How best can ground source heat pumps be deployed in a public sector context?

Submitted for the degree of Doctor of Philosophy

by

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Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: 

Date: 19th February 2018

Abstract

Geothermal heat exchange technology is well established, however its use as a valid renewable energy technology in the urban environment has not yet been fully developed. The mining legacy in Scotland, in tandem with regeneration opportunities through brownfield land, represents a significant opportunity where the use of geothermal energy and ground source heat pumps (GSHPs) can be fully explored for the provision of renewable heating.

With the demand for space heating and hot water in the UK making up a large portion (40%) of the overall UK energy use mix, the Government run Renewable Heat Incentive (RHI) scheme goes a long way towards making many projects involving renewable energy technologies economically viable and so reducing carbon emissions. The published research within this thesis shows that the RHI alone does not fully incentivise renewable heating deployment and this work examines how other new strategies can be applied.

Looking beyond the RHI as one of the main economic mechanisms for installing renewable energy technologies has identified fuel poverty as an important social factor to consider for renewable heating deployment using GSHPs. A demonstrated relationship between social housing and the proximity to brownfield land shows an increased opportunity for the use of GSHPs to meet the domestic heating energy demand for people where the cost of energy might be an issue. This is important when it is estimated that 1 in 5 households in the

UK are in fuel poverty. To examine the viability of this proposal, a dynamic energy simulation model is completed for a social housing tower block and this energy demand is met through a modelled GSHP system, using a neighbouring vacant land parcel.

The research results within this thesis suggest that an integrated policy approach can serve to improve renewable heating deployment alongside fuel poverty reduction.

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Attribution

This dissertation consists of three self-contained chapters (Chapters 3-5). This attribution page is to introduce the co-author and clarify the contribution to each chapter.

Chapter 3 was published in the peer-reviewed journal *Sustainable Energy Technologies and Assessments* in April 2014. This is included in appendix 1. Dr. Richard Lord, Department of Civil & Environmental Engineering, University of Strathclyde, United Kingdom is co-author for this research article. The article was prepared by Ross Donaldson, and Dr. Richard Lord reviewed and revised the article.

Chapter 4 was published in the peer-reviewed journal *Renewable Energy* in September 2017. This is included in appendix 2. Dr. Richard Lord, Department of Civil & Environmental Engineering, University of Strathclyde, United Kingdom is co-author for this research article. The article was prepared by Ross Donaldson, and Dr. Richard Lord reviewed and revised the article.

Chapter 5 is to be submitted to an appropriate journal in a similar format to the one presented in this thesis. Dr. Richard Lord, Department of Civil & Environmental Engineering, University of Strathclyde, United Kingdom is co-author for this research article. The article was prepared by Ross Donaldson, and Dr. Richard Lord reviewed and revised the article.

Conferences and Presentations

The research contained within this thesis has been presented at the following conferences in oral or poster format:

Donaldson, R., Lord, R., 2013. *A Systemic Approach using Ground Source Heat Pumps for the Provision of Low-cost, Renewable Heating within the Urban Environment*. Glasgow Research Partnership in Engineering Conference 2013, Glasgow, UK (poster).

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Donaldson, R., Lord, R., 2014. *Ground Source Heat Pumps and the Provision of Low-cost, Renewable Heating within the Urban Environment*. BRE Trust Research Conference 2014, London, UK (poster).

Donaldson, R., Lord, R., 2014. *Exploring the Potential for GSHP Uptake – An Integrated Approach to GSHP Deployment to address Fuel Poverty in the UK*. International Energy Agency Heat Pump Conference 2014, Montréal, Canada (oral & research paper).

Donaldson, R., Lord, R., 2014. *Exploring the Potential for GSHP Uptake – An Integrated Approach to GSHP Deployment in the UK*. Scottish Contaminated Land Forum Conference 2014, Glasgow, UK (oral).

