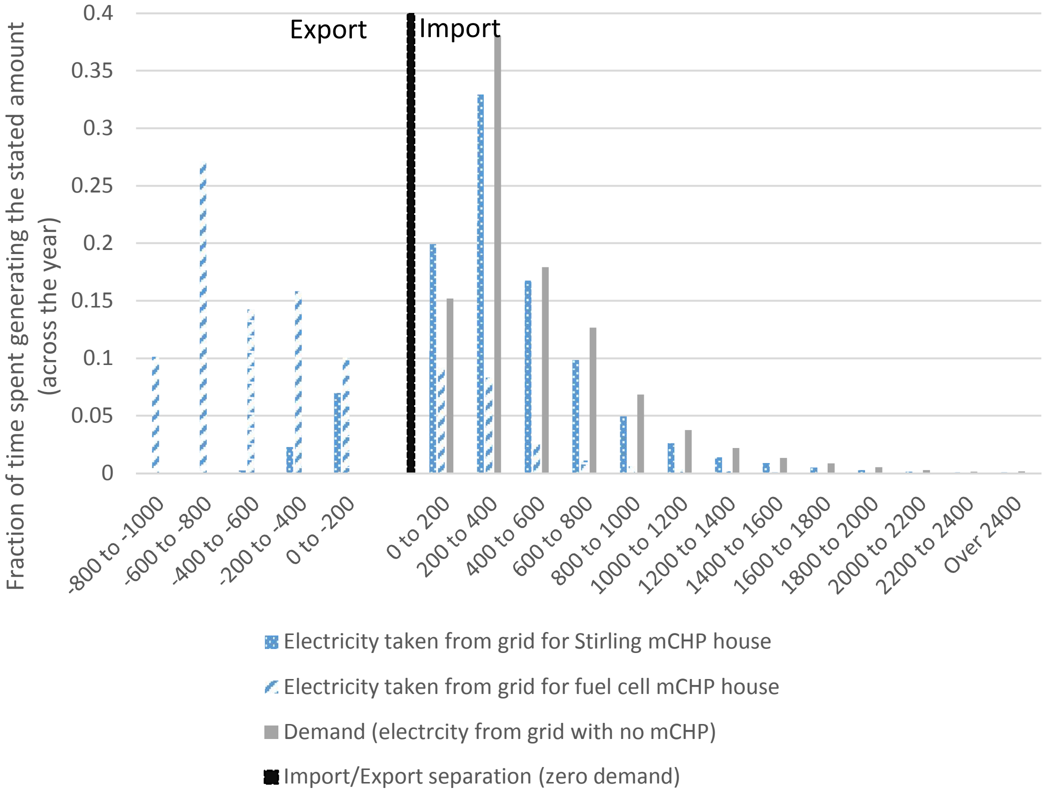

Figure 3.9 Comparison of frequency of household demand with no micro-CHP, with Stirling micro-CHP and with Fuel cell micro-CHP. The black bar represents the point of zero demand, all values to the left indicate export from the house to the grid, all values to the right represent import from the grid to the house.

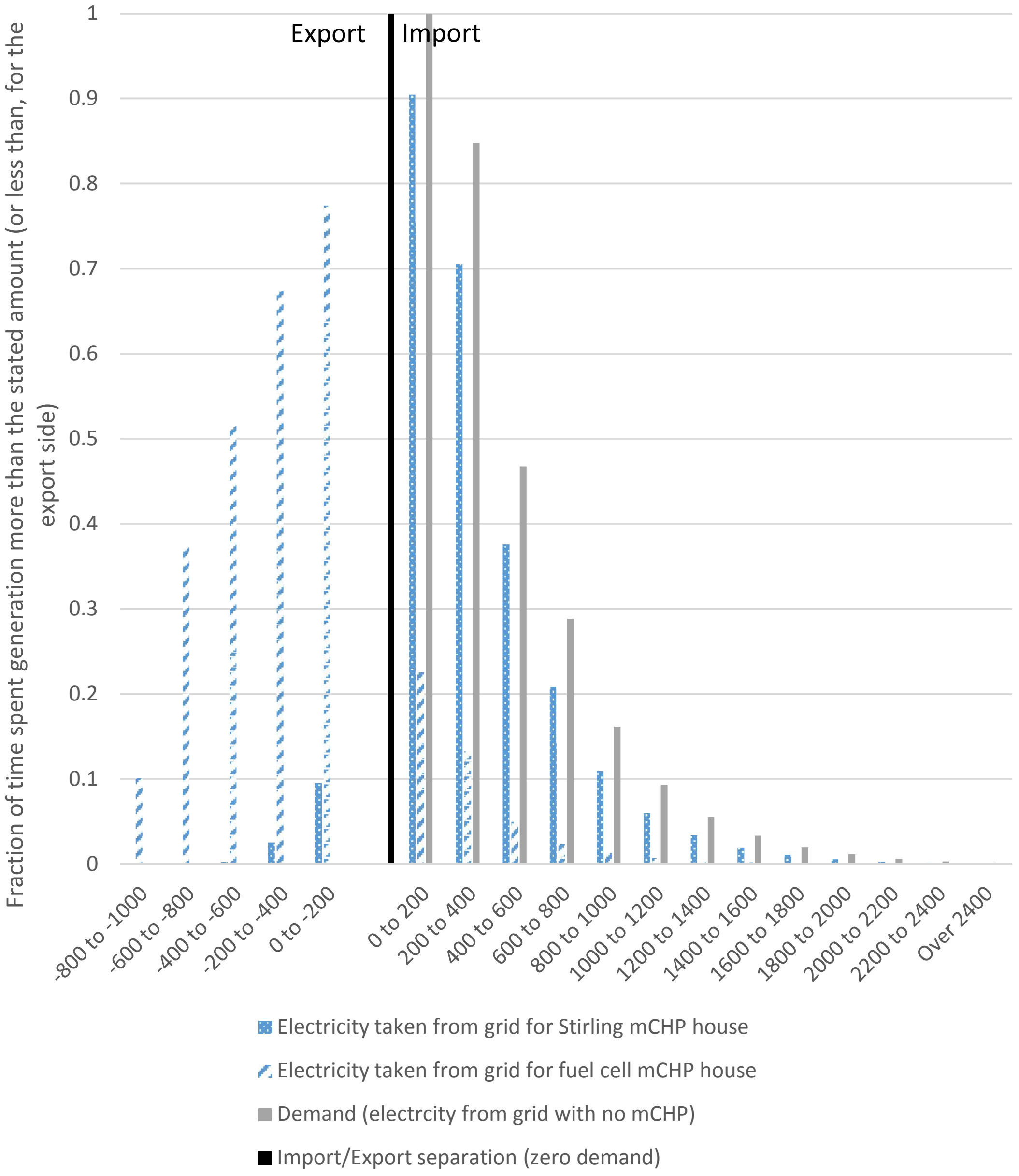

Figure 3.10 Cumulative import frequency of homes with no, Stirling engine and fuel cell micro-CHP. The black bar represents the point of zero demand.

Diurnal net demand profiles show how micro-CHP devices modify apparent electricity consumption. Figures 3.11 and 3.12 show the average daily demand profiles for January and July respectively, providing an example of how demand profiles change in winter (when energy use is highest) and summer (when it is lowest). Figure 3.11 shows that in winter, Stirling engines provide a significant reduction in demand between 6am and 9am, and throughout the late afternoon and evening, reducing the evening peak in electricity demand. There is also almost no export to the grid from Stirling engines, and when export does occur this tends to be between 6am and 8am, and mid-afternoon. This morning and evening peak reduction, along with minimal export, is broadly beneficial from the perspective of the electricity network, as evening demand is reduced while little reverse power flow is introduced. Figure 3.12 shows that in the summer, Stirling engines have only brief periods when they reduce demand, in this case in early morning and mid-afternoon. These results are in line with expectation because of the heat-driven nature of the device and the coincidence of domestic peak heat and electrical demand.

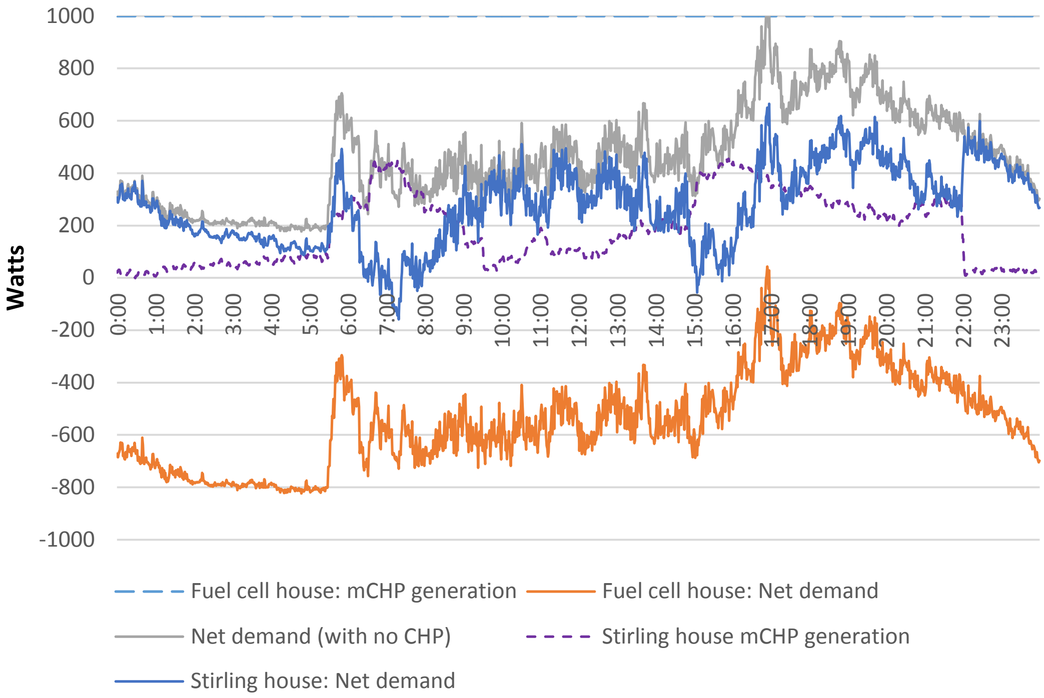

Figure 3.11 Stirling engine and fuel cell generation and net demand for January (average day).

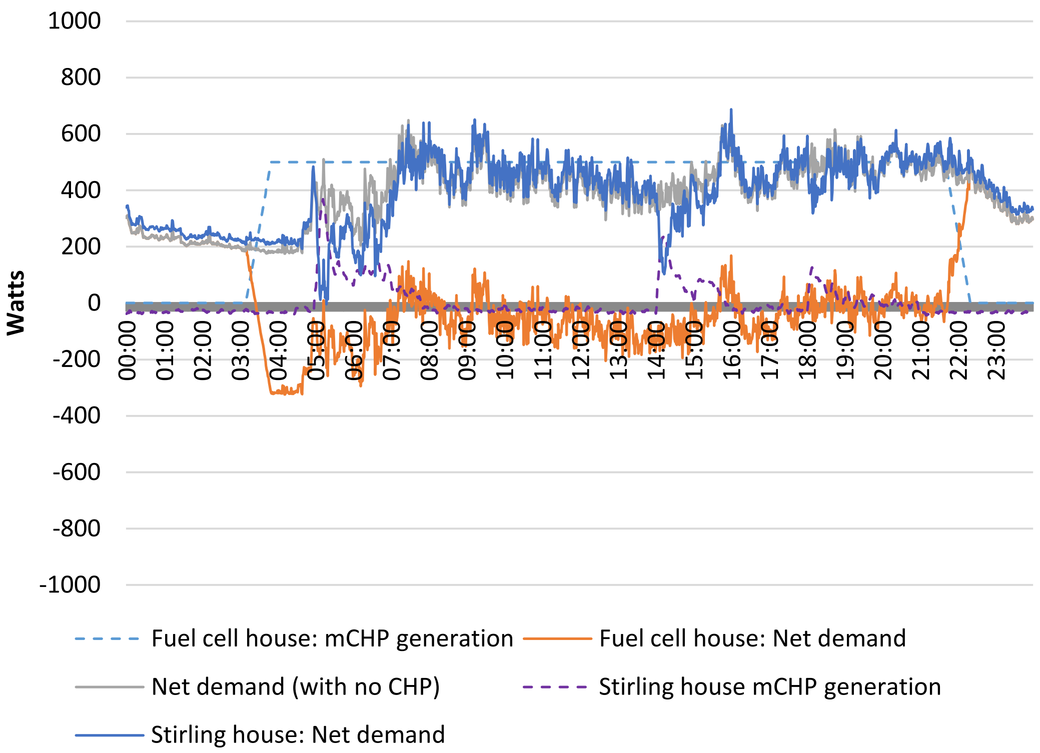

Figure 3.12 Stirling engine and fuel cell generation and net demand for July (average day).

Fuel cells cause more significant changes to demand profiles than Stirling engines. Figure 3.11 shows that winter households with fuel cell micro-CHP spend nearly all their time exporting electricity to the grid, with exports being highest during the night. In summer (Figure 3.12) the change is much less severe; the fuel cell schedule shown in Figure 3.5 explains that there is no generation during the night, and half-power generation during the day, and thus there is only moderate export during the day with the exception of early morning. This export peak is caused by heating systems warming up while householders are still asleep and not in need of electricity.

3.6 Energy use and emissions savings

Electrical efficiency is 13% for Stirling engine micro-CHP and 45% for fuel cell micro-CHP, with the efficiency of a counterfactual boiler assumed to be 90%. A Stirling engine micro-CHP device supplies 1040 kWh of electricity and 8365 kWh of heat per year, while a fuel cell will supply 6700 kWh electricity and 7350 kWh of heat; these values do not match the established heat-to-power ratios (6:1 and 1:1) due to parasitic power loss sapping some of the electrical output, lowering the amount of electricity supplied. Using the process outlined in Section 3.2.3, the extra gas used by the micro-CHP device can be calculated and compared to that of the gas needed to generate an equivalent amount of electricity from a combined-cycle gas turbine (CCGT).

	Stirling engine	Fuel Cell
Electricity generated (kWh)	1040	6700
Heat generated (kWh)	8370	7350
Gas used by micro-CHP (kWh)	10860	16330
Gas used by conventional boiler (kWh)	9290	8160
Effective gas used to generate micro-CHP's electrical output (kWh)	1570	8170
Gas used by a CCGT to generate same amount of electricity (kWh)	2080	13500
Gas saved compared to CCGT (kWh)	510	5330
Emissions saved compared to CCGT (kgCO2)	102	1066

Table 3.4 Breakdown of gas used by micro-CHP device and comparison with a boiler and CCGT, the emissions assume a gas emissions factor of 0.2 kgCO_2/kWh (Lelyveld and Woods, 2010).

Table 3.4 compares Stirling engine and fuel cell micro-CHP gas use, factoring the respective heat-to-power ratios and efficiencies, to calculate the overall primary gas consumption and hence CO_2 emissions. More gas is consumed in a micro-CHP equipped house compared to a house with just a conventional boiler and grid electricity, but less gas is used overall, resulting in global emissions savings. The emissions savings from the fuel cell micro-CHP are considerably greater than those from the Stirling engine micro-CHP, by a factor of 10. Of course, the comparison with gas consumed by a CCGT is unrealistic as grid electricity (which is what the micro-CHP is offsetting through its generation) is generated from a mix of coal, gas, nuclear and renewable sources. In order to determine the actual carbon savings it is necessary to compare the emissions of the extra gas consumed by micro-CHP to generate the electricity output, and the average carbon intensity of the grid electricity it is replacing, using equation 3-5.

For 2013, the year of the trial, the average grid carbon intensity was 470 gCO_2/kWh, and the emissions savings profile (when comparing against the hourly average grid carbon level) for the whole year is shown in Figure 3.14. The total emissions saving for Stirling engine micro-CHP is 175 $kgCO_2$, while that for fuel cell micro-CHP is 1514 $kgCO_2$. When compared against annual household emissions, this equates to a 4% saving for Stirling engine micro-CHP and a 35% saving for fuel cell micro-CHP. However, average grid carbon intensity varies annually, and Table 3.5 shows this for the period from 2009 to 2015 (Earth Notes, 2016), demonstrating that in recent years there has been a considerable fall in grid emissions, and correspondingly a fall in the emissions savings from micro-CHP. It is also worth noting that for 2013, when comparing against average grid carbon intensity, the savings are greater than when comparing against hourly grid carbon intensity. This fits with the fact that micro-CHP output only weakly correlates with peaks in demand, when grid carbon intensity is likely to be at its highest. Assuming the grid carbon factor continues to decline, emissions savings from micro-CHP will also decline, eventually becoming negative, as shown in Figures 3.14 and 3.15; once the grid carbon factor falls below 222 gCO_2/kWh, Stirling engine micro-CHP will no longer assist in reducing emissions and once it falls below 212 gCO_2/kWh neither will fuel cell micro-CHP. This is particularly concerning given the latest data, which indicates that average grid carbon intensity for 2017 was down to 237 gCO_2/kWh.

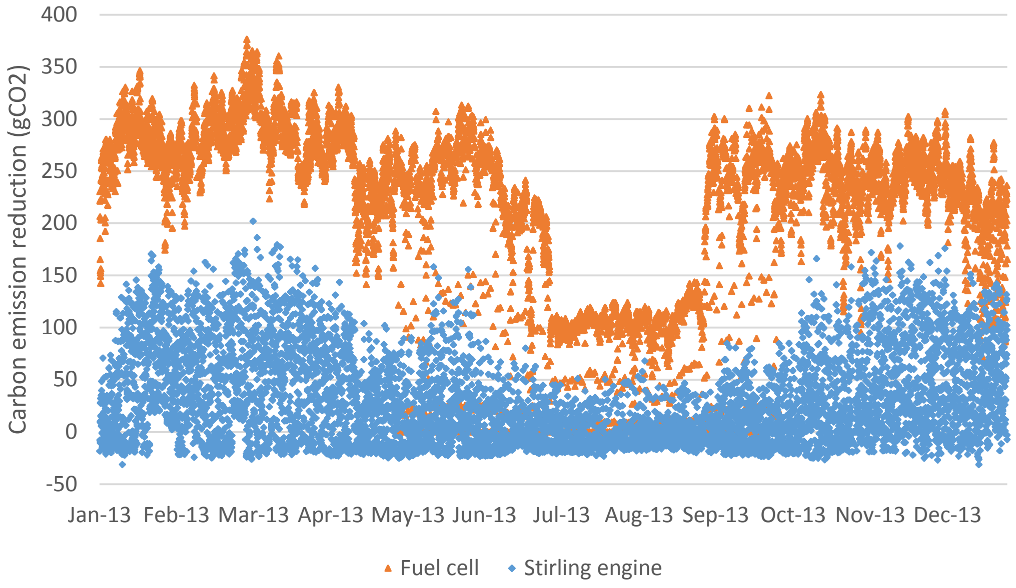

Figure 3.13 Hourly emissions savings for the whole year.

Year	Average Grid Carbon intensity (gCO2/kWh)	Stirling engine carbon savings (kgCO2)	Fuel cell carbon savings (kgCO2)
2009	429	222	1609
2010	444	227	1689
2011	436	227	1639
2012	496	274	2066
2013	470	233	1835
2014	419	200	1524
2015	367	135	1103

Table 3.5 Average grid carbon intensity and carbon savings for Stirling engines and fuel cells for each year from 2009-2015.

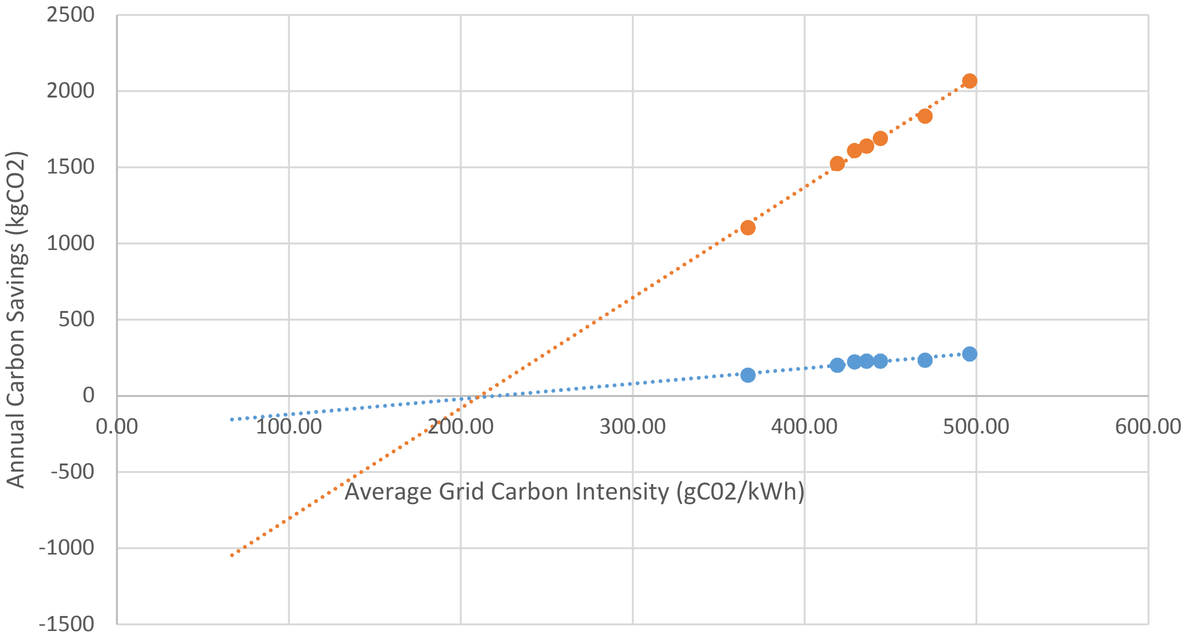

Figure 3.14 How carbon savings change with average grid carbon intensity, for Stirling engines and fuel cells.

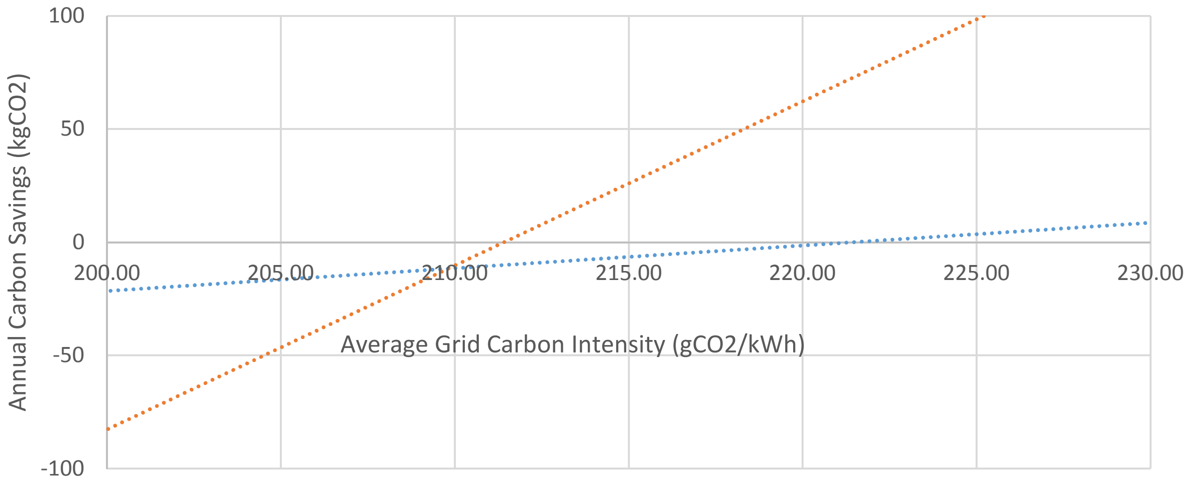

Figure 3.15 Close up of Figure 3.14 at the point where carbon savings become negative.

If micro-CHP were to only to offset marginal grid emissions, i.e. only offset electricity from gas fired plants, then it would continue to avoid 100 $kgCO_2$, for Stirling engines, and 1000 $kgCO_2$, for fuel cells, even as overall grid emissions fall. However, it would be difficult to guarantee that micro-CHP does this.

If micro-CHP consumed carbon neutral fuels, such as biogas or hydrogen from carbon neutral sources, then emissions savings will improve considerably. In this case all the electricity generated by the micro-CHP device will be carbon neutral and so, given the 2013 grid carbon intensity value of 470 gCO_2/kWh, Stirling engine micro-CHP would save 490 $kgCO_2$ and fuel cell micro-CHP would save 3150 $kgCO_2$. While these savings would still decline as grid carbon intensity declined, they would never become negative. These figures are comparing against a house which is heated by a boiler also using carbon neutral fuel, and drawing electricity from the grid.

As for heat pumps and solar PV; using 2013 grid carbon intensity, a heat pump would save 500 $kgCO_2$ considerably more than a Stirling engine but only a third of what a fuel cell would save; while solar PV would save 1700 $kgCO_2$, 200 $kgCO_2$ more than a fuel cell and nearly 10 times the savings of a Stirling engine. The savings of solar PV will decline as the electricity supply is decarbonised; however, the savings of heat pumps will increase (as they are replacing a gas based heat supply with an electricity based one), and once grid carbon intensity falls below around 400 $kgCO_2/kWh$ heat pumps will achieve better savings than fuel cell micro-CHP. Thus as of 2015 heat pumps should already be achieving better savings than micro-CHP.

3.7 Economic savings

In order to calculate the economic savings the following tariffs and prices are assumed: a grid electricity purchase price of 14.05 p/kWh; an electricity generation tariff of 13.45 p/kWh; an electricity export (sales) tariff of 4.85 p/kWh; and a gas purchase price of 4.29 p/kWh (Energy Saving Trust, 2013b, Energy Saving Trust, 2014). The costs and income are calculated in comparison to the baseline case of a household on the gas network with a gas boiler and drawing all its electricity from the grid. Table 3.6 gives a breakdown of the annual costs, savings and income of the micro-CHP units. Two important points can be drawn from this: first that the economic benefit of fuel cell micro-CHP is over six times that of Stirling engine micro-CHP; and that in both cases, generation tariff income makes up the majority of the annual gain. Thus the economic benefit of micro-CHP is highly dependent on tariff support from the government.

The cost of a Stirling engine micro-CHP unit used in the trial was £9,000 (Baxi, 2010), while fuel cell costs are estimated to be £14,000 (Harikishan R. Ellamla et al., 2015). Using these figures and the annual savings the net present value of the installation can be calculated. The NPV is defined as:

$$NPV = \sum_{t=1}^{T} \frac{R_t}{(1+i)^t} - C_0 \qquad \textbf{3-7}$$

where T is the lifetime of the installation, t is the year, R_t is the monetary return in year t, i is the interest rate (assumed to be 5%) and C_0 is the initial capital cost of the installation. The results of the calculation are shown in Table 3.6. The negative NPVs indicate that neither technology is yet capable of paying for itself over time. The price of Stirling engine micro-CHP would need to fall by more than 80% in order to break even over a 10-year period, while fuel cell micro-CHP requires a smaller fall in price of 30% to break even. Table 3.8 illustrates potential changes to the 10-year break-even price given the removal of the export tariff, generation tariff, or both. In chapter 2 (Section 2.2.2), a suggested long term price for fuel cell micro-CHP was £2,300 (Staffell and Green, 2012). All of the break-even prices in Table

3.7, except the one with no tariffs of any kind, are above this value. This suggests that in the long term fuel cell micro-CHP could still be profitable provided some tariff support is maintained.

	Stirling Engine micro-CHP	Fuel Cell micro-CHP
Total Generated (kWh)	1042	8173
Electricity used in house (kWh)	924	3683
Electricity exported (kWh)	118	3312
Extra gas used compared to a conventional boiler (kWh)	1570	8161
Savings from avoided grid electricity (£)	130	517
Generation Tariff Income (£)	140	941
Export Tariff Income (£)	6	161
Cost of Extra Gas (£)	67	350
Total Monetary Gain (£)	209	1269
Current Capital Cost (£)	9000	14000
NPV with a 10 year payback period (£)	-7386	-4201
Time to break even at current price (years)	>50	17
Break-even price with a 10 year payback period (£)	1614	9799

Table 3.6 A summary of the economic savings of micro-CHP. This shows the electricity generated by the micro-CHP units, where it is used (i.e. in the house or exported to the grid), the extra gas required, and the costs and savings that arise from the above.

	Stirling Engine micro-CHP	Fuel Cell micro-CHP
Break-even price with tariffs	1614	9799
Break-even price no export tariff	1568	7396
Break-even price no generation tariff	533	2533
Break-even price no export or generation tariff	486	1290

Table 3.7 Changes in 10 year break-even price in the absence of tariffs.

For heat pumps, the annual energy bill savings are only £20, considerably low, due to the high price of electricity in comparison to natural gas. There was no additional income through the Renewable Heat Incentive (RHI) in 2013, as the RHI began in 2014. Under the 2014 RHI the heat pump would receive 7.3 p/kWh$_{th}$ (Ofgem, 2018b), giving an additional £570 per annum, for a total of £590. This gives heat pumps a break-even price of approximately £4,000. Under the RHI in 2018, this income rises to £810 per annum, giving a break-even price of £5,500. Solar PV achieves annual savings of £910, resulting in a break-even price of £7,000, under 2013 tariffs (Ofgem, 2018a); under 2018 tariffs these savings fall to £460, giving a break-even price of £3,500. Thus of all the technologies the one with the largest annual return and thus the highest break-even price is fuel cell micro-CHP.