Donaldson, R., Lord, R., 2015. *Ground Source Heat Pumps and the Provision of Low-cost, Renewable Heating within the Urban Environment*. All Energy Conference 2015, Glasgow, UK (poster).

In addition, a conference entitled ‘Renewable Heat Incentive (RHI) Symposium’ was arranged and staged at the University of Strathclyde in January 2012 to coincide with the introduction of the UK Governments’ Renewable Heat Incentive (RHI) policy. This was completed with the help of Linzi Shearer, STEM Development Manager, City of Glasgow College. The conference brought together over 50 participants from local government, academia and industry and secured over £3,000 in funding (net) for the University of Strathclyde.

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Glossary

BGS	The British Geological Survey. A world leading geoscience centre for surveying, monitoring, modelling and research.
Brownfield Land	Areas of land usually synonymous with previously developed land. This is land that is or was occupied by a permanent structure and any associated fixed surface infrastructure.
CoP	Coefficient of Performance. A measure of output energy relative to the motive work required to output that energy.
DECC	The Department for Energy and Climate Change. A UK Government department largely responsible for energy provision in the UK. In July 2016, DECC became part of the Department for Business, Energy and Industrial Strategy.
EC	The European Commission. An institution of the European Union responsible for proposing legislation, implementing decisions and managing the day-to-day running of the European Union.
FITs	Feed-in Tariffs. A UK Government incentive scheme that makes cashback payments to producers of low-carbon or renewable electricity.

Fuel Poverty	A situation where a household spends more than 10% of household income on household energy costs.
Geothermal Energy	Energy (or heat) emanating from below the earth's surface.
GLD	Ground Loop Design software package. GLD is a software suite for designing geothermal ground source heat pump systems.
GSHP	Ground Source Heat Pump.
Hectare	A metric unit of square measure equivalent to 10,000 square metres.
HVAC	Heating, ventilation and air conditioning.
IES-VE	Integrated Environmental Solutions Virtual Environment software package. IES-VE is an energy analysis and performance modelling software suite.
KWh	A Kilowatt Hour. A unit of energy equivalent to one kilowatt of power sustained for one hour. Normally used for metering domestic energy installations.
KW_e	A Kilowatt, equivalent to 1,000 watts (where a watt is a unit of power). In this case, the subscript denotes electrical or from electricity.
KW_t	A Kilowatt, equivalent to 1,000 watts (where a watt is a unit of power). In this case, the subscript denotes thermal or from heat.

MWh	A Megawatt Hour. Equivalent to 1,000 kilowatt hours. Normally used for metering large amounts of energy.
Ofgem	The Office of Gas and Electricity Markets. The UK Government regulator for Gas and electricity companies.
Public Sector	The public sector consists of governments and all publicly controlled or publicly funded agencies, enterprises, and other entities that deliver public programs, goods, or services.
Retail Price Index	A measure of inflation in the UK published by the Office for National Statistics.
RHI	The Renewable Heat Incentive. A UK Government incentive scheme that makes cashback payments to producers of renewable heat.
SCOP	Seasonal Coefficient of Performance. The overall coefficient of performance for a unit (in this case, ground source heat pump) representative for the whole designated heating season.
SEPA	The Scottish Environmental Protection Agency. The principal environmental regulator for Scotland, UK.
SPF	Seasonal Performance Factor. The measure of the operating performance of a heat pump over a year where higher SPF value denotes greater efficiency.

SVDLS	The Scottish Vacant and Derelict Land Survey. A Scottish Government database that records progress on land re-use within Scotland, UK.
Thermal Conductivity	The property of a material relating to its ability to conduct heat.
U-value	Thermal transmittance. The rate of transfer of heat through a structure. The lower the u-value, the better the material is as a heat insulator.
W.m & W.m^{-2}	Watts per metre & watts per metre (square). The radiant flux (power) received by a surface per unit area.

1. Introduction

1.1 Ground Source Heat Pumps

Ground source heat pumps (GSHPs) are a renewable energy technology that can be used to heat (or cool) spaces by moving low-grade heat from (or to) the ground to the building when it is required. Where the common gas boiler operates at around 85% efficiency for heating purposes, an equivalent GSHP system operates with efficiencies in excess of 300%. This means that the useful heat energy output from a GSHP can be 3 or 4 times the energy input, which is a very attractive element of a GSHP installation. GSHPs can serve to reduce household energy costs and reduce carbon emissions by providing heat in this way. Whilst ground source heat pumps have been popular in many parts of the world for a number of years (Kim et al., 2010), the uptake of the technology in the UK has been considerably lower (Singh et al., 2010). The aim of this research is to understand how best GSHPs can be deployed in a public sector context and determine if this deployment and continued use is viable.

1.1.1 Energy Consumption in the UK

Of all the energy consumed in the UK, around 46% is attributed to heating with more than three quarters of this heating demand coming from residential end uses (DECC, 2012; Chaudry et al., 2015). If climate change aspirations are to be met, tackling the heating portion of the UK energy usage mix should go a long way towards meeting legally binding climate change targets of a 34% reduction in greenhouse gas emissions by 2020, and an 80% reduction by 2050, both from 1990 levels (Climate Change Act (2008)).

Within the UK, more than 80% of the consistent demand for heating is met through the use of gas fired boilers (DECC, 2012; Energy & Utilities Alliance, 2012). With the UK energy landscape having been developed around the North Seas oil and gas fields, the use of gas-fired boilers is a dominant means of heat generation even as we look to move to a low carbon economy. The supply infrastructure is heavily developed, and the price paid per unit of gas delivered has typically been lower than in many other European countries (Friends of the Earth, 2012). However, natural gas is a carbon-heavy finite recourse, is not renewable, and is not fully aligned with the strategies and roadmaps that are set to take us to a strong, secure, and resilient low-carbon economy. With renewables contributing to between 1% and 2% of all heat generation in the UK (DECC, 2012; DECC, 2014c) and heat pumps making up approximately 5% of that (0.0005% of all heat generation) (DECC, 2014b), the development of a strong renewables market has to be greatly supported if climate change aspirations are to be addressed.

1.1.2 The Renewable Heat Incentive (RHI)

The UK Government run Renewable Heat Incentive (RHI) scheme aims to tackle the large fossil fuel dependent heating demand by incentivising the uptake of renewable heating (Energy Saving Trust, 2014; DECC, 2015). For each kWh of heat produced using a technology named within the RHI, cash-back payments are made to those who produce heat in this way. The UK Government regulator for gas and electricity markets (Ofgem) is responsible for implementing and administering the RHI scheme (Energy Saving Trust, 2014; DECC, 2015). Installations must be accredited as meeting terms laid out within the RHI before payments are made.

A range of tariffs exist for technologies within the RHI, and tariffs have varied over time based on the impact on the fixed RHI budget. The current tariffs applicable from 1st April 2016 are illustrated in table 1.1.

Table 1.1: Tariffs by technology type under the RHI scheme.

Technology	Non-Domestic Installation (pence/kWh)	Domestic Installation (pence/kWh)
Ground Source Heat Pumps	8.95	19.33
Air Source Heat Pumps	2.57	7.51
Solar Thermal	10.28	19.74
Solid Biomass	2.05 to 5.24[a]	5.21
Solid Biomass CHP	4.22	n/a
Biogas	2.27 to 7.71[a]	n/a
Deep Geothermal	5.14	n/a
Municipal Solid Waste	2.05	n/a
Commercial & Industrial Waste	2.05	n/a
Biomethane	2.42 to 5.35 [a]	n/a

[a]Specific tariff varies by installation size

modified from: (http://www.icax.co.uk/RHI_tariff_tables.html).