3.8 Comparison with previous micro-CHP research

In previous literature, carbon reduction of -4% to 12% is estimated for Stirling engine micro-CHP (Alanne et al., 2010, Carbon Trust, 2011, Staffell and Green, 2012, Peacock and Newborough, 2005) and so the number shown here, a 4% carbon emissions saving for Stirling engine micro-CHP, is consistent with those from the literature. The main previous field trial undertaken in the UK, the one by Carbon Trust (2011), also found average carbon savings of 4% for Stirling engines, again consistent with the value here. Fuel cell emissions savings were 35%, within the 16-40% range in the literature (Peacock and Newborough, 2005). The grid carbon intensity below which emissions savings become negative was also examined in the literature, with Hawkes et al. (2011) estimating it to be 200 gCO$_2$/kWh for fuel cell micro-CHP. The value here is only slightly above that estimate, at 212 gCO$_2$/kWh.

Alanne et al. (2010) estimates the economic savings from micro-CHP to be £165, while Carbon Trust (2011) estimates similar savings of £169, with a generation reward and -£11 without a generation reward, the savings here (£209 for Stirling engines) were above both these values, but the savings were in accordance with the range suggested in another paper of £200-250 (De Paepe et al., 2006). On the whole, the results from the field trial are mostly consistent with the literature. The previously mentioned Carbon Trust (2011) field trial found, annual savings of £158, using a Stirling engine with a heat-to-power ratio of 12:1, this heat-to-power ratio is double that of the Stirling engine used here, which may explain the smaller savings. The savings from fuel cells here were £1,269, higher than the £750 suggested by the literature (Staffell and Green, 2009), though their FiT was 10 p/kWh while the one used here was 13.45 p/kWh. Using a 10 p/kWh FiT with the data in this research produces savings of around £1,000, still a higher saving. It may be that the simulated fuel cell profiles in this research used the fuel cell for more of the year, thus generating more electricity and higher monetary returns.

3.9 Chapter Summary

This chapter has provided a summary of the data used throughout the thesis. It comprises of field trial data from the CLNR project, and a simulation of fuel cell generation profiles, which are based on UK household heat demand. The field trial data is high frequency minute-scale data of: household and heat pump demand, and Stirling engine micro-CHP and solar PV generation. It is demonstrated that the use of high frequency minute-scale data provides more information than lower frequency ten-minute or half-hourly data, especially on times of peak demand. Such accurate data should be important from a grid perspective.

This chapter also examined the economic and emissions saving potential of Stirling engine and fuel cell micro-CHP. It found that Stirling engines produce savings of 4%, while fuel cells produce savings of 35%, however, both these values will decline as the grid is decarbonised, and may become negative. Long term it is probable that micro-CHP will only be a valid low-carbon heating option if it utilises a carbon neutral fuel source.

Stirling engine micro-CHP produces limited savings for the household of £209 per annum. Fuel cell micro-CHP produces considerably better savings of over £1,200, which is also higher than the savings of either heat pumps or solar PV. However, neither technology produces enough savings to cover their current capital cost. Fuel cells would have to fall in price to £9,000 or less to become economically viable, while Stirling engines would need to fall to £1,500. But even should prices fall to a point where micro-CHP in the form studied in this paper becomes economically attractive, the ongoing decarbonisation of the electricity network will steadily reduce the emissions case for micro-CHP. A potential boost to micro-CHP would however be from an alternative low-carbon fuel supply, which in practice would mean hydrogen (the limitations of biogas were discussed in Section 2.1.2).

4 METHODOLOGY OF NETWORK ANALYSIS

A distribution network model was developed to explore the potential impacts of micro-CHP, and other micro-generation technologies, on local distribution networks. This chapter explains the choice of method, the development of a model, and the calibration and evaluation of the model.

4.1 Chapter Introduction

As mentioned in Section 2.4.2 and 2.4.3, some studies (Ackermann and Knyazkin, 2002, Acha et al., 2009) indicate that one of the main ways that micro-generation can affect distribution network operations is through reducing network losses. Others, for example Infield et al. (2007) and Thomson and Infield (2007), suggest the impacts on voltage levels will be a key concern of micro-generation, particularly voltage rise. An alternative approach by Rogers et al. (2013) focuses on the network transformer and if it is overloaded. Ideally, the chosen methods should be able to examine all three of these parameters.

Examination of the network modelling environment determined that the best way to examine these parameters was through load flow analysis. Load flow analysis uses a specific generation and demand state and network structure to solve the steady operation state to provide voltages and power flows in the electricity system (Wang et al., 2008). While load flow analysis is a steady state analysis, by performing a load flow analysis for each time period in a set of time series data (in this study for each minute of the data), an approximation of a dynamic power system analysis can be achieved.

The chapter begins with an examination of a variety of network modelling software and justification for the choice of IPSA-Power (Section 4.2). There is then an examination of how the network is modelled within IPSA (Section 4.3) followed by an overview of the Python scripts used to perform analysis with IPSA and an outline of the scenarios (Section 4.4). The model is then tested and validated (Section 4.5), a discussion of the limitations of the model is presented (Section 4.6), and a summary of the chapter provided (Section 4.7).

4.2 The IPSA modelling environment

IPSA is a distribution network planning system in which electricity networks are defined and analysed, and which is capable of performing load flow analysis. IPSA has a complex network design system, allowing the design and testing of a wide range of networks from large meshed distribution and transmission systems to small isolated networks and anything in between (IPSA-Power, 2017).

Other power systems analysis software was examined for potential use. This software included PSS/E (SIEMENS, 2017), DIgSILENT Power Factory (DIgSILENT, 2017), ETAP (ETAP, 2017) and OpenDSS (EPRI, 2017). All of these could perform the necessary functions (i.e. load flow analysis). But only DIgSILENT, like IPSA, allowed automated analysis through the use of Python code, which the researcher was already experienced with. The fact that the models of real world distribution networks, obtained for use in this research from Northern Powergrid, were designed in IPSA made IPSA the software of choice for this research.

As mentioned above, a key advantage of IPSA for this research was its ability to interface with the Python coding software, an easy to use scripting interface which allowed powerful customisation and automation of data input and modification, and performing of load flow analyses. This automation is essential for performing load flow analyses for each data entry in a set of time series data, as discussed in the previous section (Section 4.1). TNEI also provided extensive support and training for the use of IPSA, which was also a major beneficial factor of the software. The automation of load flow analysis through the use of Python was essential for this research. Without such interface, it would be necessary to manually run a load flow analysis for each minute of the field trial data. Instead with Python, it is possible to write code that automates the process of running load flow analyses of the field trial data.

4.3 Development of an IPSA model

A model of a UK distribution network (the 'Maltby' network) was obtained from the distribution network operator Northern Powergrid. The Maltby distribution network is a low voltage (433 V) distribution network in South Yorkshire serving part of a rural town. The network serves 249 homes fed from a single fixed tap 11 kV-433 V transformer. A few hundred homes is typical for a distribution network, though 249 is towards the higher end of what is normal. The transformer is thus also larger than average, having a capacity of 1 MVA. Even then the transformer still spends a small amount of time being overloaded. Brief periods of overload however, are not necessarily a problem, provided they do not become too frequent or last for extended periods of time, which shortens the operational lifetime of the transformer; a suggested upper limit for overload is 1.5 times the rated capacity (Wang et al., 2008). The network is modelled as 34 feeders (i.e. loads), each comprising a small group of homes. The number of homes for each load ranging from 2-14. The network itself consists of 36 nodes or busbars, one either side of the transformer and one for each load connection. The wider network is essentially modelled as a grid in-feed, from which all the required electricity can be sourced (and any excess electricity sent). The diagram of the network from the IPSA model is shown in Figure 4.1.

4.3.1 Representing micro-generation and heat pumps on the network

Modelling distributed generation on the network can be done one of two ways: either as a negative load, or as a generator. If it were modelled as a negative load, for each time-step, the micro-generation output would be subtracted from the household demand, to create a new household demand to be assigned to the appropriate load on the network. For example, if a feeder consists of 7 homes, three of which have micro-CHP; for each minute of the year the load on that feeder would be found by multiplying the household demand (from the input data) by 7, and subtracting three times the micro-CHP generation. If the demand were higher than the generation then the feeder would have a positive load, if generation were higher than demand then the feeder would have a negative load, and would be exporting electricity back to the grid. If micro-generation were instead modelled as a generator, then in the network model each busbar with a feeder attached to it would also need a generator attached to it. The load on the feeder would simply be the number of homes multiplied by the household demand (plus any extra demand from heat pumps). The output of the generator will be the micro-CHP or solar PV output, multiplied by the number of homes on the feeder that have either of those technologies installed. In both cases the heat pump profiles from the data would be modelled as an additional load on the feeder.

The question then is which of the two approaches is more appropriate. In the process of developing the model both approaches were tested, for a scenario where all homes have Stirling engine micro-CHP. It was found that there was a less than 0.1% difference between all results for the two approaches, suggesting that either method would be appropriate. Modelling micro-generation as a generator on the network has the advantage of keeping the generation data separate from the load data, making it easier to extract and utilise after load flow analysis has been performed. It was primarily for this reason that the modelling as generators method was chosen. Modelling micro-CHP and solar PV as generators, which is essentially what they are, also made the model a more accurate representation of a real world network with micro-generation.

To model micro-generation in the IPSA model of the Maltby network, a generator was added to each busbar which had a feeder attached to it, resulting in the network shown in Figure 4.1. The code automating the load flow analysis could then calculate the amount of generation that should come from the group of homes on that feeder (using the generation profile and the number of homes with micro-CHP installed), and assign that generation value to the generator in IPSA.

It is possible that there would be network issues within the feeders themselves, i.e. on the wires running into/out of each individual home. However, since the agglomeration of multiple homes onto one feeder is an approach used by DNOs themselves when modelling networks, it is assumed that any such issues are of minimal concern.

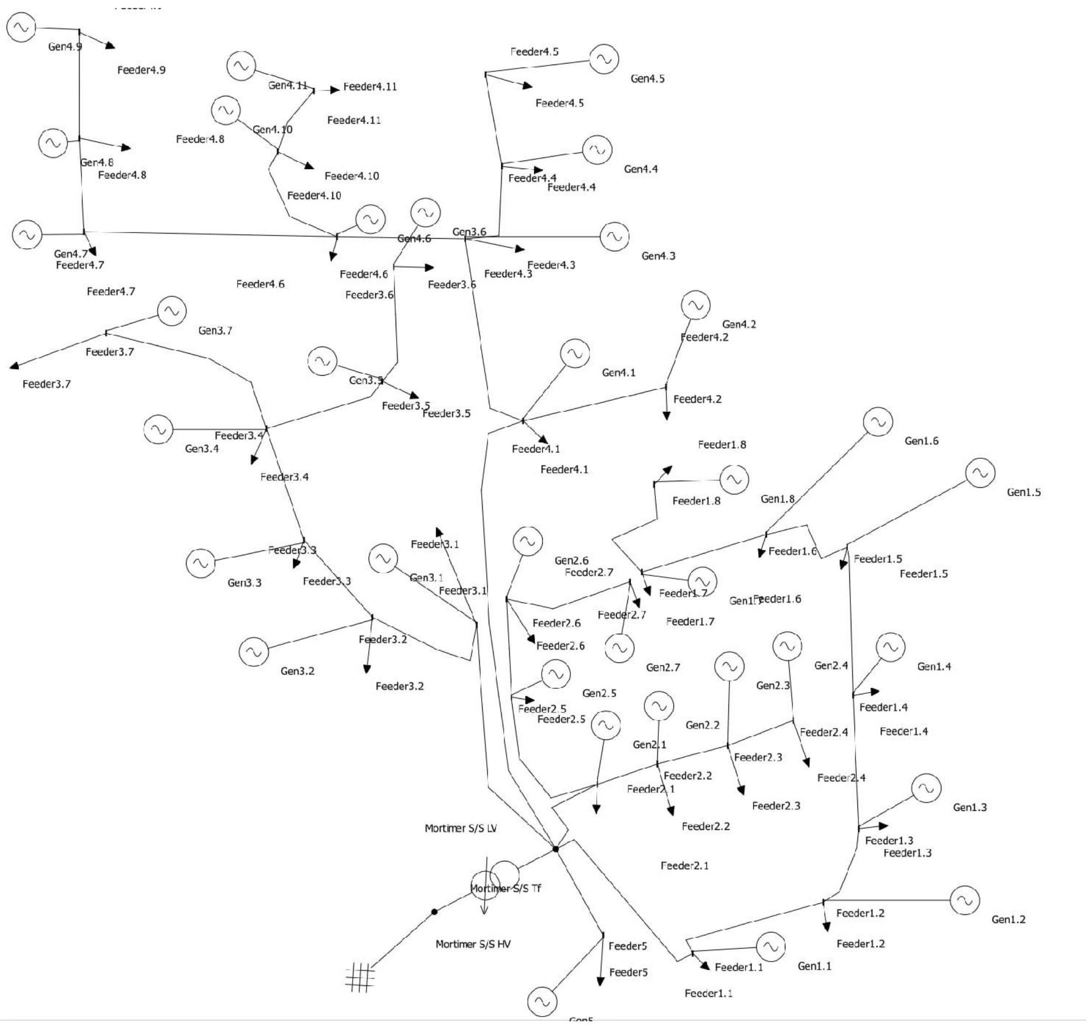

Figure 4.1 Diagram of the Maltby network, after generators have been added for this research. Black arrows indicate loads, circles with sine waves inside indicate generators, two overlapping circles with an arrow through one indicates a transformer, the small grid indicates a grid in-feed and the black dots where lines meet indicate busbars (aka nodes).

4.3.2 Parameters to be monitored

The analysis of the network focuses on three key parameters: the voltage levels across the network, power flows through the transformer, and the losses across the network; as one of the main concerns with the deployment of micro-generation is that it could lead to voltage rise on distribution networks, while reduction of network losses is often mentioned as a benefit of micro-generation. Examining voltage levels involves identifying when the voltage at any node on the network exceeds regulation limits and noting how often this happens throughout the year, as well as identifying the maximum and minimum recorded voltage levels on the network across the whole year. Losses on the network are examined by totalling the real and reactive losses across all cables on the network between the transformer and the various loads, as well as examining the real and reactive losses across the transformer itself.

The power flow through the transformer and the power drawn from the grid are also examined. The power flow across the transformer indicates whether the transformer is overloaded at any point (most likely due to the excess demand caused by heat pumps) and if this is reduced by micro-generation, or if the micro-generation itself is overloading the transformer, through generating too much electricity that lead to large upstream power flows through the transformer. The power drawn from the grid is measured to examine the extent to which the presence of micro-generation reduced the amount of electricity drawn from the grid and to monitor how often (if at all) the network becomes a net exporter of electricity to the grid, due to micro-generation during periods of low demand.

4.3.3 Model data

The data used in this research is the same as that detailed in the previous chapter (Section 3.3). This comprises field trial Stirling engine micro-CHP, solar PV and heat pump data and simulated fuel cell micro-CHP data.

4.4 Developing a system to run load flow analysis

Two Python scripts were developed to run load flow analyses on the Stirling engine and fuel cell data and generate useful outputs. The first of these scripts converts the demand and generation profiles, and the number of homes with and without micro-CHP on each feeder, into a table detailing the total load (and generation) at each feeder, over an entire year. The second script then took this table and used it to run a load flow in IPSA for every minute of the year, and output a table of results.

The first Python script (detailed in Figure 4.2) takes data from two input files, and outputs a data file for the second piece of code. The first input file is the annual profiles of the household demand, Stirling engine generation and fuel cell generation (and later in the research solar PV generation and heat pump electrical demand). These profiles are the same as those from the data described in Section 3.3. The first input file remains unmodified throughout all the runs of the model for all the various scenarios. The second input file is the number of homes at each feeder on the network along with the number of those homes with either Stirling engine or fuel cell CHP (and later solar PV and heat pumps). That input file contains lists of: the number of homes on each feeder (which does not change), the number of homes with Stirling engine micro-CHP, the number with fuel cell micro-CHP, the number with heat pumps and the number with solar PV. This data was modified for the various scenarios, the number of homes with micro-CHP, solar PV or heat pumps changed based on the penetration of those technologies in each scenario. Examples of all the input (and output) data files are given in Appendix A.

The first piece of code uses these two input files to determine the amount of demand and generation at each feeder and generator on the network, for each minute of the year. This data is then outputted into a spreadsheet which serves as the input file for the second Python script.

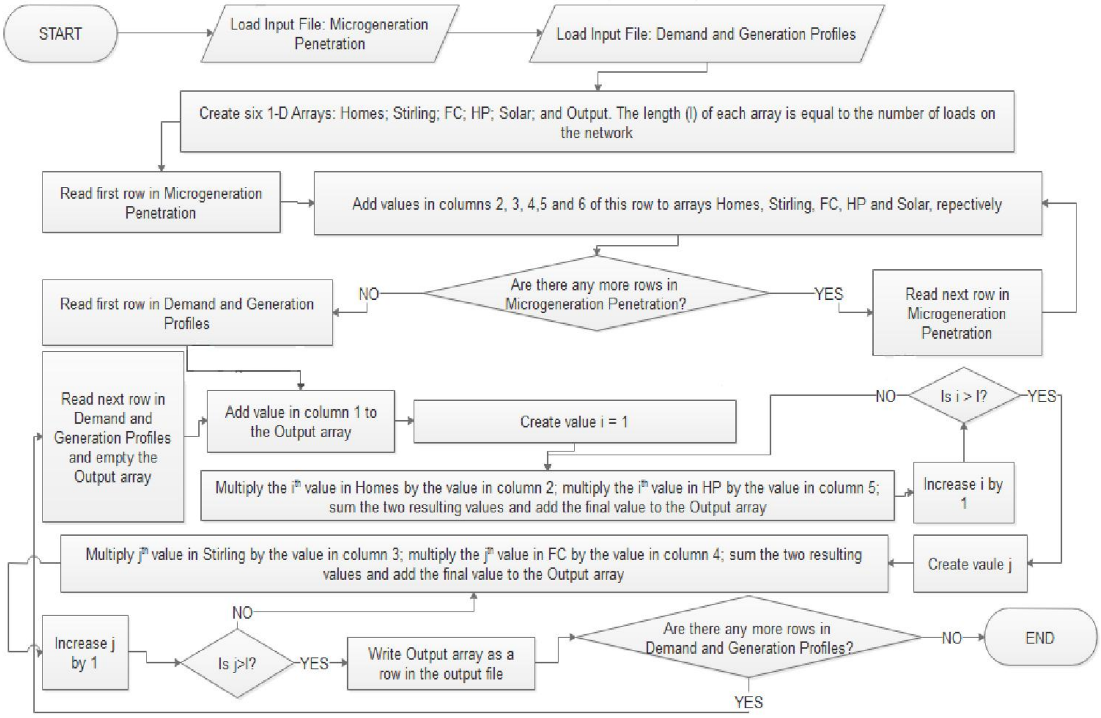

Figure 4.2 Flow diagram of the first Python script, producing the load and generation profiles for each feeder and generator on the network.

The second Python script, detailed in Figure 4.3, uses the load and generation database generated by the first script to perform the load flow analysis. For each minute of the year, the code reads in the data on the load and generation, assigns each load or generation value to the correct location on the network within IPSA and then instructs IPSA to perform a load flow analysis. The code then gathers all the necessary results from within IPSA and writes them to an output file, after which it moves on to the next minute and repeats the process. The results collected are:

- the total power load on the network;
- the branch power losses (i.e. the losses on the cables that make up the distribution network);
- the transformer power losses (i.e. the losses across the transformer(s) on the network);
- the tap position of the transformer;
- the total power generation from distributed generation in the network; and,
- the voltage levels at each busbar of the network.

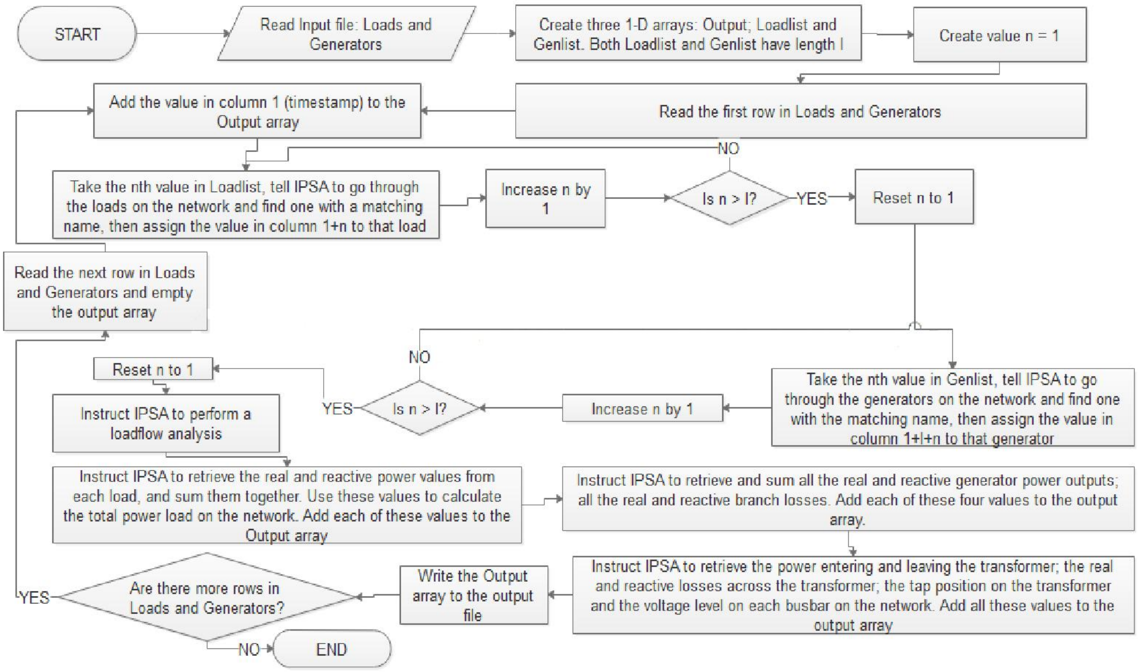

Figure 4.3 Flow diagram of the second Python script, automating the process of instructing the IPSA program to run a load flow for each minute of the year, using the data generated in the first piece of Python code.

4.4.1 Outputs generated by the Python scripts

For each set of input data, the code instructs IPSA to perform a total of 525,600 load analyses, one for each minute of the year. Thus for each minute of the year a set of data will be generated which will include:

- the total power load on the network;
- the total power generation on the network;
- the power losses across all branches (cables) on the network;

- the power losses across the transformer(s);
- the transformer tap position; and,
- the per unit voltage level at all busbars on the network (34 in total, in the case of the Maltby network).

From these results it is possible to determine if at any time voltage levels exceed statutory limits, if the transformer is overloaded, and if power is flowing upstream across the transistor. Any of these could destabilise the network, or damage the components of the network. It is also possible to determine the number of minutes in the year for which any and all of these conditions apply, any of which could be problematic to the network if they occur for substantial periods of time.

4.4.2 The scenarios that were tested

By running the code many times, with different deployments of Stirling engine and fuel cell micro-CHP on the network, it is possible to build up an idea of how the presence of such devices could affect the distribution network. For the purposes of this research the amount of CHP was varied between no homes and all homes on the network, in increments of 10%, for each of the two technologies (Stirling engines and fuel cells). In order to get an idea of how location might affect the impacts two scenarios were run for each 10% increment. In the first, micro-CHP is spread evenly across the network (i.e. 10% of the homes on each busbar have micro-CHP); while in the second micro-CHP is bunched at the end of the network (i.e. 10% of the busbars have micro-CHP installed in all homes on the busbar). An example of these scenarios is given in Figure 4.4.

The impacts of solar PV and heat pumps were similarly examined; though only in 25% increments, and only for scenarios where the technologies were evenly distributed across the network. Combinations of micro-CHP and solar PV or heat pumps on the network, were also examined by adding differing amounts of micro-CHP to each of the solar PV or heat pump scenarios. These micro-CHP amounts were added in 25% increments. For example, there would be combinations of 25% solar PV with 25%, 50%, 75% and 100% micro-CHP, and the same for each other 25% increment of solar PV. It was assumed that homes would not have both heat pumps and micro-CHP, as these are both technologies that supply low-carbon heat to the household. Therefore, a 25% heat pump penetration would only be tested in combination with 25%, 50% and 75% micro-CHP, a 50% heat pump penetration with 25% and 50% micro-CHP and a 75% heat pump penetration with just a 25% penetration of micro-CHP.

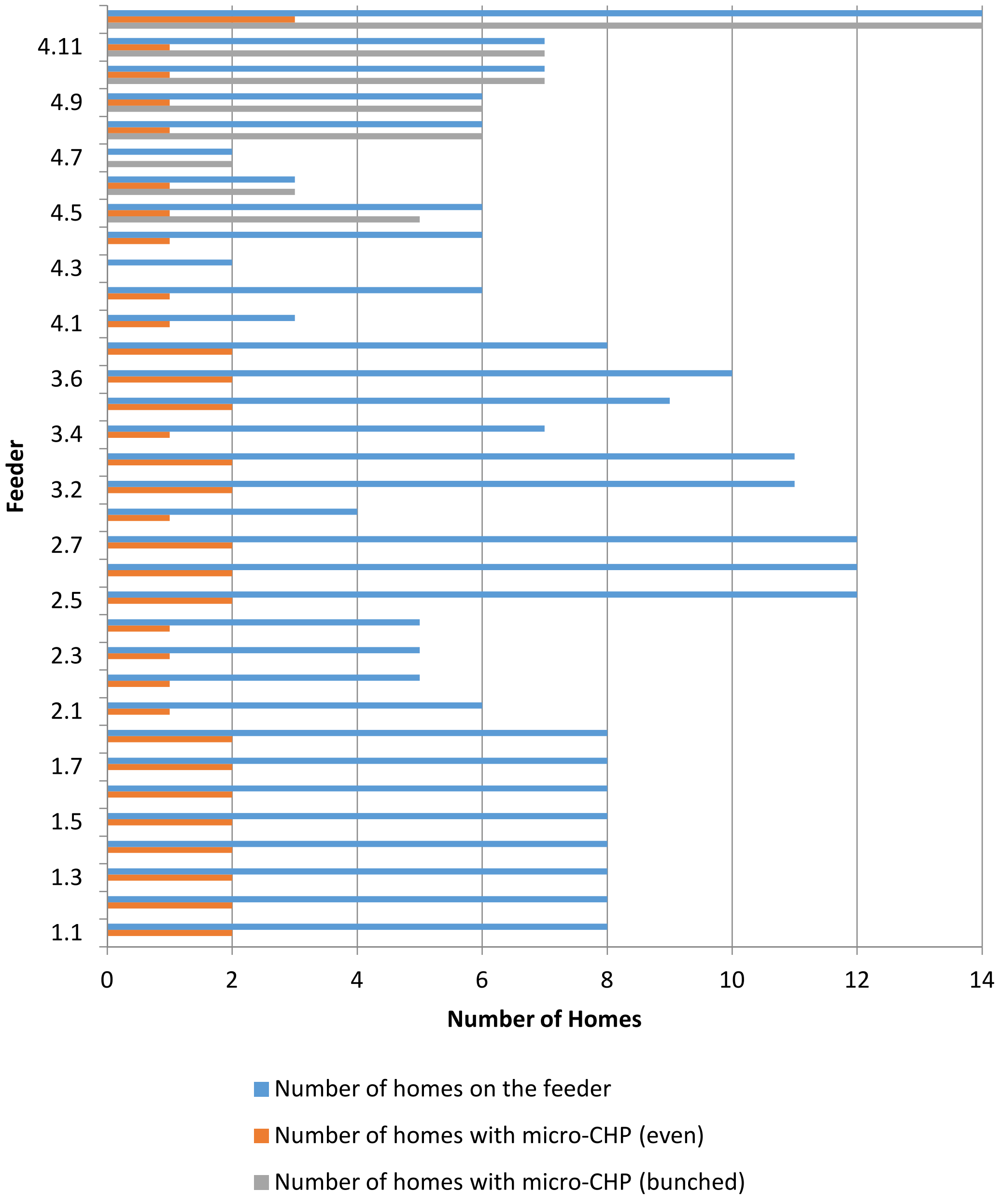

Figure 4.4 The 20% Stirling engine scenario, for both bunched and evenly spread Stirling engine micro-CHP. 20% of the homes at each busbar have Stirling engine micro-CHP (rounded to the nearest whole number). In the even scenario (red lines) the micro-CHP is spread evenly across all feeders, while in the bunched scenario (green lines) all the micro-CHP is on the upper feeders. If, for example the network had 100% Stirling engines, the red and green bars would be the same length as the blue ones.

4.4.3 Determining voltage limits

Voltage rise (or drop) is defined as voltage levels on the network deviating too much from the rated voltage. The threshold for an unacceptable rise (or drop) is defined by regulations or guidelines governing the operation of distribution networks. The limits used in this research were drawn from two sources: the EN50160 regulations (European Committee for Electrotechnical Standardization, 1999), and the Electricity Safety, Quality and Continuity Regulations (2002). The first is an EU-wide standard, while the second is a UK statutory limit. EN50160 indicates that network voltages should remain within ±10% of the rated voltage (though they can exceed this for up to 5% of the time, on a weekly basis). The Electricity Safety, Quality and Continuity Regulations state that networks should not exceed of +6% or -10% the rated voltage under normal operating conditions. Therefore, in this research both the amount of time the network exceeds the +6%/-10% limit and the amount of time it exceeds the ±10% limit were examined. Throughout the remainder of the research, per unit voltage is often used, as it is easier to use this to evaluate voltage levels against regulation limits. Per unit voltage is simply the actual voltage level (in volts) divided by the rated voltage level (also in volts). For example, for a rated voltage of 230 V, an actual voltage of 240 V would be recorded as 1.043 PU.