Tariffs are adjusted to be inline with the Retail Price Index (RPI), and tariffs can also be adjusted if payment amounts per installation type are higher than anticipated (DECC, 2014a; DECC, 2015). This is known as degression. Tariffs are monitored quarterly, to provide value for money for taxpayers (UK Government, 2016). The rates paid per kWh of heat produced by GSHPs are favourable for both non-domestic and domestic installations (table 1.1). DECC (2016) have announced that solar thermal is to be removed from the RHI scheme in 2017, a result of degression and improving value for money for taxpayers. This change alone will make GSHPs the single most favourably paying technology within the RHI. Accredited GSHP installations under the RHI since its introduction in November 2011 have amounted to a total of 438 (Ofgem, 2016) which compares poorly against other technology types such as solid biomass accredited installations totaling 13,002 to date (Ofgem, 2016). For GSHPs within the RHI, these figures illustrate that further support mechanisms are necessary to facilitate GSHP deployment towards reducing carbon emissions and lowering energy bills. In spite of favourable tariff rates for GSHPs, there are broad challenges for their implementation under the RHI scheme. This includes the initial capital cost barriers and the need for better technology and policy awareness (Donaldson & Lord, 2014).

1.1.3 Land Constraints for GSHPs

To understand why the RHI is not fully working for GSHPs, it is important to consider technology specific constraints that inhibit deployment of GSHPs. The RHI is addressing finance by providing a mechanism where large upfront costs per installation can be recouped by the owner (Energy Saving Trust, 2014). A further issue facing GSHPs is land use constraints linked with space requirements (Fankhauser et al., 2009; Hughes, 2008; Goetzler et al., 2009). A GSHP installation requires an area of land proportional to the heat load that the system is trying meet, where heat can be extracted from the ground and used to heat the required space. For example, a 1 kW_t horizontal array GSHP will typically have a proportional trench length of 10m within which the ground loop would be laid (Kensa Engineering Ltd., 2012). Engineering costs and transmission losses are a factor in GSHP design (CANMET Energy Technology Centre, 2005; Busby et al., 2009), so a location close to the heat load maximizes operating potential.

Lund (2001), Fry (2009) and Busby et al. (2009) indicate that GSHP systems operating in close proximity to one another could compromise system efficiencies. This is compounded in built-up areas with multiple systems interacting, due to ground temperatures decreasing through continued use where more heat is extracted from the ground than is being replenished. One example is London where GSHP systems are recorded as being within 250 of other GSHP systems, which increases the risk of interference effects (Busby et al., 2009).

1.1.4 Brownfield Land

The use of brownfield (i.e. previously developed), vacant or derelict land represents a novel approach through which the issue of availability of land for

GSHPs might be addressed. Within Scotland, the majority of vacant and derelict land is located in and around centres of population (Scottish Government, 2016) and planning policy looks for new and beneficial uses for previously used land (Scottish Government, 2013). This is mirrored at the European level, where the European Union (EU) already incentivises the re-use of contaminated sites (Thornton et al., 2007). The combination of land availability, policy support, and proximity to end users is a good match for tackling the space constraints associated with deploying GSHPs through using vacant and derelict sites. Reusing land also links well with regeneration aspirations. There is proven association of brownfield land and relative deprivation in Glasgow, Scotland (Maantay, 2013) which a link between brownfield land and poor public health has been illustrated in England (Bambra et al., 2014; Bambra et al., 2015).