4.4.4 Extracting specific results from the model output data

Once the outputs from the second piece of code are generated, they are examined in Excel, and specific results are extracted for each scenario:

- the number of minutes in the year for which the voltage exceeds regulations, both the +6%/-10% limit and the ±10% limit;
- the maximum and minimum voltage levels on the network, throughout the year;
- the branch losses on the network (i.e. the losses across all the wires on the network) for the whole year;
- the transformer losses on the network for the whole year;
- the maximum power flow through the transformer, across the entire year;
- the number of minutes in the year for which the transformer is overloaded; and,
- the number of minutes in the year for which the network as a whole exports electricity.

Excel is used to identify how many minutes of the year any busbar is outside of voltage regulations, how many minutes of the year the transformer is overloaded, and the number of minutes for which electricity is exported to the wider network through the grid in-feed. All of these results are in the form of ‘number of minutes for which x exceeds y’, and were calculated using conditional formulas to identify when limits were exceeded and then counting the number of times these conditions were met.

The maximum and minimum voltages on the network for the year were found by simply using Excel to find the maximum or minimum value from all the data points for each busbar for each minute of the year. The maximum power flow through the transformer was found in a similar fashion.

The branch and transformer losses were found by summing the respective losses over the entire year.

4.5 Evaluating the network model

4.5.1 Evaluating whether micro-generation can affect neighbouring networks

This research examines one distribution network in isolation, assuming that the presence of micro-CHP on one network has no or minimal impacts on other networks. Specifically assuming that the presence of micro-CHP on a network does not have an impact on the voltage levels or power flows of neighbouring distribution networks. To test this assumption, a hypothetical setup was established consisting of two Maltby networks side by side. As with the original Maltby network, each of these two networks are fed by a single fixed tap transformer. Only now the two transformers are connected to a larger 35 to 11 kV transformer, which is in turn connected to the wider network. In real life neighbouring networks would not be identical, and a single 35 to 11 kV transformer will often serve several distribution networks, not just two. Despite this, the setup examined here should be sufficient to at least determine if there are impacts on other networks.

The two networks were labelled A and B. Micro-CHP was added to network A, but not to network B, and the parameters of both networks were monitored. This was done to see if the presence of micro-CHP on one distribution network affected the neighbouring distribution network. Five scenarios were examined, one with no micro-generation or heat pumps on either network, three with 100% of homes on network A having micro-generation (Stirling engine micro-CHP, fuel cell micro-CHP and solar PV), and one with 100% of homes on network A having heat pumps.

Tables 4.3 to 4.7 detail the results of these tests. Table 4.3 examines the networks with no micro-generation deployment and confirms that the results from the two networks are identical. It also shows the baseline results for the main transformer. The remaining tables show the results for all the homes on the first network having different types of micro-generation. The first network is obviously affected. As for the second network, voltage levels and network losses are unaffected, the only slight change is that the maximum power flow through the transformer on the second network is slightly higher. As for the main transformer serving both networks, the only changes are that when micro-CHP is present on the network, the maximum power flowing through that transformer is reduced (due to electricity being generated locally), while when heat pumps are present the maximum power flow is increased (due to increased electricity demand on the network). Given the minimal impacts on the second network resulting from micro-generation being present on the first network, it was judged that it was valid to examine an individual distribution network in isolation.

	Network A	Network B	Main Transformer
Minutes of Voltage over regulations	0	0	
Minutes of Voltage under regulations	26	26	
Max Power through transformer (MVA)	1.33	1.33	2.97
Minutes of transformer overload	26	26	0
Max Voltage (PU)	1.05	1.05	
Min Voltage (PU)	0.91	0.91	
Total branch loss (MWh)	10.6	10.6	
Total transformer loss (MWh)	15.2	15.2	62.4

Table 4.1 Examining two identical networks, each with no micro-generation. The first column looks at the impacts on the first network and its transformer, the second at the second network and its transformer and the third column looks at the impacts on the transformer serving both networks.

Net A 100% Stirling	Network A	Network B	Main Transformer
Minutes of Voltage over regulations	567	0	
Minutes of Voltage under regulations	13	26	
Max Power through transformer (kVA)	1.16	1.33	2.74
Minutes of transformer overload	9	26	0
Max Voltage (PU)	1.06	1.05	
Min Voltage (PU)	0.93	0.91	
Total branch loss (MWh)	7.63	10.6	
Total transformer loss (MWh)	10.7	15.2	51.5

Table 4.2 Examining two identical networks, on one (A) all homes have Stirling engine micro-CHP. The first column looks at the impacts on the first network and its transformer, the second at the second network and its transformer and the third column looks at the impacts on the transformer serving both networks.

Net A 100% FC	Network A	Network B	Main Transformer
Minutes of Voltage over regulations	364000	0	
Minutes of Voltage under regulations	2	26	
Max Power through transformer (kW)	1.03	1.33	2.58
Minutes of transformer overload	2	26	0
Max Voltage (PU)	1.08	1.05	
Min Voltage (PU)	0.93	0.91	
Total branch loss (MWh)	7.57	10.6	
Total transformer loss (MWh)	10.6	15.2	50.3

Table 4.3 Examining two identical networks, on one (A) all homes have fuel cell micro-CHP. The first column looks at the impacts on the first network and its transformer, the second at the second network and its transformer and the third column looks at the impacts on the transformer serving both networks.

Net A 100% Solar	Network A	Network B	Main Transformer
Minutes of Voltage over regulations	124000	0	
Minutes of Voltage under regulations	20	26	
Max Power through transformer (kW)	1.33	1.33	2.97
Minutes of transformer overload	18	26	0
Max Voltage (PU)	1.14	1.05	
Min Voltage (PU)	0.93	0.91	
Total branch loss (MWh)	15.1	10.6	
Total transformer loss (MWh)	20.8	15.2	55.7

Table 4.4 Examining two identical networks, on one (A) all homes have solar PV. The first column looks at the impacts on the first network and its transformer, the second at the second network and its transformer and the third column looks at the impacts on the transformer serving both networks.

Net A 100% HP	Network A	Network B	Main Transformer
Minutes of Voltage over regulations	0	0	
Minutes of Voltage under regulations	179	26	
Max Power through transformer (kW)	1.57	1.33	3.39
Minutes of transformer overload	140	26	56
Max Voltage (PU)	1.05	1.05	
Min Voltage (PU)	0.88	0.91	
Total branch loss (MWh)	22.8	10.6	
Total transformer loss (MWh)	31.6	15.2	97.6

Table 4.5 Examining two identical networks, on one (A) all homes have heat pumps. The first column looks at the impacts on the first network and its transformer, the second at the second network and its transformer and the third column looks at the impacts on the transformer serving both networks.

4.5.2 Other assumptions that need to be tested

One other assumption is that results from the Maltby network will also hold true for other networks. To test this, some of the scenarios were also tested on another network, the 'Darlington Melrose' network. This network model was also obtained from Northern Powergrid, and like the Maltby network is situated in a suburban area, though it contains fewer homes than the Maltby network. The results from the two networks are examined and compared in the subsequent chapters (Section 5.4 and 6.4). It was found that as penetrations of micro-generation and/or heat pumps are increased, the results from the Darlington Melrose network follow the same trend as the Maltby network. This indicates that the implications from the Maltby network should hold true for other networks.

In a similar vein, while the Maltby network has a fixed tap transformer, it is possible (though uncommon) for other networks to have variable tap transformers, where the voltage output of the transformer can be raised or lowered to help regulate voltage levels on the network. As with the previous test, this is also examined in more detail in the results chapters (Section 5.3 and 6.4). The same trends in the results as micro-generation and/or heat pumps are increased is observed, though the variable tap network is better able to mitigate these trends. This would indicate that networks with variable tap transformers can accommodate more micro-generation and heat pumps before they start to cause problems.

4.6 Limitations of the data and the model

The models, and data, used within this research which have been described above are not perfect representations of reality. The models have a number of limitations which need to be taken into account, and the impacts of these limitations should be assessed before proceeding with the research. These limitations include: the small sample size of the data and the fact that the data used is simply an average over several homes; the models not simulating the entire distribution network, with the loads in the models being aggregates of the loads of several homes on the network; the assumption within the model that cable reactance does not vary and that loads are evenly distributed across all phases of the three phase supply; and, the assumption that the power factor of the loads (and generators) on the network is fixed, leading to a lack of consideration of fluctuating reactive power flows.

4.6.1 Limitations of the data

One of the key limitations of the data used in this research is its small sample size. The micro-CHP generation and household demand data from the CLNR field trial was taken from just seven households, a relatively small sample size, and in this research the average of these seven households is being used. It is assumed that all homes on the network are identical, and all have the demand and generation profile from an average house. The issue with this is that naturally all homes on the network will have different profiles, with peaks in demand and generation at different times. This is not as much of an issue as each feeder in the network model is made up of several homes (the average number of homes per feeder is 7.4), so multiplying the average demand (or generation) by the number of homes on a feeder should produce a similar demand profile to the total demand from several different homes, which is what the demand (or generation) profile at the feeder would be.

Where the data does become a problem is when looking at the impacts on the transformer. Averaging over several homes has the effect of smoothing out the demand profile. Peaks and troughs in the demand become less pronounced, reducing their impacts. Thus averaging over 249 homes would produce a smoother profile than averaging over seven homes. The impacts on the transformer are dependent on the total demand profile of all 249 homes, which in reality would be considerably 'smoother' than multiplying the average demand profile of seven homes by 249, which is done here. Thus, the impacts on the transformer seen in this research are likely to be over-estimated compared to the impacts that would be seen in reality, i.e. the modelled losses on the transformer and the power flows through the transformer are likely to be greater than in reality.

4.6.2 Limitations of the model

4.6.2.1 Cables within the feeders shown in the model

The first limitation of the model itself is that not all of the network is modelled. In the network model being used in this research homes are grouped together in order to represent loads (shown as feeders in the network model). What these feeders represent in reality are further network cables leading to individual loads. The power flow will also exhibit voltage drop (or rise) across these cables, which is not represented in the model. Given that voltage drop is relative to total load the voltage drop on these cables should be smaller than that exhibited on the main cables that are shown in the network model. This would be due to the loads on these cables being of the size of individual households rather than the size of groups or multiple groups of households, which would be the load on the cables that are represented in the network model.

It is possible to get an idea of an estimate of the upper limit on the voltage drop (or rise) that would be seen on these cables, by examining the voltage drop (or rise) seen on the cables that are represented in the network model. This is done by comparing the difference in voltage levels between busbars that are represented in the model, during periods of high demand and generation on the network. The average voltage drop (at times of high demand) from one busbar to the next adjacent busbar is 0.003 PU, whilst the average voltage drop from the transformer busbar to busbars at the end of the network is 0.025 PU. The average voltage rise (at times of high generation) from one busbar to the next is 0.002, whilst the average voltage rise between the transformer busbar and busbars at the end of the network is 0.02. It would be expected that the voltage drop (or rise) on the wires within the feeders would be at the lower end of this range, due to the lower load and the shorter cables (reducing the resistance, which contributes to voltage drop). thus it would be expected that the voltage drop experienced by cables that are within the feeders in the network model would likely be less than 0.01 PU. Thus over the course of a year, it would be expected that there would be slightly more instances of voltage drop or rise than are exhibited by the model. However, the model will still indicate whether micro-generation and low carbon heat has an impact on voltage levels, and the scale of that impact and how it changes as the amount of micro-generation and low carbon heat on the network is increased, even if it does not capture the full picture.

The wires within the feeders that are not represented in the network model will also exhibit power losses that are not captured in the modelling process. As with the voltage drop, these power losses will be relatively small compared to the power losses on the parts of the network that are modelled. This would be due to the lower amounts of power flowing through these wires compared to the power flowing through the cables that are modelled.

4.6.2.2 Cable Reactance and Phase Imbalance

Cable reactance can have an impact on voltage levels on the network, with higher cable reactance leading to higher voltage drops, and greater power losses. The network model used in this research had built in values for cable impedances(i.e.

resistance and reactance), both positive sequence and zero sequence. However, the model did not account for fluctuations in the reactance. These fluctuations occur as a result of changes in frequency, which in turn are caused by changes in the load. Given the modelling process uses a series of steady state load flow analyses, it does not account for the effects of fluctuating loads. As a result, there may be times where the reactance differs from the rated value, which could increase voltage drop, or voltage rise and either increase or decrease losses in the cables, all of which would not be captured by the model.

Both networks modelled in this research are three-phase networks. In the model there is an assumption that all the loads are evenly distributed across the three phases, whereas in reality this would not be the case. In reality each individual home would connect to one of the three phases. As a result of this there would be fluctuations in the spread of load across the three phases, there may be times where the homes on one phase have significantly higher, or lower demand than the homes on another phase. It may also be the case that a disproportionate amount of distributed generation in the network is connected to one of the phases. Either of these would result in phase imbalance which can have several effects.

Firstly, such imbalances can affect the reactance of the cable, which in turn has effects on the voltage drop and losses in the cable as discussed above. The imbalance between the phases can also directly cause increases in both voltage drop and power losses, as well as decreasing the efficiency of the network transformer, leading to further losses. Therefore, it may be that the losses derived from this research are underestimated, as will also be the case with instances of voltage drop. Phase imbalance as a result of unequally distributed household demand is not as much of an issue, as this research primarily compares networks with distributed generation to networks without, and the demand imbalances would exist in either case. Of more concern are imbalances due to uneven distribution of generation, where the greatest cause of imbalance would be more homes connected to one of the phases choosing to install distributed generation than homes on the other phases. This would be more of an issue with low amounts of distributed generation on the network (the fewer generators there are on the network, the higher the possibility that they are all on one phase). Thus any such imbalances are likely to have more of an effect on networks with low amounts of distributed generation (where the overall impacts are lower) than networks with high amounts of distributed generation.

4.6.2.3 Reactive Power flows

Reactive power arises in circuits as a result of current and voltage being out of phase. In power systems this often arises as a result of inductive loads, such as motors, which are more common in industrial rather than domestic customers. The primary cause of reactive power demand from domestic customers is AC-DC converters. Distributed generation typically produces no reactive power. In this research the reactive power is assumed to be a fixed proportion of the total load (i.e. there is a constant power factor, the ratio of real to reactive power).

One of the impacts of reactive power on the network is increased losses, which are accounted for in this research as both real and reactive power losses are monitored, however increases or decreases in reactive power losses as a result of a fluctuating power factor are not accounted for. Also not accounted for are the impacts on voltage levels, reducing or increasing the flow of reactive power in a system can cause voltage drop or rise respectively. As a result of assuming a fixed power factor it is possible that there will be fluctuations in voltage levels due to changing amounts of reactive power which are not represented in the model.

4.7 Chapter summary

The IPSA-Power network modelling software has been chosen for this research over other alternatives due to its ability to work in conjunction with Python scripts for automation of load flows, and due to the fact that the network models obtained for this research were developed in IPSA. The network being used is the Maltby network. It consists of 249 homes served by a 1 MVA, 11–433 kV transformer. The homes are modelled as 34 different loads (or feeders) on the network, each consisting of a group of homes. Micro-generation on the network is modelled as a generator on each feeder. Heat pumps are modelled as additional load.

The key parameters to monitor are:

- Voltage levels on the network, both the maximum and minimum voltage levels and the number of minutes in the year for which voltage levels exceed the aforementioned limits.

- Losses on the network, both the branch losses (i.e. power losses across the wires and cables that make up the network) and the transformer losses (i.e. the losses across the network transformer).
- Power flows through the transformer, including the maximum power through the transformer and the number of minutes in the year that the transformer spends being overloaded.
- The number of minutes in the year for which the network exports electricity.

The input data is be the same as that detailed in chapter 3 (Section 3.3), combined with data on the penetration of micro-generation and heat pumps on the network. It is fed into a Python script to determine the load and generation on each feeder and generator on the Maltby network. A second Python script instructs IPSA to assign all the values generated by the previous script to the relevant points on the network, then perform a load flow and then extract and record in an output file the results, for each minute of the year. From this output file specific results are extracted:

- the number of minutes in the year for which the voltage exceeds regulations, both the +6% and -10% limits;
- the maximum and minimum voltage levels on the network, throughout the year;
- the branch losses on the network (i.e. the losses across all the wires on the network) for the whole year;
- the transformer losses on the network for the whole year;
- the maximum power flow through the transformer, across the entire year;
- the number of minutes in the year for which the transformer is overloaded; and,
- the number of minutes in the year for which the network as a whole exports electricity.

The scenarios being tested are 10% increments of Stirling engine and fuel cell micro-CHP on the network, both bunched together and evenly spaced. Also being tested are 25% increments of solar PV and heat pump penetration on the network and combinations of 25% increments of micro-CHP with either solar PV or heat pumps.

A key assumption, that a single distribution network can be examined in isolation, is tested. This is done by constructing a hypothetical two network, done by adding a duplicate of the Maltby network to the existing IPSA model, in order to simulate two side by side networks. It is found that the presence of micro-generation or heat pumps on one of these networks did not affect the other.

Further testing examines the differences if a variable tap transformer is used in place of a fixed tap transformer. Also being tested is if the results from the Maltby network would hold true for other networks, and they do. A full analysis of the results from these two tests is presented with the evaluations of the main results from the model in the following two chapters.

5 IMPACTS OF MICRO-CHP ON DISTRIBUTION NETWORKS

5.1 Chapter Introduction

This chapter aims to understand the impacts that micro-CHP could have on the operation and stability of electricity distribution networks.

To begin with there is an examination of distribution network stability using range of metrics (Section 5.2). This is followed by an examination of if and how the impacts of micro-CHP could change if the network uses a variable tap transformer as opposed to a fixed tap transformer (Section 5.3). The results are then tested to see if they are network specific by examining another distribution network and seeing if that produces similar findings (Section 5.4). Then there is a discussion of the implications of the results, an examination of what changes occur if half-hourly or ten-minute data is used in palace of one-minute data, and a comparison of the results with other similar research in the literature (Section 5.5). Finally, there is a summary of the results and discusses some of the implications they have for the operation of electricity distribution networks (Section 5.6).

5.2 Implications from the model for how micro-CHP might affect distribution networks

In examining the impacts of micro-CHP on distribution networks, there were four key metrics that were looked at (as outlined in Chapter 4): voltage levels on the network; energy losses on the network and the transformer; stress on the local transformer; and the amount of time the network as a whole spends exporting electricity

5.2.1 Overview of the baseline scenario

A baseline scenario, with no micro-generation (CHP or otherwise), is used as a reference to understand the impacts of deploying micro-generation.

The results of IPSA modelling for the baseline scenario are summarised in Table 5.1. Several of the results examined involved the levels of voltage on the network. Specifically examined were the number of minutes throughout the year for which voltage levels go either above or below regulation limits and the maximum and minimum voltage levels on the network. The regulation limits used were drawn from the Electricity Safety, Quality and Continuity Regulations (2002), which state that networks should not exceed of +6% or -10% the rated voltage under normal operating conditions.

In the baseline scenario, the voltage reduces by more than 6% of the rated voltage (i.e. below 0.94 PU) for 26 minutes, which would not be an operational concern for the network as this amounts to just 0.005% of the year. At no point do voltage levels exceed +10% of the rated voltage. One thing of note for voltage levels is that all instances of voltage drop occurred in November and December, i.e. during times of high winter demand.

Losses on the network are relatively minor, with branch losses and transformer losses each totalling 2% of demand (4% altogether). The power flows through the transformer do exceed its rated capacity. While the transformer only spends 26 minutes overloaded (just 0.005% of the year) the power flow through the transformer rises to 1.33 MVA, over 30% higher than the rated power of 1 MVA. Short term overloading of power transformers is not uncommon on electricity networks, provided that the power flow does not exceed 1.5 times the rated capacity (which in this case would be 1.5 MVA), and that periods of overload do not last for more than half an hour (Wang et al., 2008). When aggregating the minute-scale data up to half-hourly data, it can be seen that the transformer does not spend any half-hour period overloaded.

Simulation	Baseline
Minutes voltage is under 0.94 PU	26
Minutes voltage is over 1.1 PU	0
Branch losses (MWh)	10.6
Branch losses (% of demand)	0.02
Transformer losses (MWh)	15.2
Transformer losses (% of total demand)	0.02
Max power through transformer (MVA)	1.33
Minutes of transformer overload	26
Max Voltage (PU)	1.05
Min Voltage (PU)	0.91

Table 5.1 Statistics of the network for the baseline scenario.

5.2.2 Impacts of micro-CHP on network voltage levels

5.2.2.1 Changes to instances of voltage drop

Increasing micro-generation within the network by deploying micro-CHP would be expected to reduce instances of undervoltage caused by high demand. Figure 5.1 shows the impact of micro-CHP deployment on voltage drop (i.e. the number of times voltage falls below regulation limits) in the modelled network. For Stirling engine micro-CHP, there is a gradual decline until instances of voltage drop are eventually halved when all homes on the network deploy Stirling engine micro-CHP. For fuel cell micro-CHP there is a similar decline in instances of voltage drop, with the higher power output relative to Stirling engines meaning that the decline is greater, with voltage drop almost eliminated at deployment in all homes. In both cases, if micro-CHP is bunched together at one end of the network, the initial decline in instances of voltage drop is more gradual because the micro-CHP in these bunched areas has almost no impact on areas of the network with no micro-CHP, which still experience a voltage drop.

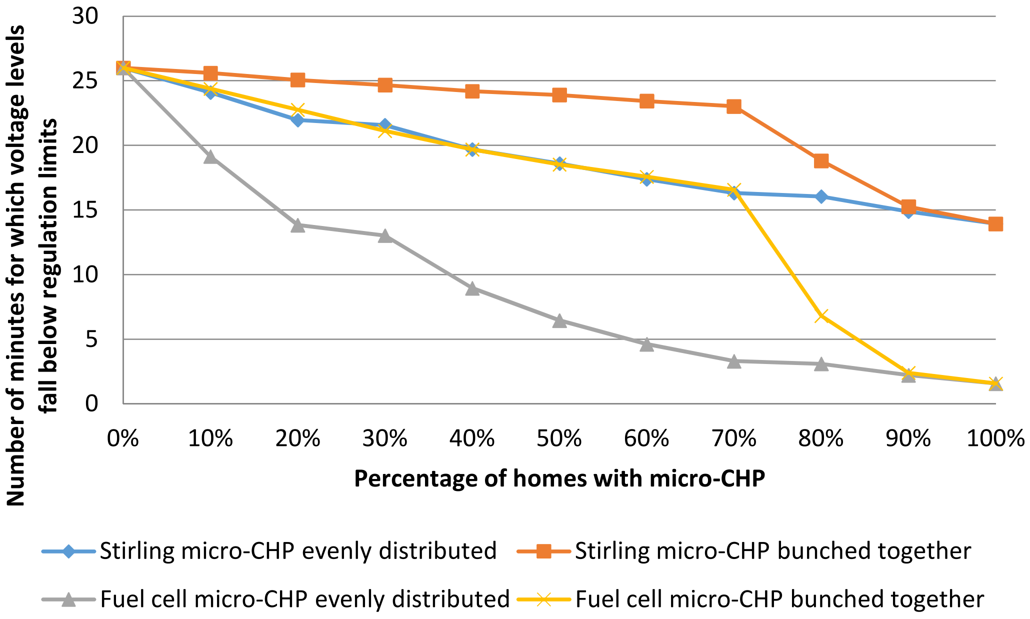

Figure 5.1 Instances of voltage drop for Stirling engine and fuel cell micro-CHP. Changes in the amount of time voltage levels on the network spend below regulation limits, for different amounts of homes on the network having micro-CHP.

5.2.2.2 Changes to instances of voltage rise

While deploying either micro-CHP technology would not raise voltage levels above the upper limit of +10%, both technologies, at sufficient concentrations, raise voltage levels above the lower limit of +6%.

5.2.2.3 Changes to maximum and minimum voltage levels

Stirling engine micro-CHP increases both maximum and minimum voltage levels by at most 0.02 PU (Figure 5.2). While fuel cell micro-CHP increases the minimum voltage level by at most 0.06 PU and the maximum voltage level by at most 0.03 PU (Figure 5.3). This difference between the two is caused by the differences in generation profiles between Stirling engines and fuel cell micro-CHP. Stirling engine generation fluctuates with heat demand while fuel cells operate at a constant output. Since they both have the same maximum output of 1 kW, and since the maximum voltage level is likely to occur when Stirling engine generation is at its peak, they are similar changes to the maximum voltage. However, the minimum voltage will occur when Stirling engines are generating less electricity, while fuel cells will still be operating at either full or potentially half output, hence why fuel cells affect the minimum voltage level by more than Stirling engines.

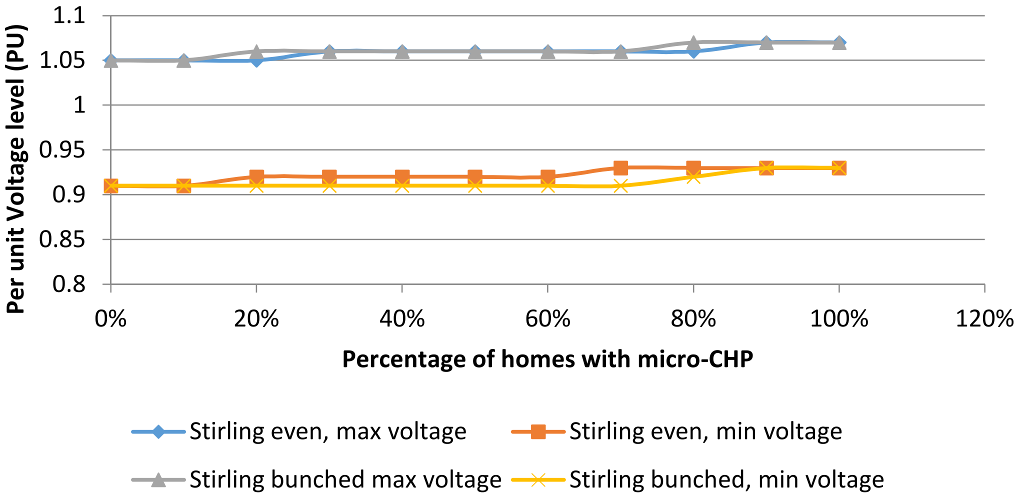

Figure 5.2 Changes to maximum and minimum voltage levels when Stirling engine micro-CHP is deployed on the network.

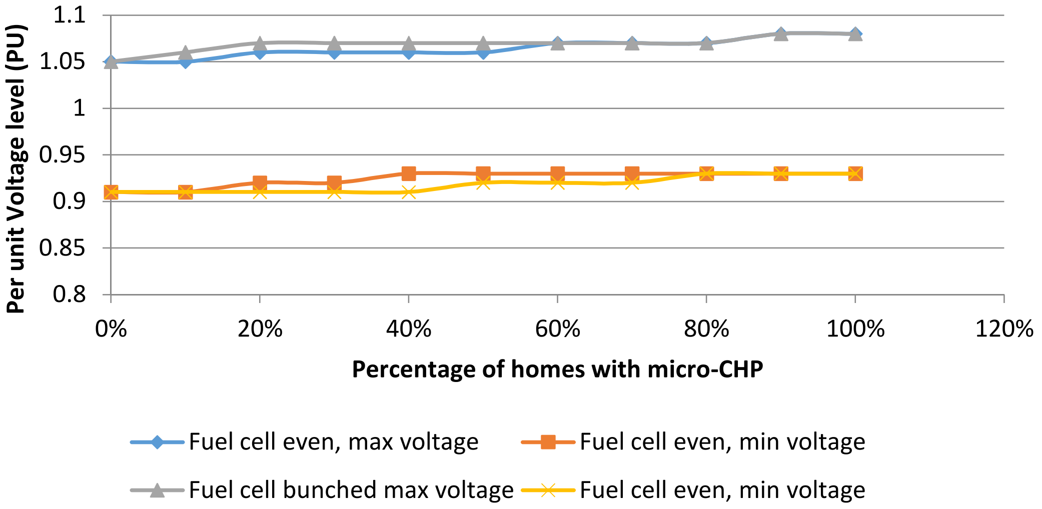

Figure 5.3 Changes to maximum and minimum voltage levels when fuel cell micro-CHP is deployed on the network.

5.2.3 Impacts of micro-CHP on network losses

Network losses are split into two types: the branch losses, which are the losses on the wires and cables that make up the network (Figure 5.4); and the transformer losses, which are the losses across the transformer (Figure 5.5).

Deploying Stirling engine micro-CHP on the network causes both the branch and transformer losses to gradually decline, by up to 3 MWh per year. This decline is caused by reduced demand for grid electricity when Stirling engines are present, meaning less energy is flowing through the transformer and wires, and thus less is being lost.

The impacts of fuel cell micro-CHP are more complicated. Losses across the transformer initially decline, and then begin to rise again. The initial decline, as with Stirling engines, is due to reduction in demand for grid electricity, leading to less power flows through the transformer. The subsequent rise is due to increases in the amount of time the network becomes an exporter of electricity, meaning the total power flows through the transformer will rise; just that much of the power will now be flowing in the opposite direction. As for the branch losses, for evenly spaced micro-CHP, power flows are initially reduced before increasing again as more electricity is generated locally. In the case of fuel cell micro-CHP being bunched at one end of the network, the losses are more linear. While bunched up fuel cell micro-CHP significantly reduces the power flows to those parts of the network where it is present, this is mitigated by a considerable amount of the generated electricity flowing to other areas of the network, leading to a more gradual reduction in the total amount of power flowing around the network.

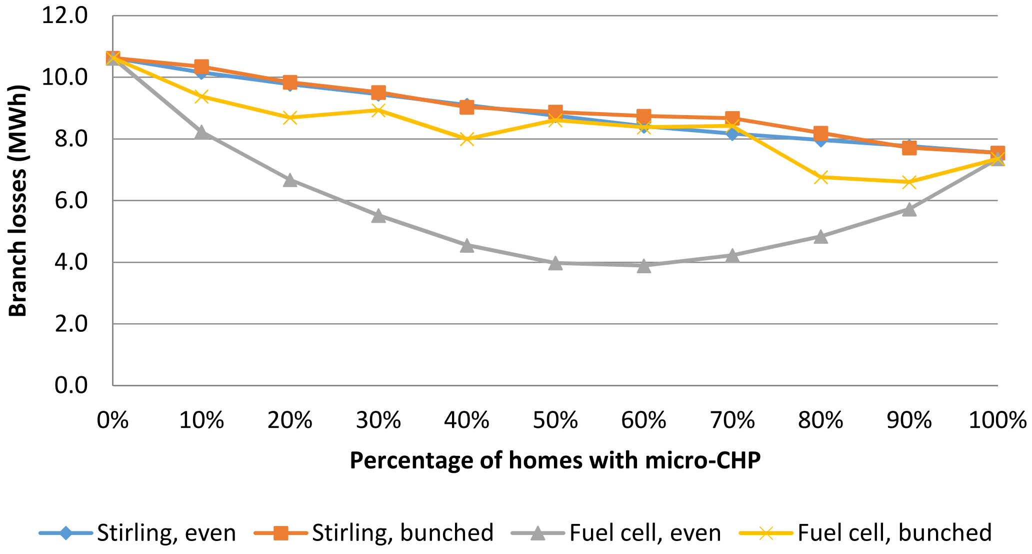

Figure 5.4 Total annual branch losses on the network. Changes in the amount of energy lost on the wires and cables of the network over an entire year, for different amounts of homes having micro-CHP.

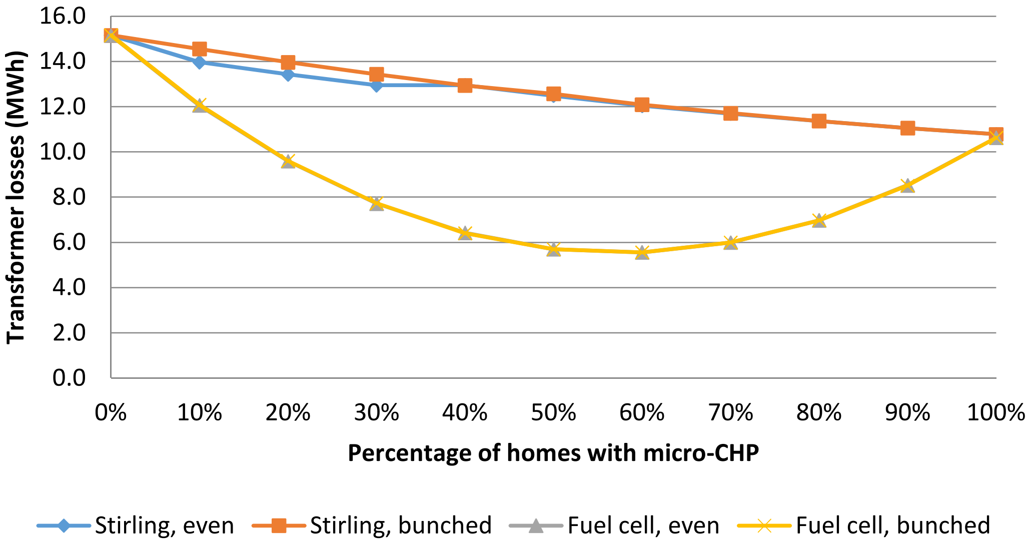

Figure 5.5 Total annual transformer losses on the network. Changes in the amount of energy lost across the network transformer over an entire year, for different amounts of homes having micro-CHP.

5.2.4 Impacts of micro-CHP on the network transformer

Two metrics are used to understand the impacts of micro-CHP on the transformer: (i) the number of minutes in the year the transformer spends being overloaded; and, (ii) the maximum power flow through the transformer.

The modelled transformer has a power rating of 1 MVA. Exceeding this rating leads to overheating and degradation of the transformer, which shortens its operational lifespan. The impacts of micro-CHP on both of metrics is generally beneficial. As seen in Figures 5.6 and 5.7, the presence of micro-CHP, either fuel cells or Stirling engines, causes a steady decline in both the number of minutes of overload and the maximum power through the transformer, with the decline being steeper in the case of fuel cell micro-CHP. This decline will be due to the presence of micro-CHP reducing demand for grid electricity, and especially reducing instances of high demand for grid electricity (as seen in Section 3.3.1) which are most likely to put strain on the transformer. This indicates that the presence of micro-CHP on the network could extend the operational lifespan of the transformer by reducing the strain on it.

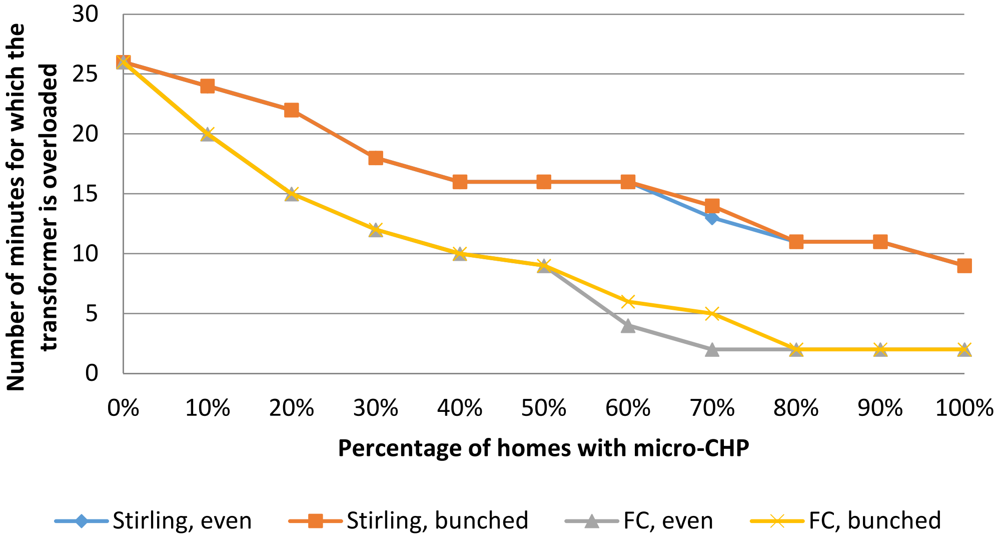

Figure 5.6 Instances of transformer overload with micro-CHP on the network. Changes in the amount of time the network transformer spends being overloaded, for different amounts of homes having micro-CHP.

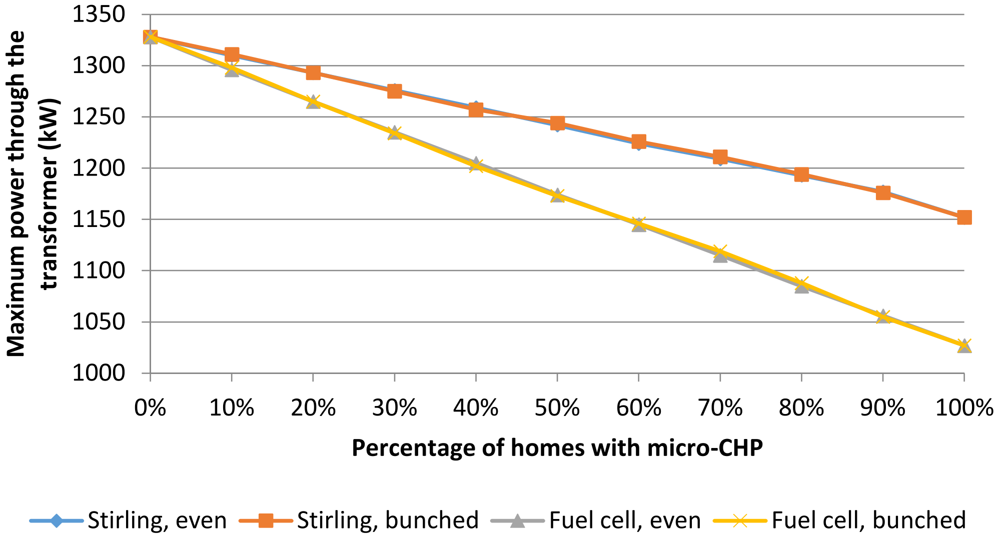

Figure 5.7 Maximum power flow through the transformer with micro-CHP on the network. Changes to the maximum power through the transformer, for different amounts of homes having micro-CHP.

5.2.5 Instances of net export from the distribution network

Given that micro-CHP at times generates more electricity than its household is consuming, it could be expected that there would be times when networks whose homes have a high penetration of micro-CHP to become net exporters of electricity to the wider grid. Figure 5.8 shows how instances of export increase as the number of homes with micro-CHP increases. Stirling engine micro-CHP causes relatively few instances of export. Even when all homes have Stirling engine micro-CHP, the network spends less than 10% of the year exporting electricity. Fuel cell micro-CHP has much more of an impact, and when all homes have fuel cell micro-CHP, the network spends over 75% of the year being a net exporter of electricity. The only impact of this export identified by the model would be an increase in transformer losses due to "reverse" power flows across the transformer, accounted for in the transformer losses, which have already been examined in Section 5.2.3. The export of electricity may have impacts further upstream on the wider electricity network which are not captured in the modelling process used in this research.

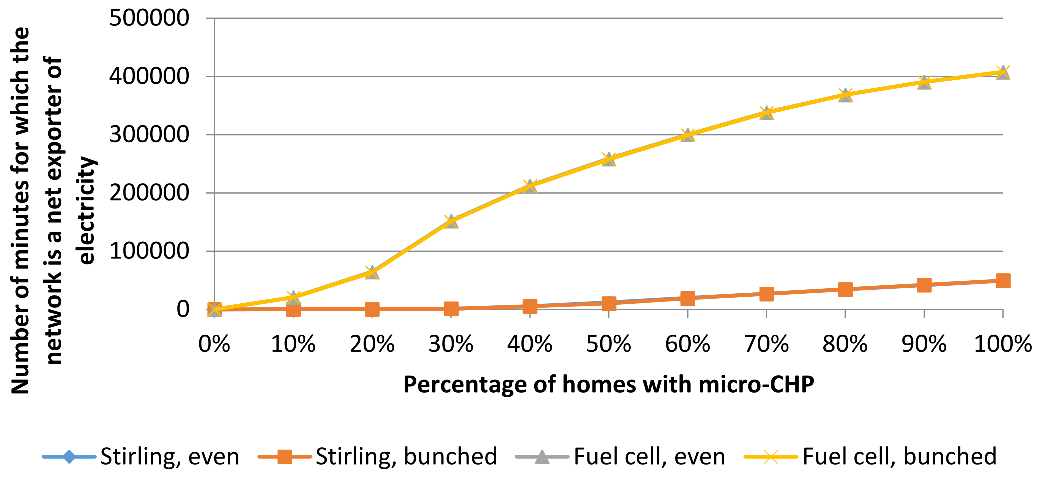

Figure 5.8 Amount of time a network with different levels of micro-CHP exports electricity.

5.3 Implications of a variable tap transformer

The insights above are for a network where the transformer tap position, which is mainly used to control the voltage levels on the network, is fixed, as is standard on most distribution networks. This section instead examines the consequences of deploying micro-CHP into an identical network with a variable tap transformer.

Losses on the network, power flows through the transformer and net export from the network as a whole are unaffected by the change to a variable tap transformer. The only operational metrics that are affected are the voltage levels, although the impacts are minor and the maximum and minimum voltage levels are unaffected.

Only the instances of voltage exceeding regulations are affected, as shown in Figure 5.9 and 5.10. Here it can be seen that although starting from the same baseline, the presence of micro-CHP on the network reduces instances of voltage drop by slightly less at low levels of micro-CHP, but slightly more at high levels of micro-CHP, though the change is only of the order of a few minutes of the year, and thus relatively small.

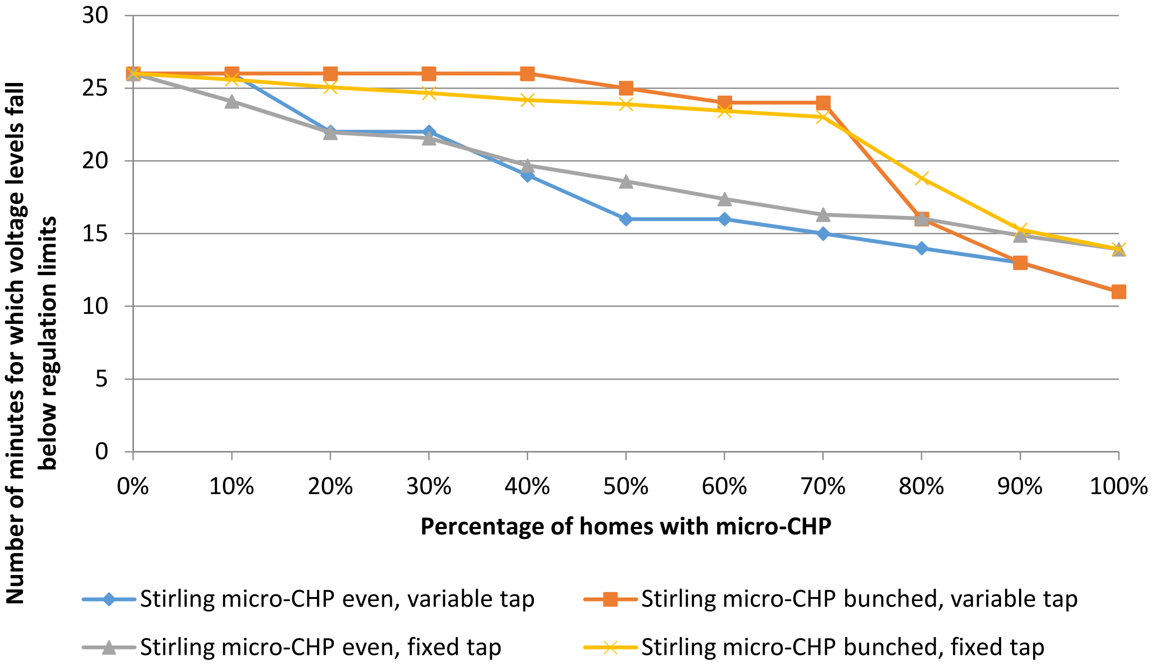

Figure 5.9 **Comparison between fixed and variable tap networks for instances of voltage drop for Stirling engine micro-CHP.**

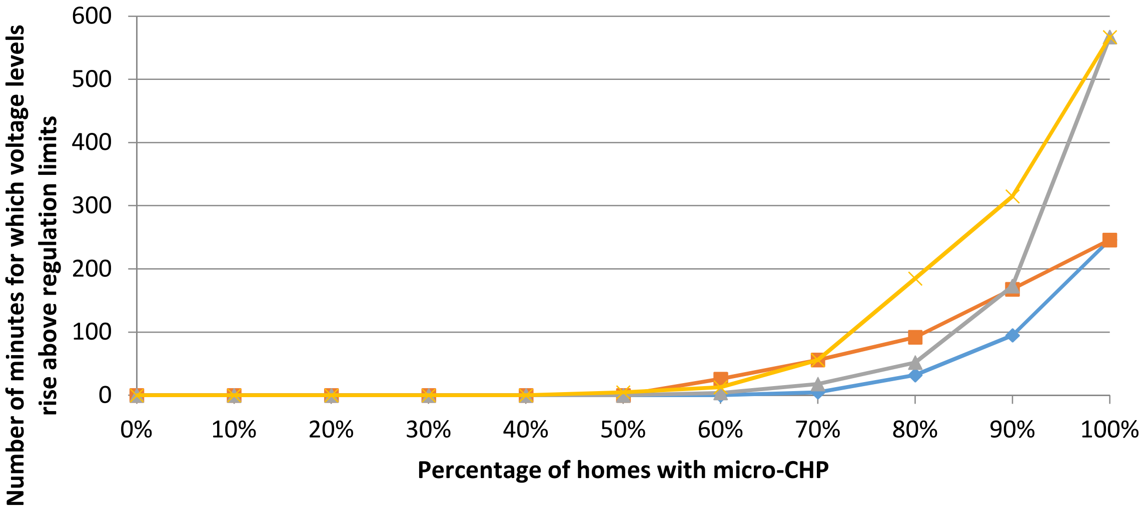

Figure 5.10 Comparison between fixed and variable tap networks for instances of voltage rise for Stirling engine micro-CHP.

5.4 Comparison with another network

The insights above are for only a single network, the 'Maltby' network, and it is important to consider whether these insights can be generalised to other distribution networks. Network data is not available for most distribution networks in the UK. A detailed of analysis of multiple distribution networks is too extensive to be covered fully in this research, not to mention the fact that access to other distribution networks is limited.

To understand whether the results presented here can be generalised to other networks, the analysis was repeated with the Darlington Melrose network. This network is located on the outskirts of a large market town in County Durham. The network has a similar makeup of homes as the Maltby network, though slightly fewer in number, with the Darlington Melrose network serving only 188 homes overall, compared to Maltby's 249. The Darlington Melrose network also has a smaller transformer, with a capacity of only 800 MVA.

The same metrics were calculated for Darlington Melrose as for Maltby. In general, the data for the Darlington Melrose network follows the same trend as the data for the Maltby network as the number of homes with micro-generation is increased, although for the Darlington Melrose network the values are generally lower than for the Maltby network.

For example, Table 5.3 shows changes in voltage drop when micro-CHP is present on the networks. Both networks see similar proportional falls in instances of voltage drop when micro-CHP is present, although as a percentage of the baseline value, the fall is greater for the Darlington Melrose network.

	Darlington Stirling engines	Maltby Stirling engines	Darlington Fuel Cells	Maltby Fuel Cells
0%	14	26	14	26
50%	9	19	2	6
100%	4	14	0	2

Table 5.2 Comparison of instances of voltage drop on the Maltby and Darlington Melrose networks.

The reason for the reduced impact of micro-CHP on the Darlington network is most likely its smaller size. Reduced overall demand and shorter distances for electricity to travel to reach homes will contribute to reduced instances of voltage drop and reduced network losses. The reduced overall demand will also lead to lower stress on the transformer. Although the transformer is also smaller than is on the Maltby network, the reduction in demand will still lead to less instances of overload as the demand is reduced by more than the capacity of the transformer, the transformer on the Darlington Melrose network is 20% smaller than on the Maltby network, while Darlington Melrose has 25% fewer homes.

5.5 Discussion

The outputs from the model indicate that the biggest impact of micro-CHP is in reducing losses on the network. Stirling engine micro-CHP causes a linear decrease in losses as the amount of micro-CHP on the network is increased, with branch and transformer losses eventually reducing by 30% compared to the baseline when all homes on the network have installed micro-CHP.

Fuel cell micro-CHP has a bigger impact on network losses than Stirling engine micro-CHP, though the reduction in losses follows a different profile as fuel cell micro-CHP is installed. When fuel cell micro-CHP is bunched together at the end of the network, there is a linear reduction in losses as more micro-CHP is installed, similar to what occurs with Stirling engine micro-CHP. When fuel cell micro-CHP is evenly distributed across the network, losses initially decline, until 60% of the network has fuel cell micro-CHP, after which losses rise again. At 60% of the network having micro-CHP losses are reduced by 63%, though this rises to just a 30% reduction when all homes have fuel cell micro-CHP.

5.5.1 Does high temporal resolution data provide more insight than lower resolution data?

This question was already examined to some extent in chapter 3 (Section 3.4). Here the effects of aggregating data will be examined further, by looking at the differences to the results from the network modelling when using half-hourly and ten-minute data.

5.5.1.1 Half-hourly data

When using half hour data, there are far fewer instances where voltage exceeds regulations. There are no instances of voltage drop in scenarios when using half-hourly data. The maximum voltage levels when using half-hourly data are similar to those seen in the one-minute data, but the minimum voltage levels are higher (by about 0.08 PU) when using the half hour data, and the changes due to the presence of micro-CHP are not as great. Thus the half hour data captures less of the impacts of micro-CHP on network voltage levels.

Losses on the network show the same overall trend as in the one minute case, but the actual numbers are 24-28% lower (depending on the scenario) than in the one-minute case. This is likely because the half-hourly data does not capture the highest instances of demand that the one minute data does, and it is these instances of high demand that cause the most losses on the network.

The impacts on the transformer are also lower when using the half-hourly data, there are no instances where the transformer is overloaded, and the maximum power through the transformer is considerably lower, though is similarly reduced by the presence of micro-CHP; as with the network losses, this difference is due to the half hour data not capturing the highest instances of demand as the one minute data does.

The export follows a similar trend as with the one minute data, and the amount of time the network spends exporting electricity is similar when using one minute data; but the total amount of exported electricity does change. The total amount of export is reduced when using half-hourly data instead of one-minute data, with the size of the reduction declining as the total amount of generation, and thus export, increases. When half the homes deploy Stirling engine micro-CHP there is a 72% decline in annual export, which falls to 5% when all homes deploy fuel cell micro-CHP.

5.5.1.2 Ten-minute data

As with the half-hourly data, when using ten-minute data there were no instances where voltage levels dropped below regulations. The maximum voltage level is similar to that seen in the one-minute and half-hourly data. The minimum voltage levels are slightly lower when using ten-minute data than when using half-hourly data, but still higher than when using the one-minute data (by about 0.6 PU). Thus as with the half-hourly data, the ten-minute data gives less information on the impacts of micro-CHP on voltage levels.

The network losses follow the same trend, but the actual losses are a 21-24% lower (depending on the scenario) than when using the one-minute data, but still higher than when using the half-hourly data. This will be for the same reason, that the ten-minute data does not capture the instances of highest demand, which cause the most losses, as the one-minute data does.

Impacts on the transformer are also reduced when using 10 minute data. At no point is the transformer overloaded, and the maximum power through the transformer is reduced, though not by as much as when using the half hour data; this is due to the ten-minute data not showing the periods of highest demand as the one-minute data does.

The network export follows the same trend as when using the one minute data, and the amount of time the network spends exporting electricity is similar when using both ten-minute and one minute data. As with the half-hourly data, the total annual export is reduced when using ten-minute data instead of one-minute data, and the reduction declines as generation increases, starting at a 44% reduction when half of homes deploy Stirling engine micro-CHP, and falling to a 3% reduction when all homes deploy fuel cell micro-CHP.

5.5.2 Comparison with the literature

Of the papers looking at micro-CHP and networks discussed back in Chapter 2 (Section 2.4.3). One performed similar research to what is presented in this chapter.

Thomson and Infield (2007) examined the effects of installing micro-CHP and solar PV on network voltage levels. They used 1.2 kW_e micro-CHP devices and 2.16 kW_p solar PV devices on a model comprising of six distribution networks. The parameters they examined were the mean peak voltages during typical winter and summer days, averaged over all connection points.

The peak summer voltage can be compared with the maximum voltages found in this research. The summer voltage is used from their research as in all cases it was higher than the peak winter voltage, and thus would be the overall maximum voltage. For micro-CHP they examined scenarios where 0, 23% and 100% of the homes had micro-CHP. Although their research used voltage values in volts, these can simply be converted to per unit voltages by dividing over the rated voltage. In the three cases the maximum voltage was found to be 1.07 PU, 1.072 PU and 1.075 PU. The maximum voltages found in this research for similar amounts of micro-CHP were 1.055 PU, 1.059 PU and 1.07 PU. Therefore their baseline case shows a higher maximum voltage, potentially due to lower demands relative to the size of the network. But it also shows a similar maximum voltage when all homes have micro-CHP and also shows a gradual increase in maximum voltage levels when micro-CHP is present on the network. The increase is smaller in their case, but this may be due to their higher baseline voltage.

Their research did differ from that presented here in that they found that having 100% Stirling on the network lead to voltages that exceeded +10% of the rated voltage. It is possible that this can be accounted for by their higher baseline voltage, meaning the presence of distributed generation raises voltages to higher levels. Alternatively it could just be that in their simulated data, Stirling engine micro-CHP generates more electricity than in the field trial data used here; recall that in chapter 3, Figure 3.8 showed that, on average, Stirling engines in the trial spent very little time generating more than 600 W, and no time at their maximum output of 1 kW.

What was not examined in their research was the number of instances of voltage rise. The literature on micro-generation has a tendency to focus on the metrics at times of peak demand and generation. However this research looks at instances of voltage rise over the entire year as well as peak voltages, and has found that the presence of Stirling engines and especially micro-CHP can substantially increase instances of voltage rise, even if they cause only a small increase in peak voltage levels. This is potentially a significant impact for the operation and stability of networks which is not examined elsewhere in the literature.

Ackermann and Knyazkin (2002) discussed potential impacts of distributed generation on networks. One possible impact they analysed was the impact on network losses. They performed an algebraic analysis of the impacts distributed generation might have on network losses and found that as long as distributed generation output is less than approximately double the load on the network losses will be reduced. Note this relationship is for the power output/demand and power losses at a specific point in time. This relationship can be examined using the data generated in this research. If their approximation holds true, then there should be a strong positive correlation between times that generation on the network exceeds twice the demand and times that losses are increased (compared to a case with no micro-generation). This can be done for fuel cell micro-CHP, when 50% of homes deploy micro-CHP, the correlation coefficient between times when generationis more than double demand and times when losses are increased is 0.79. When all homes deploy fuel cell micro-CHP, the correlation coefficient is 0.86. Both these values indicate strong positive correlation, consistent with the approximate relationship defined by Ackermann and Knyazkin (2002).

5.6 Chapter Summary

The aim of this chapter was to assess the potential impacts of different deployment levels of micro-CHP on electricity distribution networks, in order to determine if the deployment of micro-CHP would be beneficial or detrimental to the operation and stability of electricity distribution networks. To that end, four key metrics were examined: voltage levels on the network, energy losses on the network and the transformer, stress on the local transformer, and the amount of time the network as a whole spends exporting electricity.

Stirling engine micro-CHP has some beneficial impacts on the network through reducing losses and reducing excess power flows through the transformer. Fuel cell micro-CHP also benefits the network through reducing losses and excess power flows through the transformer, in both cases potentially by more than Stirling engine micro-CHP does. Neither technology has any significant detrimental impacts on the network.

6 NETWORK IMPACTS FOR COMBINATIONS OF SOLAR PV, HEAT PUMPS AND MICRO-CHP

6.1 Chapter Introduction

In this chapter, the IPSA model is used in an attempt to answer the research questions 'How are these impacts likely to compare with those of solar PV and heat pumps?’ and ‘What are the consequences of deploying combinations of both micro-CHP and other technologies on the same distribution network?' The scenarios feature varying amounts of heat pumps and solar PV, and different combinations of micro-CHP (either fuel cell or Stirling engine) and heat pumps or solar PV.

The results from the model for solar PV, both with and without micro-CHP, are examined (Section 6.2). This is followed by a similar examination of the results for heat pumps (Section 6.3). Then, there is an examination of if and how the results may change if the network uses a variable tap transformer as opposed to a fixed tap transformer, and an exploration of how the results may change beyond the Maltby network by repeating the analysis on the Darlington Melrose network (Section 6.4). The results are then compared to those from similar research in the literature

(Section 6.5). Finally, the results are summarised and some of the implications they have for the operation of electricity distribution networks are discussed (Section 6.6).

6.2 Impacts of solar PV on distribution networks

This section investigates the potential effects of domestic scale solar PV on distribution networks, to see both how they compare to the effects of micro-CHP, and how the effects of solar PV are affected by the additional presence of micro-CHP on the network.

A variety of scenarios were examined, firstly four solar PV only scenarios, where 25%, 50%, 75% and 100% of the homes on the network are examined. Then for each of these four solar PV scenarios, four levels of micro-CHP were added (again 25%, 50%, 75% and 100%), for each of the two types of micro-CHP. Thus giving a total of 36 scenarios being analysed (four solar PV only scenarios, sixteen solar PV and Stirling engine micro-CHP scenarios, and sixteen solar PV and fuel cell micro-CHP scenarios).

6.2.1 Impacts of solar PV on network voltage levels

As can be seen in Table 6.1, solar PV slightly reduces instances of voltage drop, though not by as much as either Stirling engine or fuel cell micro-CHP. The reduced impact is due to the fact that all instances of voltage drop occur during time of peak demand in November and December, when solar PV is generating little to no electricity. Of more concern are the impacts of solar PV on voltage rise. Table 6.1 also shows that solar PV can have a large impact on instances of voltage rise. Solar PV can, in sufficient quantities, causes the network to exceed the +10% limit. Half the homes having solar PV causes the network to exceed the limit for a few minutes of the year, and 75% and 100% of homes having solar PV causes the network to exceed the limit for 1.6% and 5.3% of the year. This would indicate that large amounts of solar PV on a single network can have considerable destabilising effects, through increasing instances of voltage rise.

Minimum voltage levels are slightly increased (by up to 0.02 PU) by the presence of solar PV, but maximum voltage levels are increased almost linearly as the amount of solar PV on the network increases, by up to a total of 0.09 PU.

Percentage of homes with solar PV	Minutes of voltage under 0.94 PU	Minutes of voltage over 1.1 PU	Maximum voltage (PU)	Minimum voltage (PU)
0%	26	0	1.05	0.91
25%	24	0	1.08	0.92
50%	22	2	1.1	0.93
75%	20	8780	1.12	0.93
100%	20	27880	1.14	0.93

Table 6.1 Impacts of solar PV on network voltage levels.

The results from the model indicate that the effects of solar PV on voltage levels could have considerable impacts on the operation of distribution networks. The increase in instances of voltage rise caused by the presence of solar PV may necessitate network reinforcement and changes to the way networks are operated in order to minimise instances of voltage rise.

6.2.2 Impacts of solar PV on network losses

At low levels of solar PV on the network, the losses are slightly reduced, but not by as much as micro-CHP, as shown in Figure 6.1. However; as more homes on the network have solar PV, the losses increase. The losses with high amounts of solar PV rise above the amount of losses in the baseline case; eventually increasing the total losses by 13.6 MWh, a 60% increase, when all homes deploy solar PV. Compare these losses with those of micro-CHP scenarios which were always reduced, compared to the baseline case. This increase is due to the considerable amounts of electricity being generated by the solar PV flowing around the network and upstream through the transformer.