1.1.5 Fuel Poverty

The effects of rising energy provision costs on end users and social deprivation levels can also be estimated. When a household spends more than 10% of their household income on energy (Scottish Executive, 2002), that household is classed as being in fuel poverty (Boardman, 2010). Being in fuel poverty has the potential to affect health, child development in early years, and contribute to excess winter deaths (Boardman, 2010). Negative health effects through poor housing are strongly linked with being fuel poor (Boardman, 2010; Liddell & Morris, 2010). Having less available income once energy bills have been paid can also affect other aspects of living and the choices households have to make. It is estimated that up to 1 in 5 households in the UK are living in fuel poverty

(Energy Action Scotland, 2013). As heating makes up the largest portion of household energy use (DECC, 2012), tackling costs associated with heating could greatly mitigate incidences of fuel poverty. As a global example, the UK has developed a broad understanding of fuel poverty. Research from countries including France (Legendre & Ricci, 2014; Imbert et al., 2016) Italy (Fabbri, 2015), Greece (Papada & Kaliampakos 2016), and as far away as New Zealand (Lawson et al., 2015) all link back to the fuel poverty indicators put forward by Boardman (1991).

1.1.6 Public Sector Housing

Public sector housing has a long history of association with low-income households (Carley, 1990). Recent improvements in public sector housing have tended to focus on energy efficiency measures (Hamilton et al., 2013). Rarely has this included using already vacant or derelict land to meet the heating energy needs of multiple public sector dwellings. There is a new drive to use brownfield sites for housing needs (UK Government, 2016b) and rebuild or refurbish existing public sector housing (UK Government, 2016a). It is likely therefore that those in public sector housing could stand to benefit from their proximity to vacant & derelict land if used for GSHP deployment to meet their heating requirements. Considering the aim of energy efficiency measures is to simultaneously reduce carbon emissions, lower household energy bills and improve quality of life, the economic, environmental and social viability of a proposed GSHP system on vacant and derelict land has to be examined to ensure this is met.

1.1.7 Problem Statement and Research Gap

1.1.7.1 Problem Statement

The use of ground source heat pumps is extremely low across the UK. This is illustrated within the deployment statistics of heating technologies eligible under the RHI. Heat pumps however are shown to have efficiencies in excess of 300%, meaning that the useful heat output can be 3 or 4 times the energy input.

Nearly 50% of the UK's energy demand is for space heating. At a household level, space heating makes up the largest portion of household energy use. It is reasonable to assume that in order to meet climate change aspirations, tackling space heating is absolutely necessary.

High household energy spend and low household income contributes to incidences of fuel poverty. This means negative health effects and less available household income to spend on other services. Public sector housing has a long history with low income, and represents a large enough energy demand where energy projects could be viable if this is targeted correctly.

There are known barriers to the use of heat pumps. This includes space constraints associated with their deployment. The use of heat pumps on vacant and derelict land represents an option where deployment can occur on land that has no current use or high economic value.

1.1.7.2 Research Gap

A gap in current research is highlighted as we try to answer the research question *'how best can ground source heat pumps be deployed in a public sector context?'*. New research is required that includes a more complete analysis of the total amount of vacant and derelict land available (to include also landfills). Also, the spatial relationship between vacant and derelict land and public sector housing needs to be understood if it is proposed that this be an end use. A modelled case study unique to this research will then be used test the viability of using heat pumps in this way.

1.2 Aims and Objectives

The aim of this research is to investigate if the use of ground source heat pumps can be increased through targeted deployment towards the fuel poor living in public sector housing, using nearby vacant and derelict land. These key areas are identified within the problem statement. To achieve this aim, the main policy support mechanism for renewable heating is examined, as well as determining the spatial relationship between public sector housing and vacant and derelict land. A modelled case study is then used to determine the practical viability of the proposal. The specific objectives of this research are:

1) To determine how the RHI is applied in practice and how it could be better adopted towards supporting GS heating technology.
2) To determine the total amount of vacant and derelict land available that

could be used for the deployment of GSHPs within this context.

3) To analyse the relationship between vacant and derelict land, public sector housing and relative deprivation.
4) To design and analyse a modelled GSHP system situated on vacant and derelict land for public sector housing.