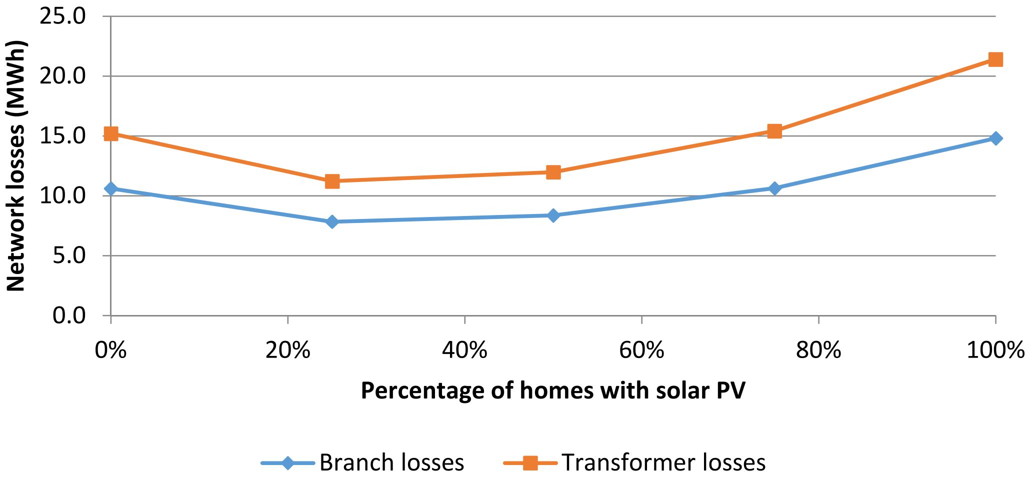

Figure 6.1 Total annual losses on the network when solar PV is present. Changes to the branch and transformer losses when solar PV is present on the network.

6.2.3 Impacts of solar PV on the transformer

Solar PV does not affect the maximum power through the transformer; this would be due to the solar PV not generating electricity when the load on the transformer is greatest. However, there is a slight impact on the number of minutes for which the transformer is overloaded. Solar PV does reduce instances of transformer overload but only by a third, at most. Not by as much as either Stirling engine (which reduces it by two thirds) or fuel cell micro-CHP (which almost eliminates it). The reduced impacts will be due to the moments when the transformer being overloaded occurring when there is high demand on the network, which in the UK is most likely to be winter evenings, which is also when the solar PV will be generating little to no electricity due to an absence of sunlight. This would indicate that solar PV has lower benefits for the network transformer than either micro-CHP technology.

6.2.4 Impacts of solar PV on network export

The presence of solar PV on the network causes the network to spend a considerable amount of time exporting electricity, much more than a network with Stirling engine micro-CHP does, but less than half as much time as a network with a similar amount of fuel cell micro-CHP does.

6.2.5 Impacts of solar PV in conjunction with micro-CHP

Micro-CHP and solar PV in conjunction will reduce instances of voltage drop more than either does in isolation, as shown in Figures 6.2 and 6.3. Though at high levels of micro-CHP, increasing solar PV has little impact.

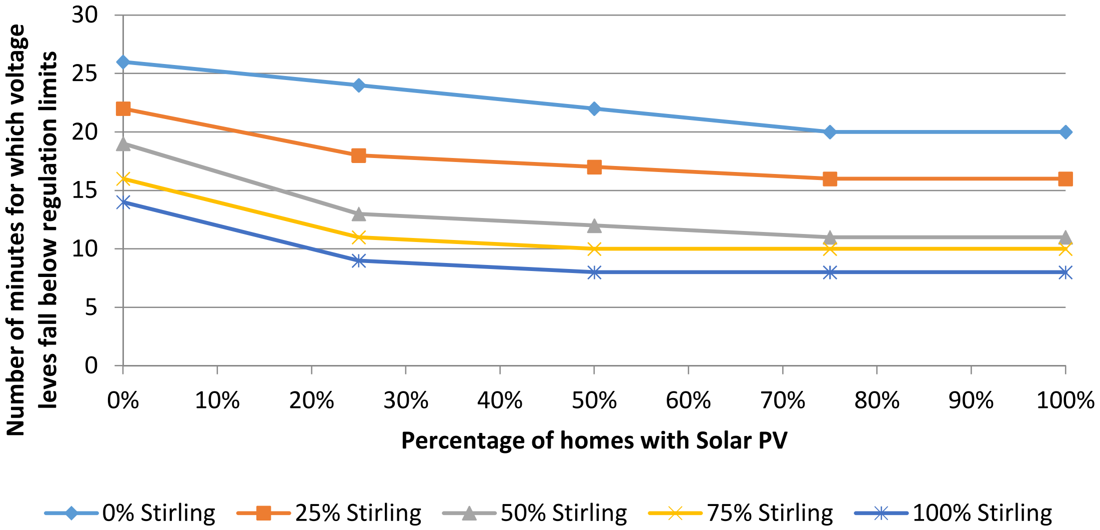

Figure 6.2 Instances of voltage drop when both solar PV and Stirling engine micro-CHP are present on the network. How different levels of Stirling engine micro-CHP on the network change the impacts of solar PV.

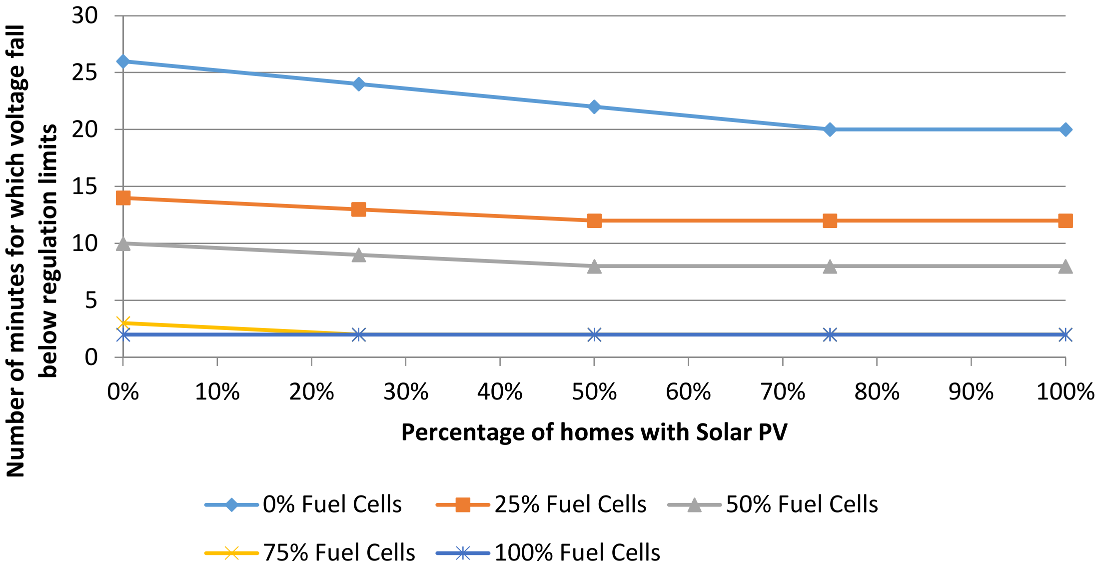

Figure 6.3 Instances of voltage drop when both solar PV and fuel cell micro-CHP are present on the network. How different levels of fuel cell micro-CHP on the network change the impacts of solar PV.

Stirling engine micro-CHP slightly increases instances of network rise, but only by a small amount compared to solar PV in isolation. Figure 6.4 shows that fuel cell micro-CHP can considerably increase the already high instances of voltage rise. Here when half the homes on the network have fuel cell micro-CHP it doubles the instances of voltage rise compared with solar PV in isolation, and when all homes have micro-CHP the instances of voltage rise are more than tripled.

The maximum voltage level is raised slightly by the presence of micro-CHP, with micro-CHP raising the voltage level by 0.02-0.03 PU, much as it does without solar PV. Minimum voltage levels are unaffected by solar PV and micro-CHP has the same impact on the minimum voltage levels as it does on networks with no solar PV.

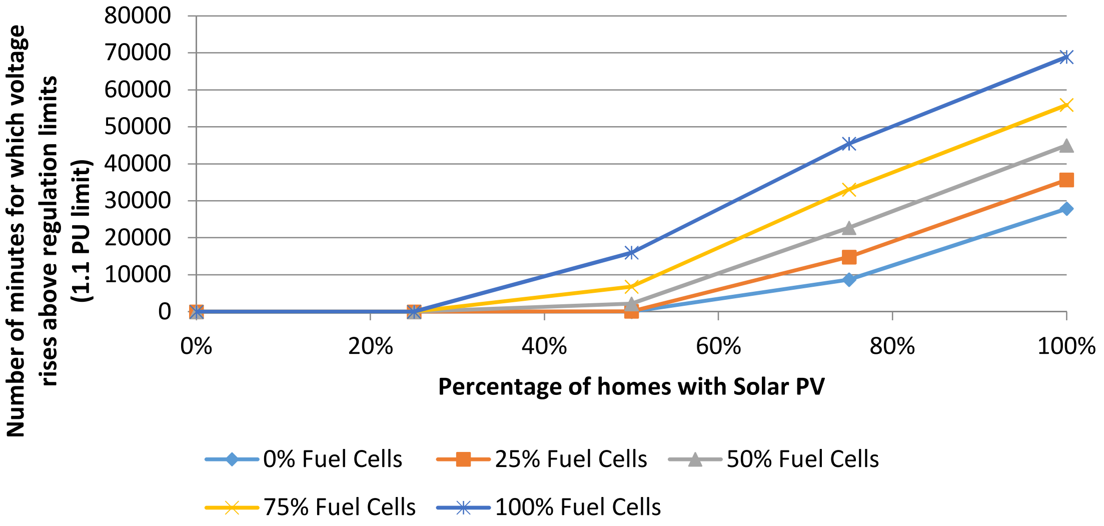

Figure 6.4 Instances of voltage rise when both solar PV and fuel cell micro-CHP are present on the network. How different levels of fuel cell micro-CHP on the network change the impacts of solar PV on the amount of time voltages on the network spend above regulation limits.

As for the impacts on network losses when solar PV and Stirling engine micro-CHP are present, the overall trend is the same as with just solar PV, but the presence of Stirling engine micro-CHP will reduce the losses by a few MWh, as seen in Figures 6.5 and 6.6. Yet the impacts of fuel cells in conjunction with solar PV are slightly more complicated, as seen in Figures 6.7 and 6.8. Low levels of fuel cell micro-CHP (25%) will generally reduce losses by a few MWh, except when there are high levels of solar PV: then losses on the transformer are increased. Increasing fuel cell micro-

CHP deployment to moderate levels (50% & 75%), leads to losses being reduced at low levels of solar PV, and increased at high levels of solar PV. Further increasing deployment to all homes, almost always increases the losses compared to when there is solar PV with no micro-CHP. Overall, at low levels of micro-CHP generation, losses are reduced, but at higher levels, micro-CHP compounds the losses of solar PV. What is going on in the network is that, generally, micro-CHP is always reducing losses during times of high demand and low solar generation (i.e. winter) but increasing losses during times of high solar PV generation, and when micro-CHP generation gets high, the increase in losses during times of high solar generation starts to exceed the reduction in losses during times of low solar generation, which leads to an overall increase in losses on the network, leading to the trends seen in Figures 6.8 and 6.9.

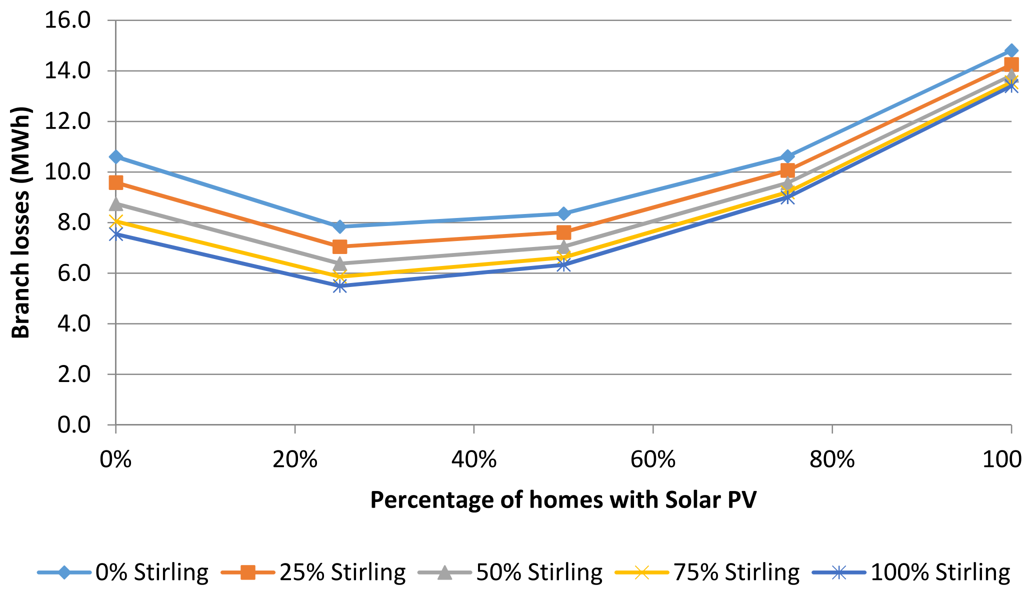

Figure 6.5 **Branch losses when Stirling engine micro-CHP and solar PV are present on the network. How different levels of Stirling engine micro-CHP on the network change the impacts of solar PV on the network branch losses.**

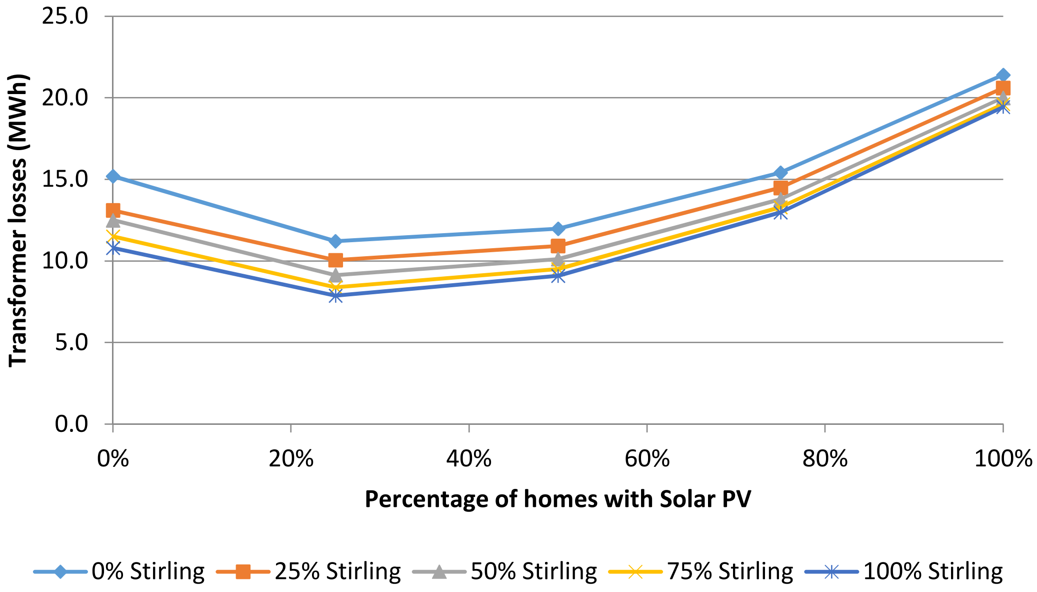

Figure 6.6 Transformer losses when Stirling engine micro-CHP and solar PV are present on the network. How different levels of Stirling engine micro-CHP on the network change the impacts of solar PV on the network transformer losses.

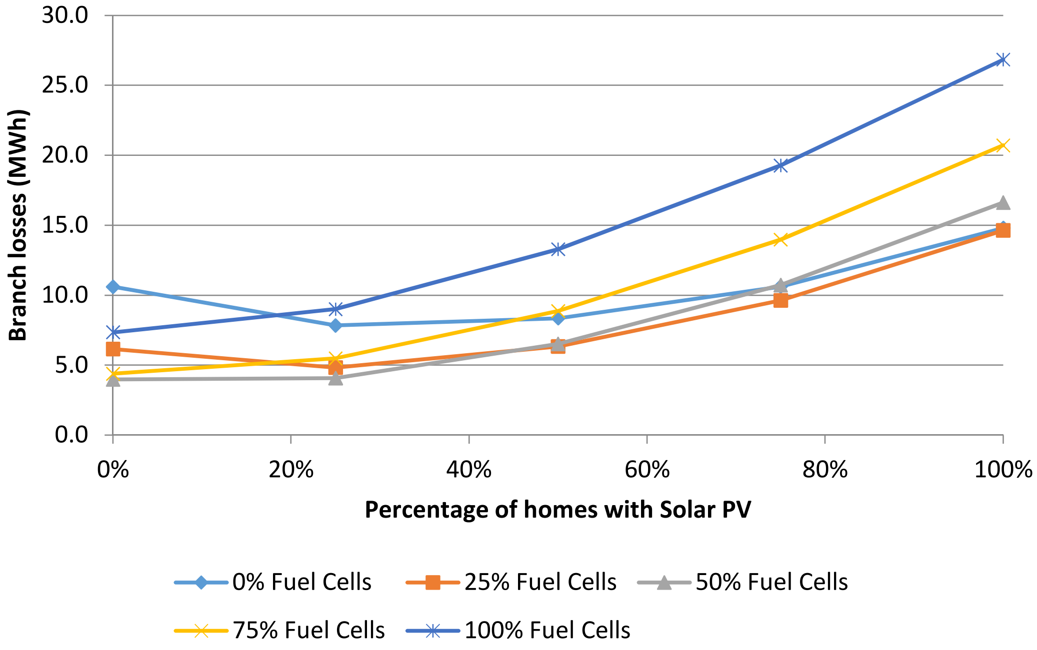

Figure 6.7 Branch losses when fuel cell micro-CHP and solar PV are present on the network. How different levels of Stirling engine micro-CHP on the network change the impacts of solar PV on the network branch losses.

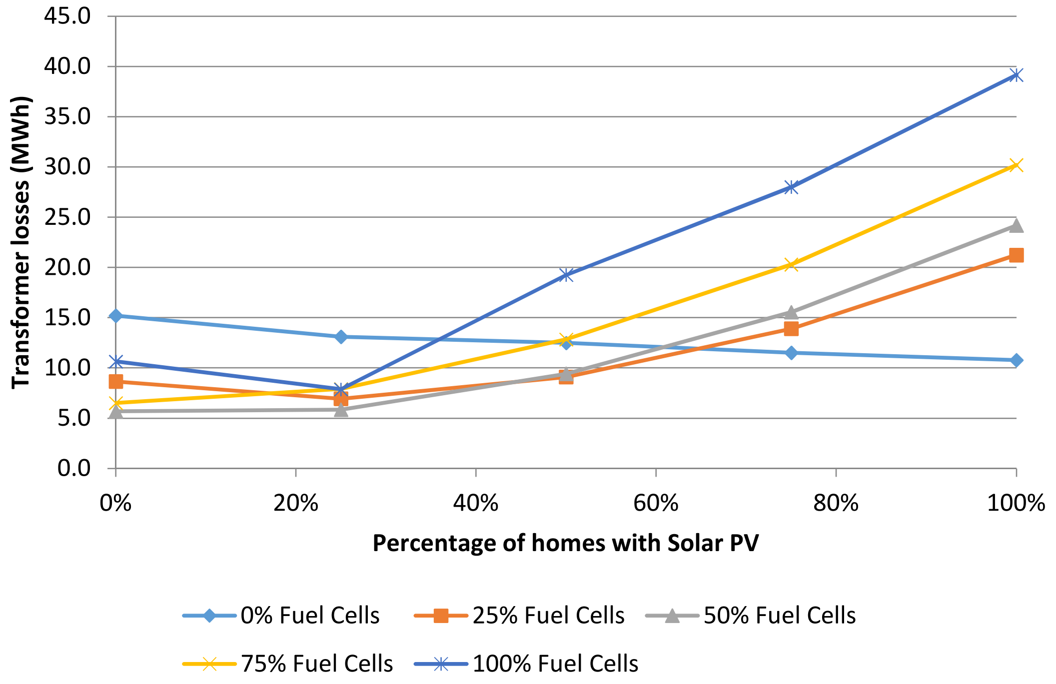

Figure 6.8 Transformer losses when fuel cell micro-CHP and solar PV are present on the network. How different levels of fuel cell micro-CHP on the network change the impacts of solar PV on the network transformer losses.

When it comes to stresses on the transformer, with the maximum power level being unchanged by the presence of solar PV, the presence of micro-CHP on the network as well just changes this as it would on networks with no solar PV. The number of minutes for which the transformer is overloaded are reduced by the presence of micro-CHP alongside solar PV (as seen in Figures 6.9 and 6.10), except in the instance where all homes on the network have both fuel cell micro-CHP and solar PV, at which point the amount of transformer overload rises again, though is still considerably lower than in the baseline case. This increase is likely due to the sheer amount of electricity now being exported upstream, as a result of both solar PV and fuel cell micro-CHP, starting to overload the transformer periodically.

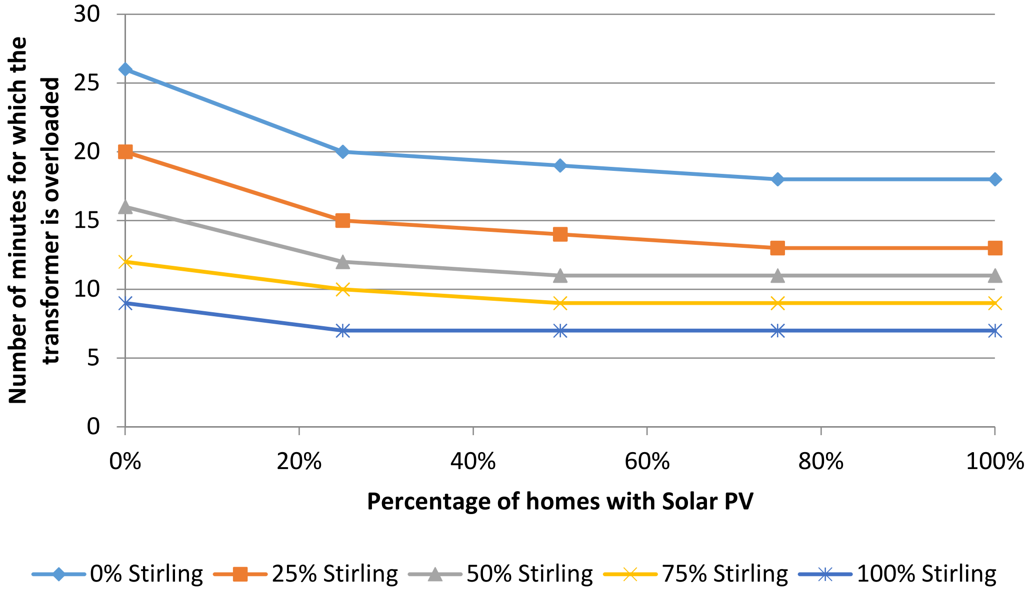

Figure 6.9 Instances of transformer overload when both Stirling engine micro-CHP and solar PV are present. How different levels of Stirling engine micro-CHP on the network change the impacts of solar PV on the network transformer losses.

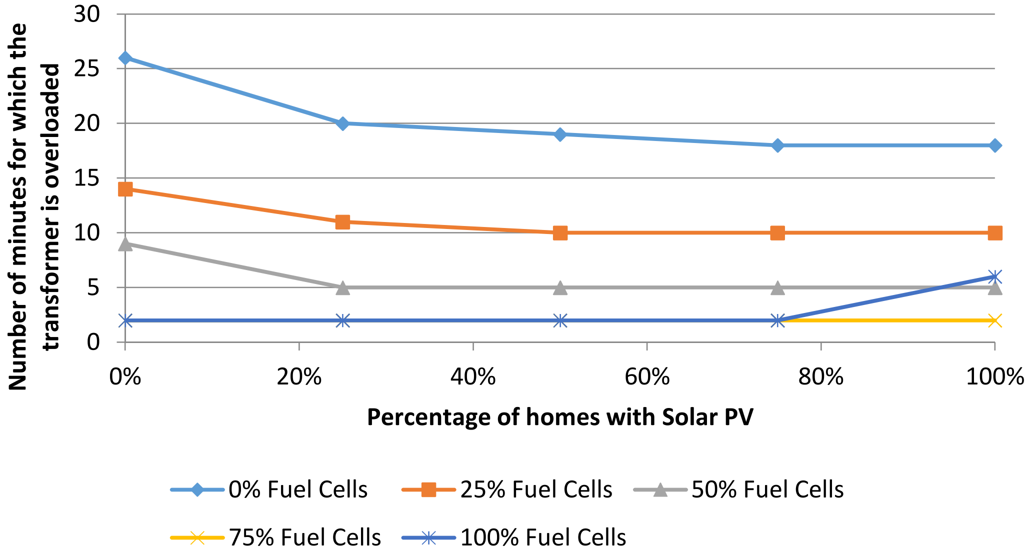

Figure 6.10 Instances of transformer overload when both fuel cell micro-CHP and solar PV are present. How different levels of fuel cell micro-CHP on the network change the impacts of solar PV on the network transformer losses.

The amount of time the network spends exporting electricity is increased by the presence of micro-CHP alongside solar PV. For Stirling engine micro-CHP while the amount of network increases with the amount of Stirling engine micro-CHP, the overall trend as solar PV is increased remains similar. With fuel cell micro-CHP as more units are installed on the network, the presence of solar PV has less of an impact on the amount of time the network spends exporting electricity, mainly due to the fact that with fuel cell micro-CHP the network already spends most of the year exporting electricity.

Overall, the presence of micro-CHP on a network which already has solar PV can worsen the effects of solar PV on voltage rise. It can also have mixed impacts on the network losses (depending on the levels of micro-CHP and solar PV), and have beneficial impacts on power flows through the transformer, except at high levels of both solar PV and fuel cell micro-CHP.

6.3 Impacts of heat pumps on distribution networks

This section investigates the potential effects of heat pumps on distribution networks, to see both how they compare to the effects of micro-CHP, and how the effects of heat pumps are affected by the additional presence of micro-CHP on the network.

As with solar PV, a variety of scenarios were examined, firstly four heat pump only scenarios, where 25%, 50%, 75% and 100% of the homes on the network install heat pumps. Then for the first scenario (25% heat pumps), three levels of micro-CHP (25%, 50%, 75%) were added for each of the two micro-CHP technologies. Note there is no 25% heat pump and 100% micro-CHP scenario as it is assumed that homes would only install one technology as they both provide low-carbon heat. For the 50% heat pump scenario, two levels of micro-CHP are added (25% and 50%), and for the 75% heat pump scenario, one level of micro-CHP is added (25%), for each of the two technologies. This gives a total of sixteen scenarios examined: four heat pump only scenarios, six scenarios with heat pumps and Stirling engine micro-CHP and six scenarios with heat pumps and fuel cell micro-CHP.

6.3.1 Impacts of heat pumps on voltage levels

Figure 6.11 shows that heat pumps can increase the amount of time voltage levels on the network fall below the -6% regulation limit. Instances of voltage falling below 0.94 PU more than triple (compared to the base case) if 50% of the network has heat pumps, and increase more than eightfold when all homes on the network have heat pumps. When all homes on the network have heat pumps, the voltage level even drops below the -10% limit for 14 minutes of the year. These changes will be due to the additional electricity demand that heat pumps place on the network driving down voltage levels, and as a result of these changes network operators will likely have to reinforce the network in the presence of heat pumps. These impacts of heat pumps on instances of voltage drop are lower than the impacts of micro-CHP (especially fuel cell micro-CHP) and solar PV on instances of voltage rise. This would suggest that the network is better able to accommodate increases in demand than the presence of micro-generation, at least from a voltage level perspective.

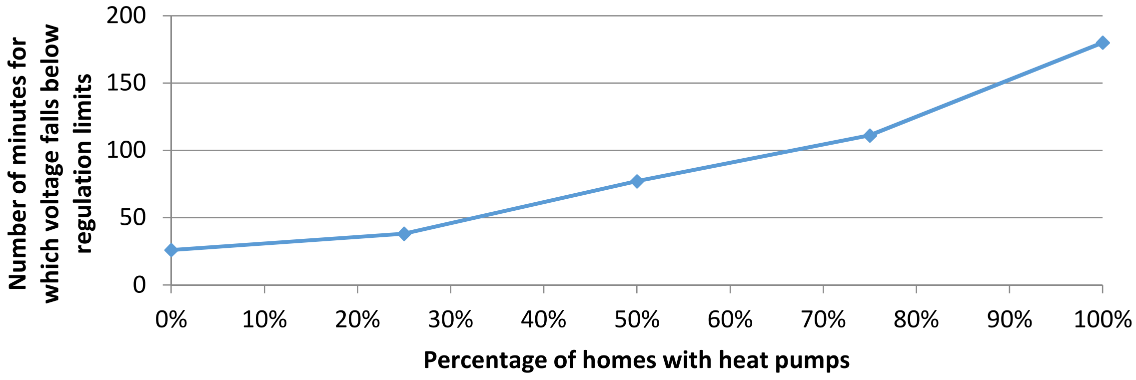

Figure 6.11 Instances of voltage drop when heat pumps are present on the network. Showing changes to the number of minutes for which voltage on the network falls below regulation limits.

6.3.2 Impacts of heat pumps on network losses

As shown in Figure 6.12, heat pumps increase losses on both the wires and transformer on the network, in comparison to micro-CHP which lowers these losses. When all the homes on the network have heat pumps, the losses are increased by 32 MWh, for comparison the best reduction in network losses achieved by (fuel cell) micro-CHP is 16 MWh. As with the voltage levels, this increase is due to the extra electricity demand heat pumps place on the network.

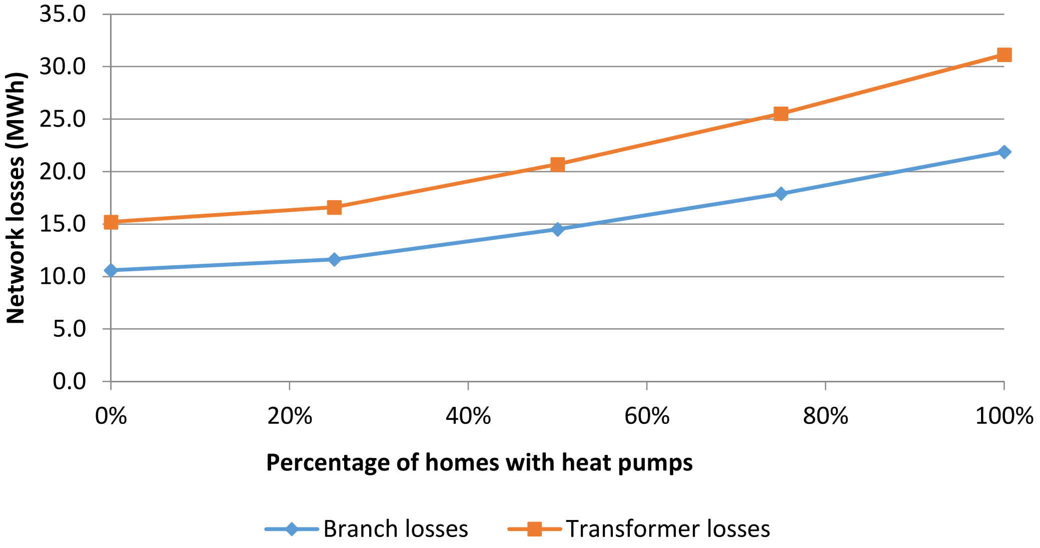

Figure 6.12 Changes to losses on the network when heat pumps are present.

6.3.3 Impacts of heat pumps on the transformer

Figure 6.13 shows the increase in instances of transformer overload, which are much greater than any decreases caused by either micro-CHP or solar PV. Meanwhile, Figure 6.14 shows that the maximum power through the transformer increases almost linearly with the amount of heat pumps, and eventually the power flows through the transformer are increased by more than 50% above the rated power. As mentioned in the previous chapter (Section 5.2.1), literature shows that short term overloading of the transformer is not a problem as long as the power flow does not exceed 1.5 times the rated capacity of the transformer. Thus the fact that the presence of heat pumps could raise the power flow above this level is concerning.

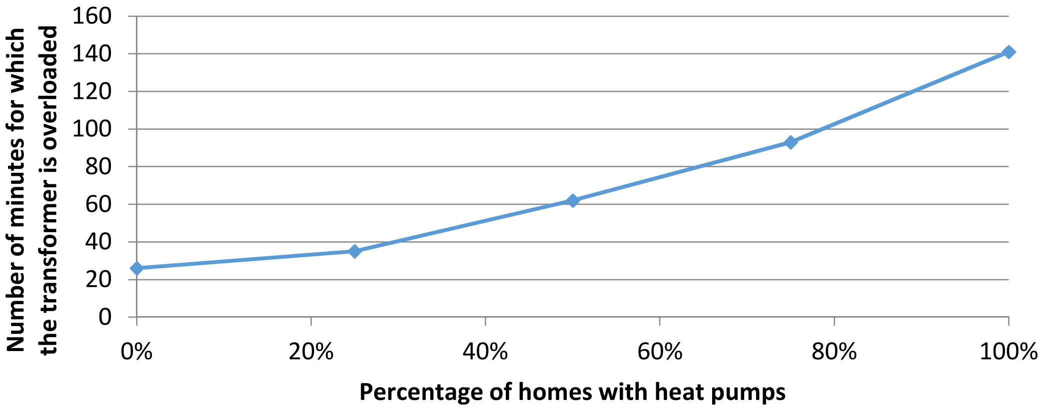

Figure 6.13 Instances of transformer overload when heat pumps are present on the network.

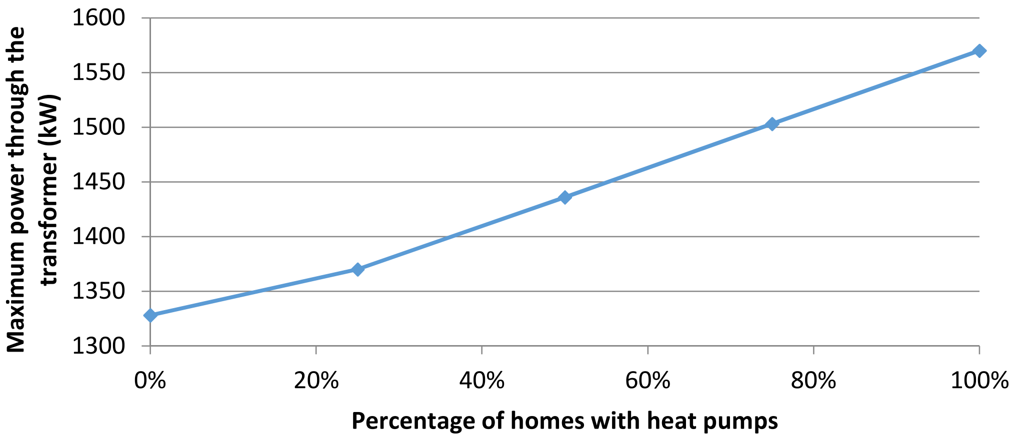

Figure 6.14 Maximum power flow through the transformer when heat pumps are present on the network.

6.3.4 Impacts of heat pumps in conjunction with micro-CHP

Figures 6.15 and 6.16 show that both Stirling engine and fuel cell micro-CHP reduce instances of voltage drop in a similar fashion, though fuel cells produce a greater reduction, when heat pumps are present on the network. With higher levels of micro-CHP and lower levels of heat pumps, instances of voltage drop are still reduced compared to the baseline case. Micro-CHP causes the same amount of increase to the minimum voltage levels; though, in the case of high levels of heat pumps, the increase is from a lower level. These changes in the instances of voltage drop will be due to the generation from micro-CHP, offsetting the additional demand of heat pumps.

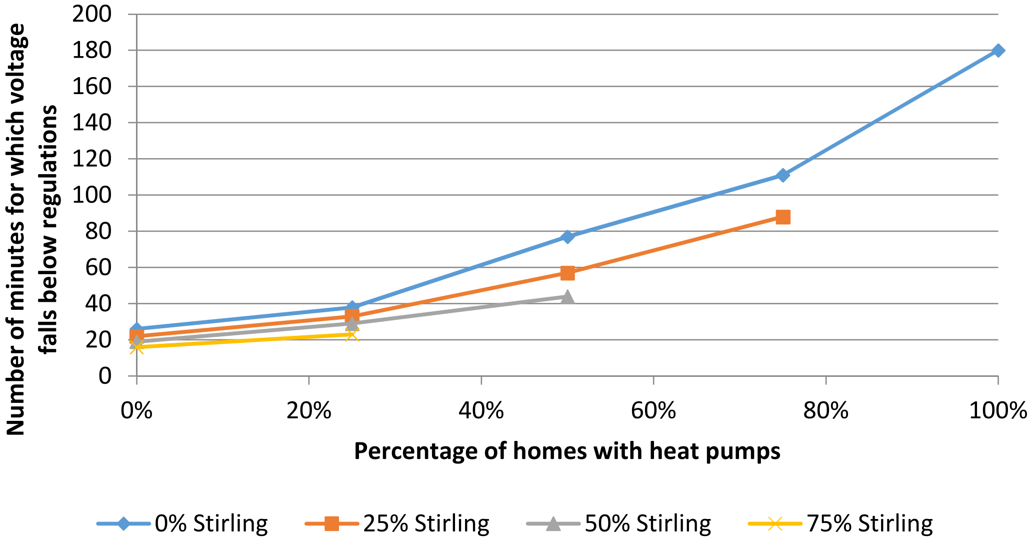

Figure 6.15 Instances of voltage drop when Stirling engine micro-CHP and heat pumps are present on the network. How different levels of Stirling engine micro-CHP adjust the changes caused by heat pumps to the amount of time voltages on the network are below network limits.

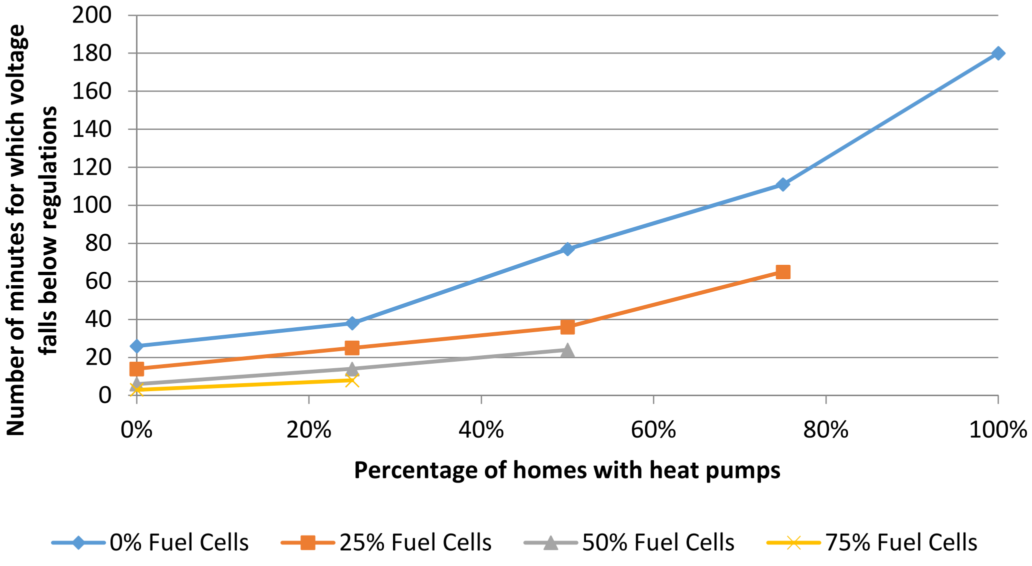

Figure 6.16 Instances of voltage drop when fuel micro-CHP and heat pumps are present on the network. How different levels of fuel cell micro-CHP adjust the changes caused by heat pumps to the amount of time voltages on the network are below network limits.

The losses on the network are reduced by the presence of micro-CHP. Stirling engines will only slightly reduce the losses on the network compared to cases with just heat pumps, and in all scenarios with heat pumps and Stirling engine micro-CHP, losses are higher than the baseline case. Fuel cells reduce losses by more than Stirling engines do, by around 30-50%, as shown in Figures 6.17 and 6.18. Losses in most cases with both heat pumps and fuel cell micro-CHP are less than those in the baseline network, until at least 75% of the homes have heat pumps, at which point losses are still higher than the baseline case even when micro-CHP is also present.

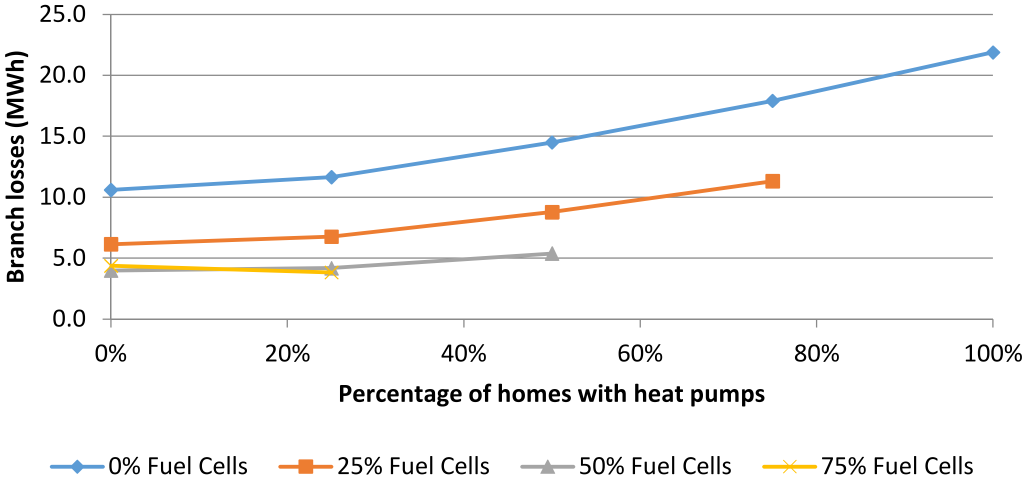

Figure 6.17 Branch losses when fuel cell micro-CHP and heat pumps are present on the network. How different levels of fuel cell micro-CHP adjust the changes caused by heat pumps to the branch losses on the network.

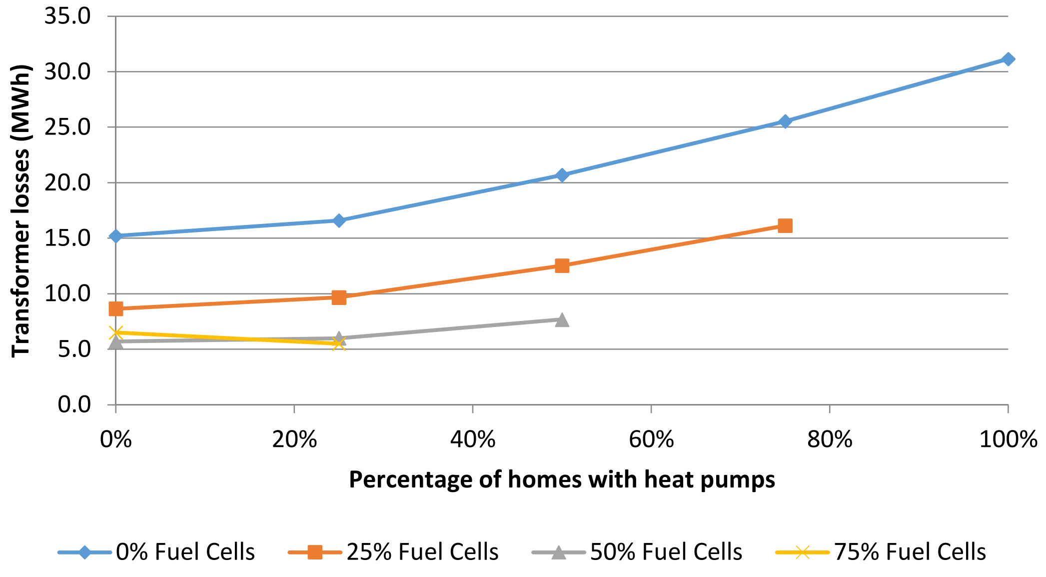

Figure 6.18 Transformer losses when fuel cell micro-CHP and heat pumps are present on the network. How different levels of fuel cell micro-CHP adjust the changes caused by heat pumps to the transformer losses on the network.

As with other parameters, the impacts of heat pumps on the transformer are mitigated by the presence of micro-CHP on the network, with fuel cell micro-CHP causing a greater change than Stirling engine micro-CHP. Once again at low levels of heat pumps and higher levels of Stirling engines, minutes of transformer overload (Figure 6.19) are reduced compared to a network with no micro-generation, and in all other scenarios with heat pumps and Stirling engine micro-CHP the minutes of overload are increased relative to a network with no micro-generation. Conversely; with fuel cell micro-CHP and heat pumps, the minutes of transformer overload (Figure 6.20) are reduced if at least 50% of homes on the network has fuel cell micro-CHP or if only 25% of homes have heat pumps and another 25% have fuel cell micro-CHP; if more than 25% of homes have heat pumps and 25% or less homes have fuel cell micro-CHP instances of overload are increased. The maximum power through the transformer is reduced by the presence of micro-CHP, by a consistent amount compared to all scenarios with just heat pumps. Stirling engines reduce it by up to 150 kW, and fuel cells reduce it by up to 250 kW.

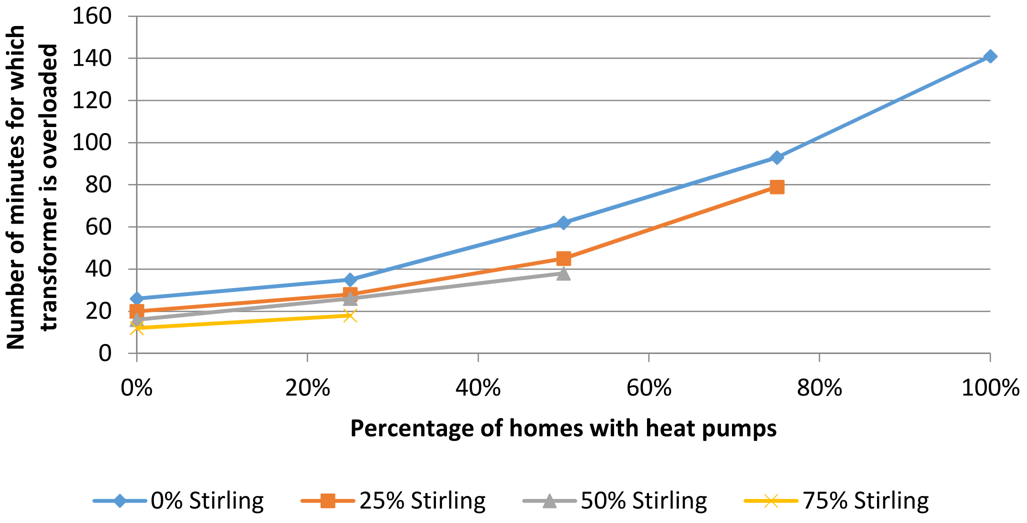

Figure 6.19 Instances of transformer overload when Stirling engine micro-CHP and heat pumps are present on the network. How different levels of Stirling engine micro-CHP adjust the changes caused by heat pumps to the amount of time the network transformer is overloaded.

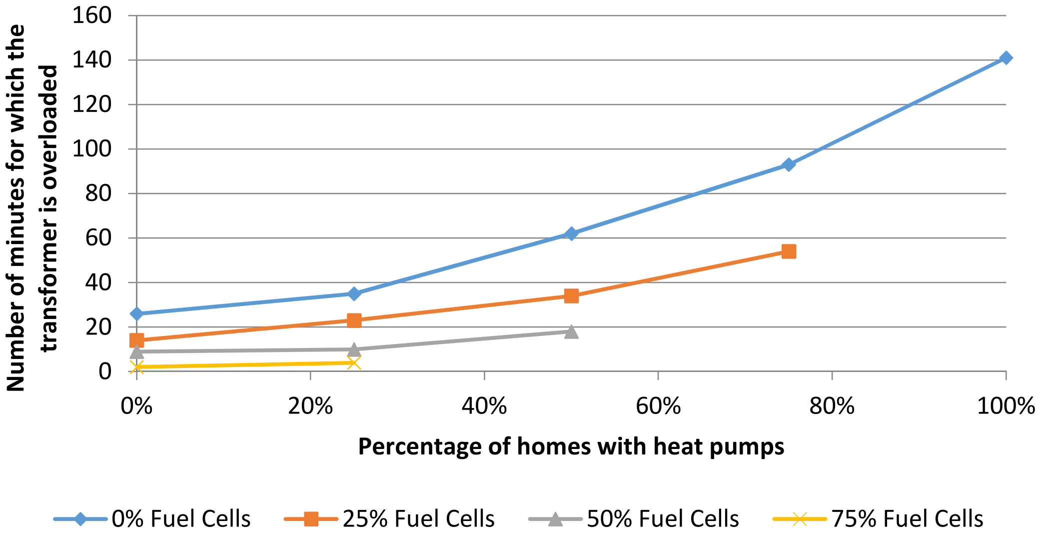

Figure 6.20 Instances of transformer overload when fuel cell micro-CHP and heat pumps are present on the network. How different levels of fuel cell micro-CHP adjust the changes caused by heat pumps to the amount of time the network transformer is overloaded.

Overall, the presence of micro-CHP can mitigate the effects of heat pumps on instances of voltage drop, though heat pumps only slightly reduce the instances of voltage rise caused by micro-CHP. Micro-CHP can also reduce the effects of heat pumps on network losses and power flows through the transformer.

6.4 Impacts on different network setups

As in the previous chapter (Sections 5.3 & 5.4), it will be beneficial to examine the results when the model uses differing networks. Two alternate network setups are here examined: the results from the Maltby network if it were to have a variable tap transformer, and the results from the Darlington Melrose network.

6.4.1 Solar PV and heat pump results on a variable tap network

When solar PV was tested on a variable tap network, the only results that changed were the voltage levels (much the same as with micro-CHP). Table 6.2 shows the changes to instances of voltage drop and rise when comparing fixed and variable tap networks. Instances of voltage drop are almost unchanged. Instances of voltage rise are considerably different. The number of minutes for which voltage levels exceed the +10% limit are considerably reduced, by almost 100% in the 75% solar PV scenario and by 82% in the 100% solar PV scenario. This would suggest (as the micro-CHP results did) that variable tap transformers can mitigate the impacts of micro-generation on instances of voltage rise.

	Fixed Tap		**Variable Tap**	
	Minutes voltage is under 0.94 PU	Minutes voltage is over 1.1 PU	Minutes voltage is under 0.94 PU	Minutes voltage is over 1.1 PU
0%	26	0	26	0
25%	24	0	24	0
50%	22	2	21	0
75%	20	8680	20	3
100%	20	27900	20	5090

Table 6.2 Instances of voltage drop and rise on variable and fixed tap networks for different percentages of homes having solar PV.

For heat pumps, when using a variable tap network rather than a fixed tap network there are almost no changes to instances of voltage drop (there are no instances of voltage rise in either case). The one minor change is in the 25% heat pump scenario where the number of minutes the voltages on the network spend below the -6% limit is reduced by one, from 38 to 37 minutes.

6.4.2 Solar PV and heat pump results on the Darlington Melrose network

Table 6.3 shows the differences in results from the network modelling, for solar PV, between the Maltby and Darlington Melrose networks. As with the comparison of micro-CHP in the previous chapter (Section 5.5), the changes to both networks follow a similar trend as the presence of solar PV on the networks is increased; though the results for the Darlington Melrose network are lower than those for the Maltby network. As stated in the previous chapter, the slightly lower results on the Darlington Melrose network are due to its smaller size compared to the Maltby network.

	Baseline		50% Solar		100% Solar	
	Darlington	Maltby	Darlington	Maltby	Darlington	Maltby
Minutes of Voltage over regulations (1.1 PU)	0	0	0	2	4652	5090
Minutes of Voltage under regulations	14	26	12	22	12	20
Max Power through transformer	980	1330	980	1310	980	1310
Minutes of Transformer overload	13	30	11	18	11	18
Max Voltage	1.04	1.05	1.07	1.1	1.11	1.14
Min Voltage	0.92	0.88	0.92	0.9	0.92	0.9
Total branch loss (MWh)	8.1	10.6	7.1	8.4	12.4	14.8
Total transformer loss (MWh)	7.5	15.2	6.6	12	11.1	21.4

Table 6.3 Results from the model for the Darlington Melrose and Maltby networks when solar PV is present.

As with solar PV and micro-CHP, when heat pumps are present, both networks show similar trends in the results, as shown in Table 6.4. Again the values of the results on the Darlington Melrose network are consistently lower than those on the Maltby network. As before this difference can be attributed to the smaller size of the Darlington Melrose network.

	Baseline		50% Heat Pumps		100% Heat Pumps	
	Darlington	Maltby	Darlington	Maltby	Darlington	Maltby
Minutes of Voltage over regulations (1.1 PU)	0	0	0	0	0	0
Minutes of Voltage under regulations	14	26	36	77	90	180
Max Power through transformer	980	1330	1080	1440	1180	1570
Minutes of Transformer overload	13	30	35	62	90	140
Max Voltage	1.04	1.05	1.04	1.05	1.04	1.05
Min Voltage	0.92	0.91	0.9	0.9	0.89	0.88
Total branch loss (MWh)	8.1	10.6	12.6	14.5	18.8	21.9
Total transformer loss (MWh)	7.5	15.2	11.7	20.7	17.4	31.1

Table 6.4 Results from the Darlington Melrose and Maltby networks when heat pumps are present.

6.5 Discussion

Solar PV and heat pumps are both shown to have considerably greater effects on networks than micro-CHP; having detrimental impacts due to instances of voltage rise in the case of solar PV, and power flows through the transformer in the case of heat pumps. Heat pumps also increased losses on the network, as did higher (>70%) penetrations of solar PV. Solar PV also causes the network to spend much time exporting electricity, though not as much as fuel cell micro-CHP does. The presence of micro-CHP alongside these other technologies can exacerbate the impacts of solar PV, but can mitigate the impacts of heat pumps.

When heat pumps are present on the network they can have a considerable impact on power flows through the transformer. Heat pumps raise instances of transformer overload, beyond 1.5 times the rated capacity when 75% of homes install them. This would indicate that heat pumps may necessitate the installation of larger transformers on networks where they are present. The presence of micro-CHP on the network can mitigate the impacts of heat pumps, reducing the effects on the transformer and network losses.

Solar PV causes the network to spend some time exceeding the +10% limit. As with heat pumps, solar PV will likely necessitate reinforcement of the network to mitigate its impact on voltage levels. Solar PV can, at penetration levels over 75%, cause network losses to increase. These impacts are increased by the presence of micro-CHP, only slightly in the case of Stirling engines, but substantially in the case of fuel cell micro-CHP, now instances of voltage rising above +10% exceed 5% of the year when at least 75% of the network has solar PV and at least 50% has fuel cell micro-CHP. Solar PV may be of more concern to the smooth operation of the network than micro-CHP, due to its more promising uptake potential and just as high (compared to fuel cell micro-CHP) or higher (compared to Stirling engine micro-CHP) network impacts; though the impacts of fuel cell micro-CHP when it is present on networks alongside solar PV are also of concern for the operation of distribution networks.

6.5.1 Comparison with the literature

Solar PV has been more extensively examined in the literature than micro-CHP, one particular paper is of interest, as examines the impacts of solar PV on the same network examined in this research. Castro et al. (2014) examined the impact of solar PV on the Maltby distribution network. They used half hour data, and examined the impacts of solar PV on maximum voltage levels during the summer day of lowest demand. They found that the network can accommodate up to 30% of homes having solar PV without any voltage rise issues. This is similar to findings in this research which suggests that more than 25% of the network having solar could cause voltage rise issues.

The previous chapter compared the micro-CHP results from this research with micro-CHP results from research in the literature that examined the impacts of micro-CHP and solar PV on distribution networks (Thomson and Infield, 2007). It is now possible to also compare the solar PV results, and the combined solar PV and micro-CHP results, with the results from that research. Thomson and Infield (2007) examined networks where 30% and 50% of the homes had solar PV. They compared the voltage levels against the EN50160 standard (±10%) and found that the 30%

solar PV penetration did not cause voltage rise issues, but the 50% solar PV penetration did. The research here also found that the 50% solar PV data pushed network voltages over the +10% limit.

Thomson and Infield (2007) also looked at combing solar PV and Stirling engine micro-CHP on distribution networks, as this research did. They examined two combinations, 50% PV and 100% micro-CHP and 28% PV and 23% micro-CHP. The first of these combinations was also studied in this research, and the latter should be similar to the 25% PV 25% micro-CHP combination in this research. The first of their combinations led to voltages in excess of the +10% limit, they found that adding micro-CHP to a network which already had 50% PV caused the maximum voltage to rise by 1 V. The research here found that adding 100% micro-CHP to a network with 50% PV led to a voltage rise of 2 V, a similar increase. Their second combination: 28% solar PV and 23% Stirling engine micro-CHP did not result in voltages exceeding the +10% limit, examining a 25% solar PV and 25% micro-CHP penetration in this research found the same result.

Rogers et al. (2013) examined using micro-CHP to support the operation of heat pumps, focusing on transformer overload. They found that just 12.5% of the network having ASHPs would cause overload on the transformer. In this research there were instances of transformer overload even with no heat pumps, though it was found that 25% of homes having heat pumps (the smallest penetration examined) would lead to instances of overload increasing by 30%. They also found that 63% of heat pumps and 38% Stirling engine micro-CHP produced no instances of transformer overload. This finding is contrary to the research presented here, where even having 50% heat pumps and 50% Stirling engine micro-CHP leads to a 70% increase in instances of overload. It may be that their simulated data showed a better correlation between times of peak micro-CHP generation and peak heat pump demand than the real world data used in this research, which would explain the discrepancy.

Ackermann and Knyazkin (2002), as discussed in the previous chapter, found that as long as distributed generation output is less than approximately double the load on the network losses will be reduced. The correlation between instances of losses increasing and instances of generation being greater than double the demand was tested for solar PV, as it was for fuel cell micro-CHP, for penetrations of 50% and 100%. With 50% solar PV the correlation coefficient between generation being more than double the demand and network losses being increased was 0.8, and for 100% solar PV it was 0.85. Both indicating strong correlation conforming to the approximate relationship suggested by Ackermann and Knyazkin (2002).

6.6 Chapter Summary

The aim of this chapter was to assess the potential impacts of different deployment levels of solar PV and heat pumps on electricity distribution networks, both on their own and in combination with micro-CHP. In order to both compare the effects of an alternate low-carbon heating technology (heat pumps) and an alternate micro-generation technology (solar PV) to those of micro-CHP, and to see how the presence of micro-CHP on the same network can change the effects of these technologies.