Based on the findings for how the RHI works in practice, it will be possible to make conclusions on how well GSHPs deployment is currently supported. Investigating the available land will focus on data for Scotland, UK, where a new baseline figure, including some former landfills, will be calculated from local council data which has not been attempted before. For the spatial analysis, a map showing social housing per capita against quantity of brownfield land per electoral ward will be attempted for Glasgow, UK. The upper and lower quartiles of the relationship between social housing and brownfield land is used as a proxy for high and low opportunity respectively for GSHP deployment. The design of a modelled GSHP system is selected for an area within one of the predetermined opportunity zones, and focuses on the thermal response of the subsurface over time, investigating if there is sufficient capacity within the ground to meet the heating demand of a public sector housing building.

1.3 Research Methodology & Thesis Structure

1.3.1 Research Methodology

To fully answer the question '*how best can ground source heat pumps be deployed in a public sector context?*', this thesis is split into 3 distinct sections. Firstly, the application of current renewable heat policy is discussed (chapter 3). The RHI is considered within the context of a ground source heat pump installation taking place in a school refurbishment project. This serves to illustrate the benefits of the RHI scheme, but crucially how the RHI is applied in practice. The project occurred early on in the RHI scheme and serves as one of the first insights into how the RHI was handled and understood at the project level. A reference to renewable heat policy here is a key step in setting the scene for any proposed renewable heat installations, as outlined later within this thesis. The outcome of this discussion is intended to show that whilst the RHI exists and aims to transform the renewable heating market, it has a long way to go to be successful and cannot exist in isolation.

Secondly, a novel theoretical approach to heat pump deployment is put forward that makes use of vacant and derelict land whilst targeting those determined to be in fuel poverty (chapter 4). This approach uses calculated data for the town of Glasgow, UK, where areas of 'opportunity' are determined where available land and indicators of fuel poverty are shown to be high. This translates into an 'opportunity' for heat pump deployment. The outcome of this approach is intended to show that alongside the RHI, an integrated method using different variables can be successful in identifying where heat pumps can be deployed to maximise their chances of success.

Thirdly, a modelled case study is created (chapter 5) from the theoretical approach put forward in the previous section. A modelled heat pump system is designed for a residential public sector building that falls within an area of high opportunity for heat pump deployment. A dynamic energy model of the residential building is created and the heating energy demand of the building is sought to be met. This is done using a modelled ground source heat pump system on neighbouring vacant and derelict land. This is a key step in proving the theoretical viability of such an approach. It is assumed that the energy demand of the building can be met using a financially viable modelled ground source heat pump system, but that it may face some sub-surface challenges that occur when working on previously developed land.

Having the research methodology arranged in this way allows for exploratory inquiry, a working analysis of the effectiveness of the UK renewable heat incentive policy, and tests the viability of the proposed heat pump deployment strategy. Individual methodologies for these key steps are contained within chapters 3 to 5 for reference purposes.

1.3.2 Thesis Structure

The research methodology and key steps can be best illustrated within a flowchart layout (Figure 1.1). This illustrates the dynamic relationship between all chapters within the thesis, and highlights feedback mechanisms when they occur. Chapters 1 and 2 serve as introductory chapters. The core methodology (as previously discussed) is worked through across chapters 3-5. Chapter 6 discusses outcomes and identifies contributions to the field, including limitations and future work.