Solar PV causes voltage levels on the network to rise beyond statutory limits. When 50% or of homes on the network have solar PV, the network will spend some time in breach of the +10% limit. Network losses are initially lowered by the presence of solar PV, but as deployment increases they rise again, eventually exceeding the losses in the baseline case. The presence of micro-CHP (especially fuel cell micro-CHP) on the network alongside solar PV can exacerbate the impacts of the latter on instances of voltage rise and network losses.

The presence of heat pumps on the network could increase instances of voltage drop, though by less than micro-generation (both solar PV and micro-CHP) increases instances of voltage rise. They will also increase network losses, and can raise power flows through the transformer to concerning levels (i.e. >1.5 times the rated capacity). The presence of micro-CHP on the network alongside heat pumps could reduce their effects on voltage drop, network losses and power flows through the transformer.

7 SUMMARY

This chapter summarises the overall conclusions of the thesis in Section 7.1. Following this, opportunities for future work are suggested in section 7.2. Then an overview of the key findings in section 7.3 concludes the work.

7.1 Overall Summary

Micro-CHP has been considered as a potential low-carbon heating source in the UK for at least the last two decades. It has seen uptake in Japan and commercial units are available in the UK. Though micro-CHP remains a fringe technology in the UK, and there is uncertainty regarding its uptake potential. Also uncertain are the economic benefits of micro-CHP to the household, the contribution micro-CHP can make to decarbonisation, and the impacts of micro-CHP on electricity networks. This research attempts to examine these uncertainties.

Another micro-generation technology, solar PV, is also examined. Having seen more uptake than micro-CHP, solar PV is a helpful technology to compare micro-CHP against. There is also concern of the impacts of both micro-CHP and solar PV being present on the same network.

As an alternative low-carbon heating technology, which could have impacts on the electricity network through increased demand, heat pumps were also examined. This was to find their impacts on the network and compare them to micro-CHP and to examine if the impacts of heat pumps could be mitigated by the presence of micro-CHP, and vice versa.

7.1.1 Types of micro-CHP

Stirling engines are a well established technology, and are expected to be the fastest growing micro-CHP technology in the short term (Hawkes and Leach, 2005, Hudson et al., 2011, Alanne et al., 2010). They have the advantage of high overall efficiency, but the disadvantage of low electrical efficiency, and hence a high heat to power ratio. Internal combustion engines are a similarly well established technology, and have better electrical efficiency than Stirling engines. Yet, they have a number of disadvantages (detailed in Section 1.1.2), and no commercial presence in the UK. For these reasons ICEs are not considered in this research.

Fuel cells have high electrical efficiencies, and correspondingly low heat to power ratios. They are the subject of considerable research, and are seen as a promising long term micro-CHP technology. Though there are fuel cell micro-CHP devices commercially available, their prices remain high at around £14,000 (Harikishan R. Ellamla et al., 2015). The main disadvantage of fuel cells is that they operate best when they are constantly on, as frequent on/off switching will degrade the fuel cell. This means that fuel cells are best suited to providing base-load heat, which can be topped up by a supplemental boiler at times of high demand.

7.1.2 Key questions over micro-CHP deployment

The main issues surrounding the deployment of micro-CHP are the uncertainties over price and economic viability (Staffell and Green, 2012, Tokyo Gas Co. Ltd. and Panasonic Corporation, 2011, Alanne et al., 2010, Ren and Gao, 2010), which in turn will lead to uncertainties over uptake and penetration rates. The deployment of micro-CHP could have significant impacts on electricity distribution networks (Ackermann and Knyazkin, 2002, Acha et al., 2009, Aki et al., 2006), due to the export of electricity from properties with micro-CHP installed. Also of interest is how micro-CHP compares against other micro-generation, specifically solar PV, and if it compounds the impacts of that technology. Heat pumps also have the potential to impact electricity networks through increasing demand, which may be mitigated by micro-CHP.

The research questions that have been developed are:

- How might micro-CHP affect the cost of heating and greenhouse gas emissions from households?
- What impacts might micro-CHP have on distribution networks?
- How are these impacts likely to compare with those of solar PV and heat pumps?
- What are the consequences of deploying combinations of both micro-CHP and other technologies on the same distribution network?

7.1.3 Data used in the thesis

The Stirling engine, household demand, solar PV and heat pump data used in this research all came from field trials conducted as part of the CLNR project, and was minute-scale data. The fuel cell data was simulated based on the heat demand of the average UK house and the assumption that fuel cells would provide base-load heat, being run at a constant level of output rather than fluctuating to meet changing heat demands. The total annual electricity demand of homes in the trial was compared to the annual electricity demand of the average UK household, and was found to be within 3% of the latter value, suggesting that homes in the field trial roughly corresponded to the average UK household. This was further supported by the fact that the generation profile of the Stirling engine micro-CHP matched the heat demand profile of a typical UK house.

7.1.4 Changing patterns of grid electricity import as a result of micro-CHP

When analysing the data, the amount of time in the year that the household spends importing different levels of electricity from the grid was examined. While both Stirling engines and fuel cells reduce the amount of time the household spends at all grid electricity consumption levels (above zero, that is), both technologies also considerably reduce the amount of time spent at high levels of grid electricity consumption (i.e. electricity consumptions of over 1 kW). Also demonstrated is the difference between the two technologies when it comes to household export of electricity. A household with Stirling engine micro-CHP spends less than 10% of the year exporting electricity, while a household with fuel cell micro-CHP spends over 75% of the year exporting electricity.

7.1.5 Examination of the factors that could influence micro-CHP uptake

The economic benefit to the household of Stirling engine micro-CHP is £200 per year for the homes in the field trial. The economic benefit for the simulated fuel cell micro-CHP is £1250 per year. Both these benefits are dependent on tariff support. The annual savings lead to break even prices of £1,700 and £10,000 for Stirling engine and fuel cell micro-CHP respectively. The cost of a Stirling engine micro-CHP unit used in the trial was £9,000, while fuel cell costs are estimated to be £14,000 (Harikishan R. Ellamla et al., 2015, Dodds and Hawkes, 2014). Fuel cells could fall to as low as £2,300 /kWh (Staffell and Green, 2012), resulting in savings to the household, over a ten year period, of over £7,500. It is important to note that the annual economic benefit is dependent on current government tariffs. Despite this, as long as fuel cell micro-CHP continues to receive similar monetary compensation for exported electricity as it does now, the break-even price would still be above the long term price of £2,300, even if generation tariffs were removed entirely; though in this case the 10-year savings would be in the order of a few hundred pounds.

The annual economic benefits of heat pumps and solar PV were found to be £520 and £910 respectively, for the homes in the field trials. This gives break even prices of £4,000 for heat pumps and £7,000 for solar PV.

Given the total electricity and heat generation of micro-CHP, and the average grid carbon intensity in the year of the trial (which was 2013) it is found that Stirling engines avoid 233 kgCO_2 emissions while fuel cells avoid 1835 kgCO_2 emissions. However, as the grid is decarbonised this value will decline. Using 2015 grid carbon levels the savings are reduced to 135 kgCO_2 and 1103 kgCO_2 for Stirling engine and fuel cell micro-CHP respectively, and this will decline further as the UK's electricity supply is decarbonised. If micro-CHP were to use a carbon-neutral fuel supply, such as either biogas or hydrogen, then it would deliver greater carbon savings, and would continue to deliver savings until grid carbon intensity becomes zero (at which point the carbon savings of micro-CHP would also be zero).

For comparison, heat pumps avoid 500 kgCO_2 emissions per year, whilst solar PV avoids 1700 kgCO_2 per year. Like with micro-CHP, the emissions savings from solar PV will decline as the electricity grid is decarbonised. The emissions savings from heat pumps, on the other hand, will increase as the electricity grid is decarbonised.

7.1.6 Conditions for micro-CHP uptake

The key barrier to micro-CHP uptake is the high capital cost relative to the lifetime savings. In order for micro-CHP to see substantial uptake in the UK the capital costs would have to fall to below £1,500 /kWh for Stirling engines and £9,500 /kWh for fuel cells; ideally tariff support would remain in place, otherwise costs would have to fall further, to as low as £400 /kWh for Stirling engines and £1,000 /kWh for fuel cells if all tariffs are removed. Studies have shown that the cost of fuel cell micro-CHP could fall below £9,000 by 2020, with some claiming costs as low as £4,500 by 2020, making fuel cells economically viable given current tariffs (Staffell and Green, 2012, Maru et al., 2010, Spendelow et al., 2011, Staffell, 2014). Suggested long term prices of £2,000 to £3,000, would see fuel cells be economically viable even with the complete removal of generation (but not export) tariffs.

Problematically as prices fall and so the economic case for micro-CHP improves, the emissions reduction benefits for micro-CHP could decline, due to the decarbonisation of the electricity network. When comparing the savings from micro-CHP using grid carbon intensity figures from 2013 and 2015 there is a marked decline; Stirling engine savings fall from 233 $kgCO_2$ per annum to 135 $kgCO_2$ per annum and fuel cell savings fall from 1835 $kgCO_2$ per annum to 1103 $kgCO_2$ per annum. If fuel cell micro-CHP continues to use natural gas as a fuel source, the UK's grid carbon factor would have to remain above 212 gCO_2/kWh. While there has been a significant decline in grid carbon intensity in recent years to 370 gCO_2/kWh in 2015 from 440 gCO_2/kWh in 2010 (Hart-Davis, 2016), this is mainly due to the phasing out of coal, suggesting reductions in grid carbon intensity will likely level off in the near future. Assuming that natural gas were the only remaining carbon intensive fuel source in the electricity generation mix, it would need to continue to provide at least 60% of the UK's grid electricity for fuel cell micro-CHP to continue reducing emissions. Alternatively, the development of a hydrogen economy and the use of carbon-neutral hydrogen as a fuel source for fuel cell micro-CHP would also result in continuing emissions reduction. Research into the development of a hydrogen economy in the UK has found that it can bring considerable benefits to the UK (Dodds and Hawkes, 2014, Steinberger-Wilckens et al., 2017, UKCCC, 2016, Dodds et al., 2015), but is in no way guaranteed.

7.1.7 Developing a method to test the network

Analysis of the literature identified three key network properties that may be affected by micro-generation and low-carbon heating: voltage levels, network losses and transformer overload (Acha et al., 2009, Ackermann and Knyazkin, 2002, Infield et al., 2007, Thomson and Infield, 2007, Rogers et al., 2013). Changes to voltage levels, leading to increased instances of voltage drop or rise could require network reinforcement to help the network better manage voltage levels and keep them within regulation limits. Increasing instances of transformer overload could require the installation of larger transformers. Reducing losses on the network is beneficial from an energy efficiency viewpoint. Load flow analysis (Wang et al., 2008) was determined to be the best way to examine the impacts of micro-generation and heat pumps on these three aspects of the network; with multiple analyses performed in order to use what is a steady state analysis to simulate a dynamic network.

There are several network modelling programs capable of performing load flow analysis: IPSA Power (IPSA-Power, 2017), PSS/E (SIEMENS, 2017), DIgSILENT Power Factory (DIgSILENT, 2017), ETAP (ETAP, 2017) and OpenDSS (EPRI, 2017). Of these IPSA power was chosen for use in this thesis for two primary reasons: its ability to automate load flow analysis through the use of Python code (which the researcher was already familiar with), and the fact that the network models obtained for analysis had already been designed in IPSA. The models in question were obtained from Northern Powergrid. The bulk of the research focused on the Maltby network, with examination of the Darlington Melrose network being used to test if the results from the Maltby network would hold true for other networks.

The Maltby network itself is a large distribution network consisting of 249 domestic customers served by a single 1 MVA 11 kV to 433 V transformer. The domestic customers are an assortment of detached and semi-detached houses, with the bulk of the homes being semi-detached. The customers are modelled on the network as 34 loads. Each load represents a group of 2-14 homes. The Darlington Melrose network serves 188 homes, also from a single transformer, this time 800 kVA, modelled in a similar fashion.

Aside from the network itself, the input data consisted of the demand and generation profiles from the CLNR project (Section 7.1.3) and a table detailing of the number of homes at each load point on the network, and the number of those homes that had micro-CHP, solar PV or heat pumps. This table could be modified to represent different penetrations of micro-generation and heat pumps on the network.

The Python code used to automate the load flow analysis consisted of two scripts. The first of these took the demand and generation profile data and the data on the number of homes and micro-generation/heat pumps on each load point. It then calculated the load and generation amount for each network feeder for each minute of the year and put that data into a spreadsheet. The second script then took the data in that spreadsheet, and for each minute of the year instructed IPSA to assign the load and generation values to each point on the network, run load flow analysis and output the relevant results to a spreadsheet. The relevant results, obtained for each minute of the year, were:

- The total power load on the network
- The total power generation on the network
- The power losses across all branches (cables) on the network
- The power losses across the transformer(s)
- The transformer tap position
- The per unit voltage level at all busbars on the network (34 in total, in the case of the Maltby network)

From these results, the relevant parameters mentioned at the beginning of this subsection can be identified, specifically:

- The number of minutes in the year for which the voltage exceeds regulations, both the -6% limit and the +10% limit
- The maximum and minimum voltage levels on the network, throughout the year
- The branch losses on the network (i.e. the losses across all the wires on the network) for the whole year
- The transformer losses on the network for the whole year
- The maximum power flow through the transformer, across the entire year
- The number of minutes in the year for which the transformer is overloaded
- The number of minutes in the year for which the network as a whole exports electricity

7.1.8 Testing of assumptions

Three key assumptions were made in this research: a single distribution network can be examined in isolation; one minute data provides more information than 10-minute or half-hour data; and the results from the Maltby network will hold true for other networks. All of these assumptions were tested as part of the research.

In order to test if a single network can be monitored, a hypothetical network was constructed in IPSA which consisted of two Maltby networks linked together and served by a 35 to 11 kV transformer (each network still had its own 11 kV to 433 V transformer). One network had micro-generation and heat pumps added to it while the other network was left as it is. The network with micro-generation and heat pumps added behaved in the same way as when it is monitored in isolation. The other network was unaffected except for a 2% rise in the maximum power flow through the transformer. This indicates that a single network can be examined in isolation.

The assumption that one minute data gives more information than 10-minute or half-hour data was tested by analysing the 50% and 100% micro-CHP scenarios using ten-minute and half-hour data. It was found that losses are reduced when using less frequent data, by a few MWhs per annum. There are also no instances of transformer overload when using lower frequency data, except when heat pumps are present, compared with the one minute data when the network is overloaded for at least some of the year in all scenarios. There are also more instances of voltages exceeding regulations when using one minute data. For example, when using half hour data the network spends 0.2% of the year outside regulations when all homes have fuel cell micro-CHP, while using one minute data results in the network spending 69% of the year outside regulations. This indicates that one minute data does provide more information than 10-minute or half-hour data.

The final assumption, that results from the Maltby network hold true for other networks, was tested in two ways: by examining another network and by examining the same network with a variable tap transformer rather than a fixed tap transformer. The other network was the Darlington Melrose network. The model for this network was also obtained from Northern Powergrid and contained just 188 homes, compared to Maltby's 249. Both of the alternate networks showed similar trends to the Maltby network as the penetration of micro-generation or heat pumps is increased; though the actual values of the parameters for the Darlington Melrose network were lower, due to its smaller size. Meanwhile, the Maltby network with a variable tap transformer was able to mitigate the increases in instances of voltage rise.

7.1.9 Results and implications

7.1.9.1 Results of modelling the network with micro-CHP

Micro-CHP was found, in the model, to have some beneficial impacts on the network, and one considerable detrimental impact. The negative impact that micro-CHP can have is causing voltage rise on the network. Neither Stirling engine nor fuel cell micro-CHP causes voltage levels on the network to exceed +10% of the rated voltage.

The benefits to the network are a reduction in instances of voltage dropping below the -6% limit, though from an already low baseline, a reduction in losses on the network and a reduction in power flows through the transformer. Losses on the network are reduced almost linearly as the amount of Stirling engine micro-CHP on the network is increased, by up to 29% below the baseline losses. Fuel cells reduce losses more rapidly than Stirling engines. However at higher penetrations, >60%, losses begin to rise again, and when all homes have fuel cell micro-CHP the losses are only 0.3 MWh lower than when all homes have Stirling engines. At the optimum penetration (from the perspective of reducing losses), of 60%, fuel cell micro-CHP reduces losses by 63%. In the baseline scenario, the transformer is overloaded for 26 minutes of the year. Both Stirling engines and fuel cell micro-CHP reduce this. When all homes have Stirling engines the transformer spends 9 minutes of the year overloaded, and when all homes have fuel cells it spends 2 minutes of the year overloaded.

The implications of these results are that micro-CHP has some benefit to the network through reducing losses, thereby saving energy, and through reducing power flows through the transformer which could avoid or delay needing to upgrade the transformer if network demands rise. They also imply that the network could accommodate all homes having Stirling engines without too many instances of voltage rise. The network could also accommodate 60% of homes having fuel cell micro-CHP, but any higher and there will be considerable increases to voltage rise potentially necessitating network reinforcement.

7.1.9.2 Results of modelling the network with solar PV and heat pumps

Solar PV has similar impacts to micro-CHP in the model. It reduces instances of voltage drop, though only down to 20 minutes of the year, a lower reduction than micro-CHP. It also reduces losses, until the percentage of homes with solar PV rises above 25%, at which point losses begin to rise again, becoming higher than the baseline losses once 75% or more of homes on the network have solar PV. Solar PV does not reduce the peak power flow through the transformer, and only reduces instances of overload down to 18 minutes of the year (from 26), a smaller reduction than micro-CHP.

Solar PV also has an impact on instances of voltage rise; the presence of solar PV can cause voltage levels to exceed the +10% limit, something that micro-CHP does not cause. Half the homes having solar PV causes the network to exceed the limit for a few minutes of the year, and 75% and 100% of homes having solar PV causes the network to exceed the limit for 1.6% and 5.3% of the year.

The impacts of Stirling engines alongside solar PV on the network are largely negligible. The presence of fuel cell micro-CHP alongside solar PV on the network will exacerbate the impacts of solar PV on voltage rise, while slightly reducing instances of voltage drop, and further reducing the power flows through the transformer. Though when all homes have both fuel cell micro-CHP and solar PV, instances of transformer overload will rise.

Heat pumps cause a considerable rise in electricity demand on the network. Through this they cause increases to instances of voltage drop, network losses and instances of transformer overload. Half the homes on the network having heat pumps cause instances of voltage dropping below -6% to triple compared to the baseline scenario; and they increase eightfold when all homes have heat pumps. Also when all homes have heat pumps network losses are more than doubled. The impacts heat pumps can have on the transformer are also considerable: increasing instances of overload up to fivefold when all homes have heat pumps. Once 75% or more of the homes on the network have heat pumps, the peak power flow through the transformer rises above 1.5 times its rated capacity, which may cause the transformer to fail. The impacts of heat pumps on voltage levels and the transformer could necessitate network reinforcement.

The presence of micro-CHP on the network alongside heat pumps will reduce their impacts on voltage levels, network losses and instances of transformer overload. The most considerable reduction is in power flows through the transformer. If 75% of homes have heat pumps, and the rest have either Stirling engine or fuel cell micro-CHP, the maximum power flow through the transformer will no longer exceed 1.5 times its rated capacity. The implications of this are that the presence of micro-CHP could reduce or delay the need for network reinforcement caused by the presence of heat pumps.

7.2 Further research

Three avenues for further research are suggested in this section. They are: an examination of the ways in which storage of electrical energy can change the impacts of micro-generation, studies of rural and urban distribution networks (i.e. those most different from the networks examined in this research), and a study of the costs or savings to the network of micro-generation and heat pumps.

7.2.1 Electrical Energy Storage

By storing excess electricity generation from micro-generation devices, and using that stored energy at times of peak demand, EES has the potential to significantly change the import and export profile of households in which it is installed. Large scale EES can also be installed on the grid itself to mitigate the impacts of micro-generation.

Modelling in house energy storage should be a straightforward case of determining when micro-generation output exceeds demand, and when demand exceeds micro-generation output. In the former case, any excess electricity generation is sent to storage, until the storage unit is full, at which point it is exported as usual. In the latter case, electricity is drawn from storage until the storage unit is empty. This should be achievable by running the demand and generation profiles through a piece of code. This code would subtract the demand from the generation and if the resulting value is positive add it to the storage, unless this would take the storage over a maximum value, in which case it is exported; if the value is negative it subtracts it from the storage, unless the storage is empty. The code would then output the original demand and generation, along with the amounts of electricity sent to and taken from the storage unit, the amount of export, and the total amount of electricity in the storage unit. For the purposes of IPSA modelling, the generator output could now be the generation value minus however much electricity is sent to storage, and the demand for grid electricity could be the electricity import (after taking into account micro-generation) minus however much electricity is taken from the storage unit. The EES device could also be restricted to only being used at times of peak demand or generation, in order to have maximum impact. This could be done by modifying the code so that electricity is only sent to the storage device if the generation is above a certain value, and only drawn from the storage device if demand is above a certain value. Experimentation would be needed to find the optimum demand and generation values for which electricity would be sent to or drawn from the EES device.

If modelling large scale EES on the grid itself, this could be done by adding another grid in-feed to the network model, but rather than having a variable output to meet the electricity demands of the network, as the first grid in-feed does, it would have a fixed electrical output or input. These fixed values would be calculated by analysing the demand and generation for the entire network, in a similar fashion to how the demand and generation for a single household was examined above. This analysis could be used to determine how much electricity is sent to or drawn from the EES, and these values could be used as the input/output of the second grid in-feed in the model.

7.2.2 Study of urban and rural distribution networks

Both of the networks examined in this research were located in towns, and while the findings here may hold true for other town and sub-urban networks, they may not do so for rural or urban networks. Testing such networks would be a matter of first obtaining models of urban and rural distribution networks, and then applying the same process used in this research. Some changes may need to be made to the demand and generation profiles. Urban networks will tend to have smaller dwellings, leading to lower heat demand and thus lower micro-CHP output, and will likely have less roof space for solar PV. Therefore it can be expected that household demand, micro-CHP and solar PV generation and heat pump demand will all be lower in urban dwellings. Rural dwellings will be larger increasing electricity and heat demands, thus raising micro-CHP output and heat pump demands, along with the non-heat related electricity demands of the household.

Rural networks, being more spread out and thus having longer cables will likely have already greater network losses and instances of voltage drop, but may well see more uptake of micro-generation; micro-CHP will be attractive to large rural homes with high heat demands as they will get more use out of it, and thus earn more money from it, though this may be mitigated by the higher price of fuel for homes not on the gas network; similarly heat pumps may be an attractive heating option for rural homes, again as homes not on the gas network will benefit more from switching from heating with high fuel costs to electric heating, and as rural homes are likely to have a larger land area which lends itself to the more effective ground source heat pumps. As for the distribution networks, they are likely to see greater benefits from the presence of micro-CHP, and greater problems from the presence of solar PV and heat pumps. Urban networks are likely to see lower uptake of micro-generation and what micro-generation is installed will be smaller in scale. Heat based micro-generation devices (i.e. micro-CHP and heat pumps) may be unlikely in very densely populated areas where heat networks could be a possibility, thus the impacts from micro-generation in these areas are likely to be lower. It should be kept in mind that this last paragraph has been entirely speculation on what the author expects the differences to be on other networks (plus the reasoning behind that speculation) to establish a rough hypothesis and more research will be needed to determine what the differences actually are.

7.2.3 Study of the cost to the network from the impacts of micro-generation and low-carbon heat

While this research has examined the impacts on the networks of micro-generation and heat pumps, it has not examined what the cost (or benefit) of those impacts to the network might be. Such an examination would necessitate identifying what steps may need to be taken to reinforce the network against the impacts of micro-generation and heat pumps.

Two options have already been mentioned in this research, variable tap transformers and electrical energy storage. Both could go some way to mitigating the impacts of micro-generation. It would be necessary to identify, firstly by how much EES can avoid the impacts of micro-generation, and then the scale and cost of EES required. For the transformer it would be a case of determining the cost of replacing the fixed tap transformer with a variable tap transformer. The cost to the network of heat pumps can also be analyses through transformer costs, this time through the cost of upgrading the transformer to one with a higher capacity, better able to cope with the increased electricity demand from heat pumps.

Other voltage control measures include static synchronous compensators and network capacitors. As with EES and upgrading the transformer, the scale and associated costs of these technologies, for differing penetrations of micro-generation would need to be determined in order to establish the costs to the network of micro-generation.

Benefits to the network come through reducing power flows through the transformer and reducing network losses. Reducing power flows through the transformer could delay or negate the need for upgrades, thus the economic benefit to the network would be determined by identifying the money saved by not upgrading the transformer.

7.3 Summary of key findings

- Stirling engine micro-CHP saves the household £200 per annum, while fuel cell micro-CHP saves it £1250 per annum. These values lead to break-even prices of £1,700 and £10,000, both considerably lower than current prices. Though the cost of fuel cell micro-CHP is predicted to fall below that break-even price in the future. Also, the savings from micro-CHP are highly dependent on FiT support. Solar PV saves the household £910 per annum, leading to a break-even price of £7,000, while heat pumps save the household £520 per annum, resulting in a break-even price of £4,000.
- Carbon emissions are reduced by 233 kgCO_2 per annum for Stirling engine micro-CHP and by 1835 kgCO_2 per annum for fuel cell micro-CHP. Though both these values will decline as the grid is decarbonised, with savings from fuel cell micro-CHP becoming negative when grid carbon intensity falls below 212 gCO_2/kWh. Solar PV saves 1700 kgCO_2 per annum, while heat pumps save 500 kgCO_2 per annum. As with micro-CHP, the carbon savings from solar PV will decline as the grid is decarbonised, though they will not become negative. The carbon savings from heat pumps will increase as the grid is decarbonised.

- Benefits to the network of micro-CHP include reducing instances of voltage drop, though from an already low baseline, and reducing network losses and power flows through the transformer. Stirling engines reduce losses by up to 29% when all homes have them installed. Fuel cells reduce losses by at most 63%, when 60% of homes have them installed. When more homes install fuel cell micro-CHP losses begin to rise again.
- These results hold true for at least one other distribution network, which exhibits the same trends as the penetration of micro-CHP on the network is increased. Networks with variable tap transformers will not suffer as much from the increases to voltage rise caused by micro-CHP. For example 70% of homes having micro-CHP on such a network cause it to spend 6% of the year over voltage regulations, as opposed to 11% for networks with fixed tap transformers, however this is still a concerning amount of time for the network to be in breach of regulation limits.
- Solar PV can increase voltage levels. High proportions (>50%) of homes having solar PV causes voltages to breach the upper +10% limit. Like fuel cell micro-CHP solar PV causes losses to at first fall, but once more than 25% of homes have solar PV they will rise again, becoming higher than the baseline losses once 75% of homes have solar PV. Solar PV does little to reduce the maximum power flow through the transformer, and does not reduce instances of transformer overload by as much as micro-CHP.
- The presence of fuel cell micro-CHP alongside solar PV can exacerbate the impacts of solar PV on voltage rise, and cause a greater increase in network losses. If all home share both technologies then it will lead to an increase in instances of transformer overload.
- The presence of heat pumps on the network could cause an increase to instances of voltage drop, though only to 0.03% of the year at most, considerably less than the instances of voltage rise caused by micro-generation. They could more than double electrical losses on the network. Their greatest impact would be through increases to power flows through the transformer. Half the homes having heat pumps would cause instances of transformer overload to more than double compared to the baseline case. If more than 75% of homes have heat pumps, the peak power flow through the

transformer could rise above 1.5 its rated capacity, which is considered an upper limit on transformer overload.

- The presence of micro-CHP on the network in addition to heat pumps will reduce their impacts on instances of voltage drop, network losses and power flows through the transformer, with fuel cells reducing the impacts of heat pumps by more than Stirling engines micro-CHP. The biggest impact to be reduced is power flows through the transformer. In all measured scenarios featuring heat pumps and either micro-CHP technology, the power through the network transformer did not rise above 1.5 times its rated capacity.

REFERENCES

2002. Electricity Safety, Quality and Continuity Regulations 2002. U.K.

2008. Climate Change Act.

ACHA, S., GREEN, T. C. & SHAH, N. 2009. Impacts of Plug-in Hybrid Vehicles and Combined Heat and Power technologies on Electricity and Gas Distribution Network losses. *Sustainable Alternative Energy (SAE), 2009 IEEE PES/IAS.* Valencia.

ACHARYA, N., MAHAT, P. & MITHULANANTHAN, N. 2006. An analytical approach for DG allocation in primary distribution network. *International Journal of Electrical Power & Energy Systems,* 28**,** 669-678.

ACKERMANN, T. & KNYAZKIN, V. 2002. Interaction between Distributed Generation and the Distribution Network: Operation Aspects. *IEEE/PES Transmission and Distribution Conference and Exhibition.* IEEE.

AKI, H. 2007. The Penetration of Micro CHP in Residential Dwellings in Japan. *Power Engineering Society General Meeting, 2007. IEEE***,** 1-4.

AKI, H., YAMAMOTO, S., KONDOH, J., MAEDA, T., YAMAGUCHI, H., MURATA, A. & ISHII, I. 2006. Fuel cells and energy networks of electricity, heat, and hydrogen in residential areas. *International Journal of Hydrogen Energy,* 31**,** 967-980.

ALANNE, K., SÖDERHOLM, N., SIRÉN, K. & BEAUSOLEIL-MORRISON, I. 2010. Techno-economic assessment and optimization of Stirling engine micro-cogeneration systems in residential buildings. *Energy Conversion and Management,* 51**,** 2635-2646.

BARELLI, L., BIDINI, G., GALLORINI, F. & OTTAVIANO, A. 2011. An energeticeexergetic comparison between PEMFC and SOFC-based micro-CHP systems. *International Journal of Hydrogen Energy,* 36**,** 3206-3214.