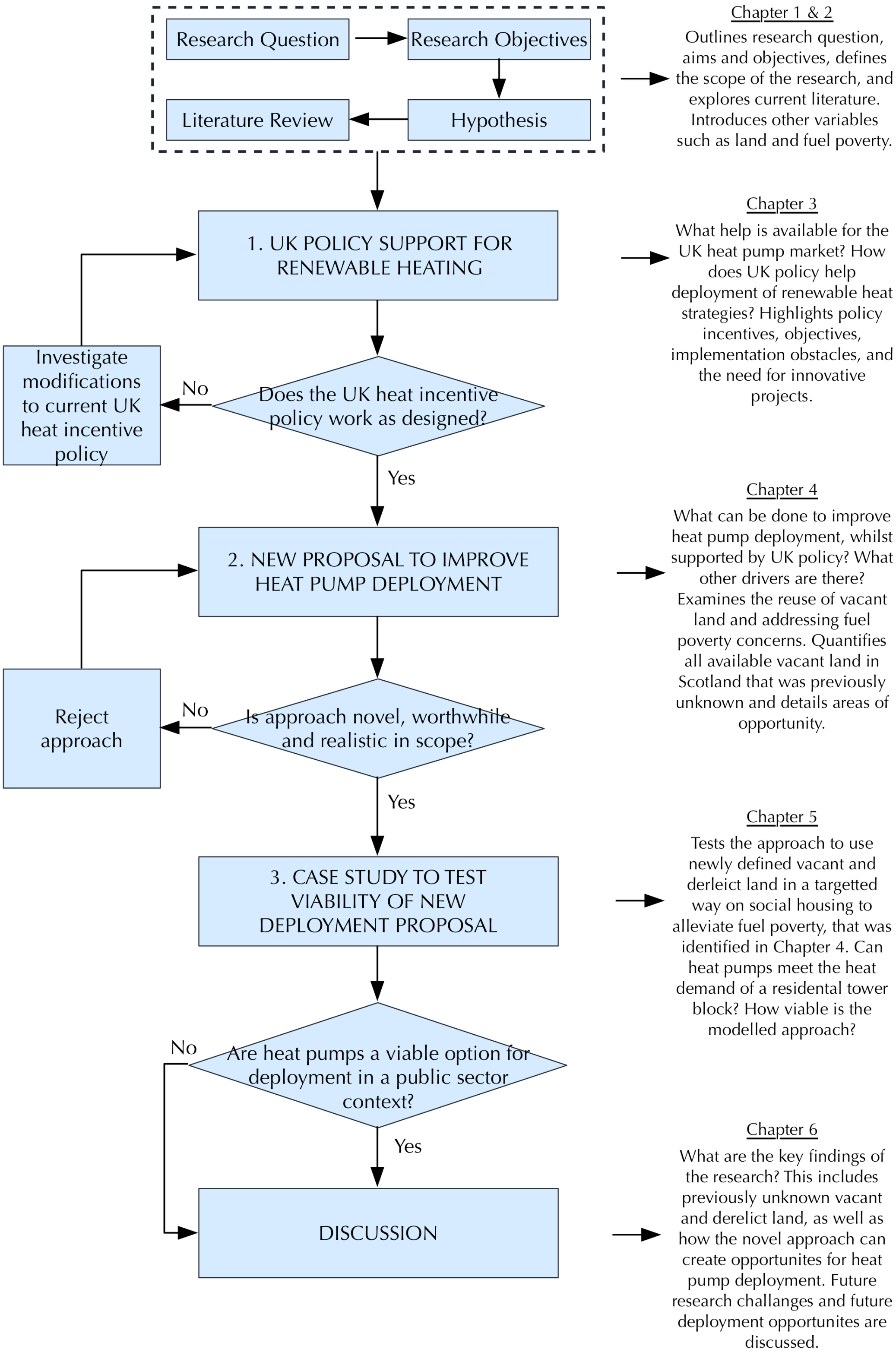

Figure 1.1: Thesis Structure and Component Relationship.

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2. Literature Review

2.1 Geothermal Energy and Heat Extraction

There is continued interest in reducing the effects of climate change through the use of renewable energy technologies. Ground Source Heat Pumps (GSHPs) are one such technology that uses shallow geothermal energy as a means of heating or cooling buildings. GSHPs have been a popular renewable energy technology option in various parts of the world (Kim et al., 2010), however the UK remains to have one of the least developed heat pump markets in Europe (Hannon, 2015). This chapter considers this disparity between need and use and new solutions to improve uptake of the technology. This research is backed by current UK energy policy that supports the use of renewables for heating purposes.