BARRETO, L., MAKIHIRA, A. & RIAHI, K. 2003. The hydrogen economy in the 21st century: a sustainable development scenario. *International Journal of Hydrogen Energy***,** 267-284.

BAXI 2010. Ecogen: The Baxi Ecogen Dual energy System. *In:* BAXI (ed.).

BEIS 2016. Digest of United Kingdom Energy Statistics 2016. *In:* DEPARTMENT OF BUSINESS, ENERGY & INDUSTRIAL STRATEGY (ed.). Office of National Statistics.

BEIS 2017. Energy Consumption in the UK (ECUK) 2017 Data Tables. *In:* DEPARTMENT OF BUSINESS, ENERGY & INDUSTRIAL STRATEGY (ed.).

CARBON TRUST 2011. Micro-CHP Accelerator. Carbon Trust.

CASTRO, M., YELLEN, D., HOLLINGWORTH, D., MUKHERJEE, R., BARTECKZO-HIBBERT, C., WARDLE, R., DENT, C. & WAY, R. 2014. Review of the Distribution Network Planning and Design Standards for the Future Low Carbon Electricity System. Consumer Led Network Revolution.

CLNR. 2014. *CLNR - The Project* [Online]. Consumer Led Network Revolution. Available: http://www.networkrevolution.co.uk/the-project/.

CLNR 2015. SPECIFICATION OF DOMESTIC AND SME CUSTOMER DATA *In:* POWERGRID, N. (ed.). Consumer Led Network Revolution Project.

COCKROFT, J. & KELLY, N. 2006. A comparative assessment of future heat and power sources for the UK domestic sector. *Energy Conversion and Management,* 47**,** 2349-2360.

CURRIE, R. A. F., AUK, G. W., FOOTE, C. E. T., G.M.BURT & J.R.MCDONAID 2004. Fundamental Research Challenges for Active Management of Distribution Networks with High Levels of Renewable Generation. Institute for Energy and the Environment, University of Strathclyde.

DE PAEPE, M., D’HERDT, P. & MERTENS, D. 2006. Micro-CHP systems for residential applications. *Energy Conversion and Management,* 47**,** 3435-3446.

DECC 2011. Regional Energy Consumption Statistics. *In:* DEPARTMENT OF ENERGY AND CLIMATE CHANGE (ed.). Office of National Statistics.

DECC 2012. The Future of UK Heating 2012. *In:* DEPARTMENT OF ENERGY AND CLIMATE CHANGE (ed.).

DECC 2013. The Future of Heating: Meeting the challenge. *In:* DEPARTMENT OF ENERGY AND CLIMATE CHANGE (ed.).

DECC 2014. Preliminary data from the RHPP heat pump metering programme. *In:* DEPARTMENT OF ENERGY AND CLIMATE CHANGE (ed.).

DEMOULLIN, S. 2012. *Assessment of the Feasibility and Benefits of the Conversion of the UK National Grid from Natural Gas to Hydrogen.* University College London.

DIGSILENT 2017. PowerFactory Applications.

DODDS, P. E. & DEMOULLIN, S. 2012. Conversion of the UK gas system to transport hydrogen. *International Journal of Hydrogen Energy,* 38**,** 7189-7200.

DODDS, P. E. & HAWKES, A. 2014. *The role of Hydrogen and Fuel Cells in providing affordable, secure low carbon heat,* H2FC SUPERGEN, London, UK.

DODDS, P. E. & MCDOWALL, W. 2013. The future of the UK gas network. *Energy Policy,* 60**,** 305-316.

DODDS, P. E., STAFFELL, I., HAWKES, A. D., LI, F., GRÜNEWALD, P., MCDOWALL, W. & EKINS, P. 2015. Hydrogen and fuel cell technologies for heating: A review. *International Journal of Hydrogen Energy,* 40**,** 2065-2083.

DONG, L., LIU, H. & RIFFAT, S. 2009. Development of small-scale and micro-scale biomass-fuelled CHP systems – A literature review. *Applied Thermal Engineering,* 29**,** 2119-2126.

DONKELAAR, M. T. & SCHEEPERS, M. J. J. 2004. DISPOWER: A socio-economic analysis of technical solutions and practices for the integration of distributed generation. ECN Policy Studies.

EARTH NOTES. 2016. *Earth Notes: A Note On Variations in UK/GB Grid Electricity CO2 Intensity with Time* [Online]. http://www.earth.org.uk/note-on-UK-grid-CO2-intensity-variations.html#fullyear2015.

ENERGY SAVING TRUST 2013a. Detailed analysis from the second phase of the Energy Saving Trust's heat pump field trial. *In:* DECC (ed.).

ENERGY SAVING TRUST. 2013b. *Our Calculations* [Online]. Available: http://www.energysavingtrust.org.uk/Energy-Saving-Trust/Our-calculations [Accessed 31/09/2013.

ENERGY SAVING TRUST. 2014. *Feed-In-Tariffs scheme (FITs)* [Online]. Available: www.energysavingtrust.org/Generating-energy/Getting-money-back/Feed-In-Tariffs-scheme-FITs.

ENERGY SAVING TRUST. 2017. *Solar Panels Electricity* [Online]. Available: http://www.energysavingtrust.org.uk/renewable-energy/electricity/solar-panels.

EPRI. 2017. *Simulation Tool - OpenDSS* [Online]. smartgrid.epri.com. Available: http://smartgrid.epri.com/SimulationTool.aspx.

ETAP 2017. Distribution Network Analysis, Planning, Protection and ADMS

EUROPEAN COMMITTEE FOR ELECTROTECHNICAL STANDARDIZATION 1999. EN50160 Voltage characteristics of electricity supplied by public distribution systems.

FARHAD, S., HAMDULLAHPUR, F. & YOO, Y. 2010. Performance evaluation of different configurations of biogas-fuelled SOFC micro-CHP systems for residential applications. *International Journal of Hydrogen Energy* 35**,** 3758-3768.

FUEL CELL TODAY 2012. Water Electrolysis and Renewable Energy Systems. *In:* FUEL CELL TODAY (ed.).

GREENE, D. L., DULEEP, K. G. & UPRETI, G. 2011. Status and Outlook for the U.S. Non-Automotive Fuel Cell Industry: Impacts of Government Policies and Assessment of Future Opportunities. Oak Ridge National Laboratory.

HARIKISHAN R. ELLAMLA, IAIN STAFFELL, PIOTR BUJLO, BRUNO G. POLLET & PASUPATHI, S. 2015. Current status of fuel cell based combined heat and power systems for residential sector. *Journal of Power Sources,* 293**,** 312-328.

HART-DAVIS, D. 2016. *Earth Notes: A Note on Variations in UK/GB Grid Electricity CO2 Intensity with Time* [Online]. Earth Notes. Available: http://www.earth.org.uk/note-on-UK-grid-CO2-intensity-variations.html.

HAWKES, A. & LEACH, M. 2005. Impacts of temporal precision in optimisation modelling of micro-Combined Heat and Power. *Energy,* 30**,** 1759-1779.

HAWKES, A., STAFFELL, I., BRETT, D. & BRANDON, N. 2009. Fuel cells for micro-combined heat and power generation. *Energy & Environmental Science,* 2**,** 729.

HAWKES, A. D., BRETT, D. J. L. & BRANDON, N. P. 2011. Role of fuel cell based micro-cogeneration in low carbon heating. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy,* 225**,** 198-207.

HEWITT, N. J., HUANG, M. J., ANDERSON, M. & QUINN, M. 2011. Advanced air source heat pumps for UK and European domestic buildings. *Applied Thermal Engineering,* 31**,** 3713-3719.

HINNELLS, M. 2008. Combined heat and power in industry and buildings. *Energy Policy,* 36**,** 4522-4526.

HUDSON, L., WINSKEL, M. & ALLEN, S. 2011. The hesitant emergence of low carbon technologies in the UK: the micro-CHP innovation system. *Technology Analysis & Strategic Management,* 23**,** 297-312.

INFIELD, D. G., SHORT, J., HORNE, C. & FRERIS, L. L. 2007. Potential for Domestic Dynamic Demand-Side Management in the UK. *Power Engineering Society General Meeting, 2007. IEEE.* Tampa, FL, USA

IPSA-POWER. 2017. *Power system analysis software - Ipsa 2* [Online]. Available: https://www.ipsa-power.com/?page_id=766.

KUHN, V., KLEMES, J. & BULATOV, I. 2008. MicroCHP: Overview of selected technologies, products and field test results. *Applied Thermal Engineering,* 28**,** 2039-2048.

LAKERVI, E. & HOLMES, E. J. 2003. *Distribution Network Design*, Institution of Engineering and Technology.

LELYVELD, T. & WOODS, P. 2010. Carbon emissions factors for fuels - Methodology and values for 2013 & 2016. *Zero Carbon Hub.*

LOVE, J., SUMMERFIELD, A., BIDDULPH, P., WINGFIELD, J., MARTIN, C., GLEESON, C. & LOWE, R. 2017. INVESTIGATING VARIATIONS IN PERFORMANCE OF HEAT PUMPS INSTALLED VIA THE RENEWABLE HEAT PREMIUM PAYMENT (RHPP) SCHEME. UCL Energy Institute: RAPID-HPC.

MAALLA, E. M. B. & KUNSCH, P. L. 2008. Simulation of micro-CHP diffusion by means of System Dynamics. *Energy Policy,* 36**,** 2308-2319.

MARTıNEZ-PEREZ, N., CHERRYMAN, S. J., PREMIER, G. C., DINSDALE, R. M., HAWKES, D. L., HAWKES, F. R., KYAZZE, G. & GUWY, A. J. 2007. The potential for hydrogen-enriched biogas production from crops: Scenarios in the UK. *Biomass and Bioenergy,* 31**,** 95-104.

MARU, D. H., SINGHAL, D. S. C., STONE, D. C. & WHEELER, M. D. 2010. 1–10 kW Stationary Combined Heat and Power Systems Status and Technical Potential. National Renewable Energy Laboratory.

MCDOWALL, W. & EAMES, M. 2007. Towards a sustainable hydrogen economy: A multi-criteria sustainability appraisal of competing hydrogen futures. *International Journal of Hydrogen Energy,* 32**,** 4611-4626.

MIARA, M., GUNTHER, D., KRAMER, T., OLTERSDORF, T. & WAPLER, J. 2010. Heat Pump Efficiency: Analysis and Evaluation of Heat Pump Efficiency in Real Life Conditions. Fraunhofer ISE: Federal Ministry of Economics and Technology.

NATIONAL GRID 2004. The Grid Code. NATIONAL GRID COMPANY PLC.

NATIONAL GRID 2011. UK Future Energy Scenarios. NATIONAL GRID COMPANY PLC.

NEIJ, L. 2008. Cost development of future technologies for power generation—A study based on experience curves and complementary bottom-up assessments. *Energy Policy,* 36**,** 2200-2211.

OCHA, L. F. & HARRISON, G. P. 2011. Minimizing Energy Losses: Optimal Accommodation and Smart Operation of Renewable Distributed Generation. *IEEE TRANSACTIONS ON POWER SYSTEMS,* 26**,** 198-205.

OCHA, L. F., PADILHA-FELTRIN, A. & HARRISON, G. P. 2006. Evaluating Distributed Generation Impacts With a Multiobjective Index. *IEEE TRANSACTIONS ON POWER DELIVERY,* 21**,** 1452-1458.

OFGEM 2017. Feed-in Tariff Installation Report 30 September 2017.

OFGEM. 2018a. *Feed in Tariffs (FiT) rates* [Online]. Available: https://www.ofgem.gov.uk/environmental-programmes/fit/fit-tariff-rates.

OFGEM. 2018b. *Tariffs and payments: Domestic RHI* [Online]. Available: https://www.ofgem.gov.uk/environmental-programmes/domestic-rhi/contacts-guidance-and-resources/tariffs-and-payments-domestic-rhi/current-future-tariffs.

OMER, A. M. 2008. Ground-source heat pumps systems and applications. *Renewable and Sustainable Energy Reviews,* 12**,** 344-371.

ONOVWIONA, H. I. & UGURSAL, V. I. 2006. Residential cogeneration systems: review of the current technology. *Renewable and Sustainable Energy Reviews,* 10**,** 389-431.

ONOVWIONA, H. I., UGURSAL, V. I. & FUNG, A. S. 2007. Modeling of internal combustion engine based cogeneration systems for residential applications. *Applied Thermal Engineering,* 27**,** 848-861.

P.MOÇOTÉGUY, LUDWIG, B., J.SCHOLTA, Y.NEDELLEC, D.J.JONES & ROZIÈRE, J. 2009. Long-TermTesting in DynamicMode of HT-

PEMFCH3PO4/PBI Celtec-P Based Membrane Electrode Assemblies for Micro-CHP Applications. *Fuel Cells,* 10**,** 299-311.

PEACOCK, A. D. & NEWBOROUGH, M. 2005. Impact of micro-CHP systems on domestic sector CO2 emissions. *Applied Thermal Engineering,* 25**,** 2653-2676.

POSSIDENTE, R., ROSELLI, C., SASSO, M. & SIBILIO, S. 2006. Experimental analysis of micro-cogeneration units based on reciprocating internal combustion engine. *Energy and Buildings,* 38**,** 1417-1422.

QUEZADA, V. H. M., ABBAD, J. R. & ROMÁN, T. G. S. 2006. Assessment of Energy Distribution Losses for Increasing Penetration of Distributed Generation. *IEEE TRANSACTIONS ON POWER SYSTEMS,* 21.

RAO, R. S., RAVINDRA, K., SATISH, K. & NARASIMHAM, S. V. L. 2013. Power Loss Minimization in Distribution System Using Network Reconfiguration in the Presence of Distributed Generation. *IEEE TRANSACTIONS ON POWER SYSTEMS,* 28.

REN, H. & GAO, W. 2010. Economic and environmental evaluation of micro CHP systems with different operating modes for residential buildings in Japan. *Energy and Buildings,* 42**,** 853-861.

ROGERS, J., COOPER, S., HAMMOND, G. & MCMANUS, M. 2013. Use of micro CHP plants to support the local operation of electric heat pumps. *3rd International Conference in Microgeneration and Related Technologies in Buildings: Microgen 3*.

SIEMENS 2017. Power Transmission System Planning Software.

SINGH, H., MUETZEB, A. & EAMESC, P. C. 2010. Factors influencing the uptake of heat pump technology by the UK domestic sector. *Renewable Energy* 35**,** 873-878.

SOROUDI, A., EHSAN, M. & ZAREIPOUR, H. 2011. A practical eco-environmental distribution network planning model including fuel cells and non-renewable distributed energy resources. *Renewable Energy,* 36**,** 179-188.

SPENDELOW, J., MARCINKOSKI, J. & PAPAGEORGOPOULOS, D. 2011. Micro CHP Fuel Cell System Targets. *DOE Hydrogen and Fuel Cells Program Record.* Department of Energy, United States of America.

STAFFELL, I. 2009. *FUEL CELLS FOR DOMESTIC HEAT AND POWER: ARE THEY WORTH IT?* Doctor of Philosophy, University of Birmingham.

STAFFELL, I. 2014. Fuel Cell Technologies. *In:* DODDS, P. E. & HAWKES, A. (eds.) *The role of hydrogen and fuel cells in providing affordable, secure low-carbon heat.* . H2FC SUPERGEN, London, UK.

STAFFELL, I., DODDS, P., SCAMMAN, D., ABAD, A. V., MACDOWELL, N., WARD, K., AGNOLUCCI, P., PAPAGEORGIOU, L., SHAH, N. & EKINS, P. 2017a. *The role of hydrogen and fuel cells in future energy systems: A H2FC Supergen white paper,* London, UK, H2FC SUPERGEN.

STAFFELL, I. & GREEN, R. 2012. The cost of domestic fuel cell micro-CHP systems. *International Journal of Hydrogen Energy*.

STAFFELL, I., GREEN, R., GROSS, R. & GREEN, T. 2017b. Electric Insights Quaterly: January - March 2017. *Drax.*

STAFFELL, I. & GREEN, R. J. 2009. Estimating future prices for stationary fuel cells with empirically derived experience curves. *International Journal of Hydrogen Energy,* 34**,** 5617-5628.

STEINBERGER-WILCKENS, R., DODDS, P. E., KURBAN, Z., VELAZQUEZ ABAD, A. & RADCLIFFE, J. 2017. *The role of hydrogen and fuel cells in delivering energy security for the UK,* H2FC SUPERGEN, London, UK.

SUMMERFIELD, A. J., ORESZCZYN, T., HAMILTON, I. G., SHIPWORTH, D., HUEBNER, G. M., LOWE, R. J. & RUYSSEVELT, P. 2015. Empirical variation in 24-h profiles of delivered power for a sample of UK dwellings: Implications for evaluating energy savings. *Energy and Buildings,* 88**,** 193-202.

SWEETT GROUP 2013. Research on the costs and performance of heating and cooling technologies. *In:* DEPARTMENT OF ENERGY AND CLIMATE CHANGE (ed.).

THOMSON, M. & INFIELD, D. G. 2007. Network Power-Flow Analysis for a High Penetration of Distributed Generation. *IEEE Transactions on Power Systems,* 22.

TOKYO GAS. 2013. *Development of the new model of a residential fuel cell, "ENE-FARM"* [Online]. http://www.tokyo-gas.co.jp/techno/stp1/00h1_e.html: Tokyo Gas. Available: http://www.tokyo-gas.co.jp/techno/stp1/00h1_e.html.

TOKYO GAS CO. LTD. & PANASONIC CORPORATION. 2011. *Tokyo Gas and Panasonic to Launch New Improved "Ene-Farm" Home Fuel Cell with World-Highest Power Generation Efficiency at More Affordable Price* [Online]. Panasonic News. Available: http://panasonic.co.jp/corp/news/official.data/data.dir/en110209-2/en110209-2.html 2014].

UK POWER. 2013. *Breakdown of solar panel earnings and costs* [Online]. Available: https://www.ukpower.co.uk/solar-panels/breakdown-of-solar-panel-earnings-and-costs.

UKCCC 2016. Next steps for UK heat policy. *In:* COMMITTE ON CLIMATE CHANGE (ed.).

WANG, X.-F., SONG, Y. & IRVING, M. 2008. *Load Flow Analysis*, Springer, Boston, MA.

WETO-H2 2006. World Energy Technology Outlook - 2050. European Comission.

WHICH? 2018. *Feed in tariff savings and earnings* [Online]. Available: https://www.which.co.uk/reviews/feed-in-tariffs/article/feed-in-tariffs/feed-in-tariff-savings-and-earnings.

WINSKEL, M., MARKUSSON, N., MORAN, B., JEFFREY, H., ANANDARAJAH, G., HUGHES, N., CANDELISE, C., CLARKE, D., TAYLOR, G., CHALMERS, H., DUTTON, G., HOWARTH, P., JABLONSKI, S. & KALYVAS, C. 2009. Decarbonising the UK Energy

System: Accelerated Development of Low Carbon Energy Supply Technologies. *UKERC Energy 2050 Research Report No. 2.* UK ERC.

APPENDIX A: DATA TABLES USED IN THE STUDY

Time	Mean mCHP power consumption & production	Mean whole home power import
01/10/2012 00:00	0	349
01/10/2012 00:01	-18	342
01/10/2012 00:02	-18	344
01/10/2012 00:03	-18	462
01/10/2012 00:04	-17	485
01/10/2012 00:05	-17	352
01/10/2012 00:06	-17	352
01/10/2012 00:07	-17	349
01/10/2012 00:08	-17	341
01/10/2012 00:09	-17	339
01/10/2012 00:10	-18	337
01/10/2012 00:11	-17	336
01/10/2012 00:12	-18	335
01/10/2012 00:13	-18	335
01/10/2012 00:14	-18	334
01/10/2012 00:15	-18	334
01/10/2012 00:16	-18	335
01/10/2012 00:17	-17	334
01/10/2012 00:18	-18	334
01/10/2012 00:19	-17	334
01/10/2012 00:20	-18	333
01/10/2012 00:21	-18	333

01/10/2012 00:22	-18	333
01/10/2012 00:23	-18	331
01/10/2012 00:24	-18	203
01/10/2012 00:25	-17	202
01/10/2012 00:26	-18	202
01/10/2012 00:27	-18	203
01/10/2012 00:28	-18	201
01/10/2012 00:29	-18	203
01/10/2012 00:30	-17	201
01/10/2012 00:31	-18	201
01/10/2012 00:32	-17	200
01/10/2012 00:33	-18	200
01/10/2012 00:34	-18	200
01/10/2012 00:35	-18	200
01/10/2012 00:36	-17	199
01/10/2012 00:37	-18	198
01/10/2012 00:38	-18	197

Table A 1 The CLNR test cell 4 field trial data, averaged all locations. Showing rows 1-40 of 789121.

TIME	Demand	Stirling Generation	FC Generation	Heat Pump Demand	Solar Generation
01/01/2013 00:00	864.5	-1	960	190	0
01/01/2013 00:01	482.5	-67.75	960	160	0
01/01/2013 00:02	480.25	-58.75	960	160	0
01/01/2013 00:03	649.75	-58.5	960	170	0
01/01/2013 00:04	861.25	-58.5	960	160	0
01/01/2013 00:05	979.25	-61	960	190	0
01/01/2013 00:06	881	-54.5	960	230	0
01/01/2013 00:07	957.42	-86.33	960	220	0
01/01/2013 00:08	852.75	86	960	210	0
01/01/2013 00:09	460.75	126.25	960	220	0
01/01/2013 00:10	723	150	960	220	0
01/01/2013 00:11	394.75	159.25	960	240	0
01/01/2013 00:12	323.75	163.75	960	230	0
01/01/2013 00:13	1027.75	166.5	960	250	0
01/01/2013 00:14	702.25	39.5	960	250	0
01/01/2013 00:15	727	-94	960	280	0
01/01/2013 00:16	728	-58.25	960	300	0

01/01/2013 00:17	326	-58.5	960	290	0
01/01/2013 00:18	585.75	-56.75	960	320	0
01/01/2013 00:19	329.25	-57	960	290	0
01/01/2013 00:20	604.25	-56.5	960	320	0
01/01/2013 00:21	700.75	-56.75	960	330	0
01/01/2013 00:22	319.5	-57	960	310	0
01/01/2013 00:23	717.25	-85	960	330	0
01/01/2013 00:24	697	-51	960	340	0
01/01/2013 00:25	743.75	-24.5	960	300	0
01/01/2013 00:26	289.75	-4.5	960	270	0
01/01/2013 00:27	670.25	-35.5	960	250	0
01/01/2013 00:28	670.25	-94.5	960	240	0
01/01/2013 00:29	282.25	-58.5	960	290	0
01/01/2013 00:30	340.5	-57	960	290	0
01/01/2013 00:31	658.5	-57	960	260	0
01/01/2013 00:32	264.25	-57.25	960	260	0
01/01/2013 00:33	488.75	-57	960	260	0
01/01/2013 00:34	654.5	-56.75	960	230	0
01/01/2013 00:35	501.25	-73.25	960	270	0
01/01/2013 00:36	313.75	-58.5	960	250	0
01/01/2013 00:37	650.25	-50.25	960	300	0
01/01/2013 00:38	264.5	-6.75	960	320	0
01/01/2013 00:39	986.75	-43.5	960	310	0

Table A 2 The demand and generation profiles used in the research. Showing rows 1-40 of 525600

Feeder	Number of homes on the feeder	Number of homes with Stirling engine micro-CHP	Number of homes with fuel cells	Number of homes with heat pumps	Number of homes with solar PV
1.1	8	0	0	0	0
1.2	8	0	0	0	0
1.3	8	0	0	0	0
1.4	8	0	0	0	0
1.5	8	0	0	0	0
1.6	8	0	0	0	0
1.7	8	0	0	0	0
1.8	8	0	0	0	0

2.1	6	0	0	0	0
2.2	5	0	0	0	0
2.3	5	0	0	0	0
2.4	5	0	0	0	0
2.5	12	0	0	0	0
2.6	12	0	0	0	0
2.7	12	0	0	0	0
3.1	4	0	0	0	0
3.2	11	0	0	0	0
3.3	11	0	0	0	0
3.4	7	0	0	0	0
3.5	9	0	0	0	0
3.6	10	0	0	0	0
3.7	8	0	0	0	0
4.1	3	0	0	0	0
4.2	6	0	0	0	0
4.3	2	0	0	0	0
4.4	6	0	0	0	0
4.5	6	0	0	0	0
4.6	3	0	0	0	0
4.7	2	0	0	0	0
4.8	6	0	0	0	0
4.9	6	0	0	0	0
4.10	7	0	0	0	0
4.11	7	0	0	0	0
5	14	0	0	0	0

Table A 3 Table of homes on each feeder of the Maltby network (the Micro-generation Penetration file listed in the flowchart for the first Python script). Column 2 shows the (unchanging) total number of homes on the feeder. Columns 3-6 show the number of those homes with micro-generation or low-carbon heat technologies, these numbers can be adjusted depending on the scenario. The current numbers represent the baseline scenario, with no micro-generation or low-carbon heat.

01/01/2013 00:14	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	4.21	3.51	3.51	3.51	8.43
01/01/2013 00:13	8.22	8.22	8.22	8.22	8.22	8.22	8.22	8.22	6.17	5.14	5.14	5.14	12.33
01/01/2013 00:12	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	1.94	1.62	1.62	1.62	3.89
01/01/2013 00:11	3.16	3.16	3.16	3.16	3.16	3.16	3.16	3.16	2.37	1.97	1.97	1.97	4.74
01/01/2013 00:10	5.78	5.78	5.78	5.78	5.78	5.78	5.78	5.78	4.34	3.62	3.62	3.62	8.68
01/01/2013 00:09	3.69	3.69	3.69	3.69	3.69	3.69	3.69	3.69	2.76	2.30	2.30	2.30	5.53
01/01/2013 00:08	6.82	6.82	6.82	6.82	6.82	6.82	6.82	6.82	5.12	4.26	4.26	4.26	10.23
01/01/2013 00:07	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	5.74	4.79	4.79	4.79	11.49
01/01/2013 00:06	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	5.29	4.41	4.41	4.41	10.57
01/01/2013 00:05	7.83	7.83	7.83	7.83	7.83	7.83	7.83	7.83	5.88	4.90	4.90	4.90	11.75
01/01/2013 00:04	6.89	6.89	6.89	6.89	6.89	6.89	6.89	6.89	5.17	4.31	4.31	4.31	10.34
01/01/2013 00:03	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.20	3.90	3.25	3.25	3.25	7.80
01/01/2013 00:02	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	2.88	2.40	2.40	2.40	5.76
01/01/2013 00:01	3.86	3.86	3.86	3.86	3.86	3.86	3.86	3.86	2.90	2.41	2.41	2.41	5.79
01/01/2013 00:00	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	5.19	4.32	4.32	4.32	10.37

Table A 4 Loads and Generators data file, the output of the first python script and the input file for the second. Showing columns 1-15 of 73 and rows 1-15 of 525600. Columns 2-37 show the load on each feeder, while columns 38-73 would show the generation on each feeder.

01/01/2013 00:14	0.18	0.17	0.03	0.00	0.00	0.00	0.00	179.14	178.34	0.00	0.00	-8.00	1.05
01/01/2013 00:13	0.26	0.26	0.04	0.00	0.00	0.00	0.00	263.54	261.81	0.00	0.00	-8.00	1.05
01/01/2013 00:12	0.08	0.08	0.01	0.00	0.00	0.00	0.00	82.04	81.87	0.00	0.00	-8.00	1.05
01/01/2013 00:11	0.10	0.10	0.02	0.00	0.00	0.00	0.00	100.16	99.91	0.00	0.00	-8.00	1.05
01/01/2013 00:10	0.18	0.18	0.03	0.00	0.00	0.00	0.00	184.45	183.60	0.00	0.00	-8.00	1.05
01/01/2013 00:09	0.12	0.11	0.02	0.00	0.00	0.00	0.00	117.04	116.70	0.00	0.00	-8.00	1.05
01/01/2013 00:08	0.21	0.21	0.03	0.00	0.00	0.00	0.00	218.08	216.90	0.00	0.00	-8.00	1.05
01/01/2013 00:07	0.24	0.24	0.04	0.00	0.00	0.00	0.00	245.28	243.79	0.00	0.00	-8.00	1.05
01/01/2013 00:06	0.22	0.22	0.03	0.00	0.00	0.00	0.00	225.42	224.16	0.00	0.00	-8.00	1.05
01/01/2013 00:05	0.25	0.24	0.04	0.00	0.00	0.00	0.00	250.97	249.40	0.00	0.00	-8.00	1.05
01/01/2013 00:04	0.22	0.21	0.03	0.00	0.00	0.00	0.00	220.25	219.05	0.00	0.00	-8.00	1.05
01/01/2013 00:03	0.16	0.16	0.03	0.00	0.00	0.00	0.00	165.56	164.88	0.00	0.00	-8.00	1.05
01/01/2013 00:02	0.12	0.12	0.02	0.00	0.00	0.00	0.00	121.97	121.60	0.00	0.00	-8.00	1.05
01/01/2013 00:01	0.12	0.12	0.02	0.00	0.00	0.00	0.00	122.61	122.24	0.00	0.00	-8.00	1.05
01/01/2013 00:00	0.22	0.22	0.03	0.00	0.00	0.00	0.00	221.11	219.89	0.00	0.00	-8.00	1.05

Table A 5 Final output table for the baseline scenario. Showing columns 1-14 of 48 and rows 1-15 of 525600. Column 2 is the total load on the network, Columns

3 and 4 the total real and reactive loads, columns 5 and 6 the total real and reactive generation, columns 7 and 8 the real and reactive branch losses, columns 9 and 10 the power flow into and out of the transformer, columns 11 and 12 the real and reactive transformer losses, column 13 the tap position of the transformer and columns 14 to 48 (of which just the first is shown) the voltage level on each busbar of the network.