Geothermal is defined as relating to or produced by the internal heat of the earth (Oxford Dictionary of English, 2010). Energy produced in this way ('geothermal energy') has been used by humans for thousands of years. Hot springs such as at Bath, UK were exploited during the Roman Empire (Gallois, 2007) and made use of fractures in rock that channel water at 70°C to the surface from approximately 3000 metres deep (Andrews et al., 1982). Exploiting energy in this way makes use of free geothermally heated water, however limits options to areas where hot springs occur naturally.

Geothermal energy is also available at a much shallower depth ('shallow geothermal energy') and is not dependent on naturally occurring hot springs. Measurements show that the temperature at depth is predominantly stable all year round (Banks, 2008). Figure 2.1 gives a representation of ground temperature with depth.

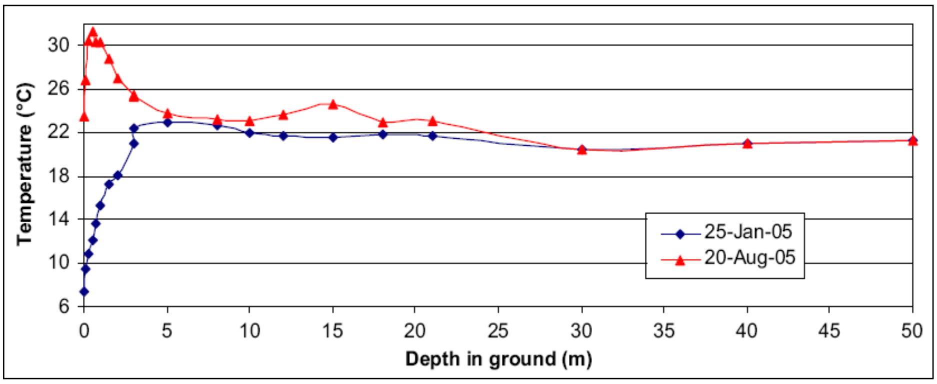

Figure 2.1: Ground Temperature by depth from a borehole in Nicosia, Cyprus.
(Florides & Kalogirou, 2007).

Ground temperatures and ground temperature gradients change by location. Table 2.1 illustrates temperature variation by latitude at constant depth beyond the area of the depth profile affected by solar influx.

Table 2.1: Ground temperature by latitude at constant depth

Location	Latitude	Depth	Temperature
Nicosia, Cyprus	35.1856°	20 metres	22.5°C *(Florides & Kalogirou, 2007)*
Istanbul, Turkey	41.0082°	20 metres	16°C *(Murat et al., 2015)*
London, England	51.5074°	20 metres	12.5°C *(Loveridge et al., 2013)*

In all cases there remains a geothermal gradient where temperature changes with depth, as illustrated in figure 1. The UK average geothermal gradient is 2.6 degrees Celsius per 100 metres (Busby et al., 2009). This sits in line with the earth's broader geothermal gradient of 1-3 $°C.m^{-1}$ (Banks, 2008). These temperatures are up to 80% cooler than those used to heat hot springs and are lower than necessary for useful space heating.

2.2 Heat Pumps

The second law of thermodynamics prohibits the flow of heat from a colder area to a warmer area, unless mechanical work is done to achieve this (Atkins, 2010; Moran et al. 2014). A heat pump can complete this work using a vapour compression cycle driven by electrical energy. Low-grade heat is harnessed and increased in temperature sufficiently to heat a space.

The origins of the modern day heat pump were first put forward by Lord Kelvin over 150 years ago (Thomson 1852, cited in Banks (2012), p.121). Lord Kelvin anticipated that the direct combustion of fuels for heating would lead to energy reserves eventually being depleted and the energy needed to drive machinery ('motive power') would be unavailable. Using air as working fluid, Lord Kelvin demonstrated his 'heat multiplier' (Reay & Macmichael, 1988; Koronakis, 2009) (figure 2.2).

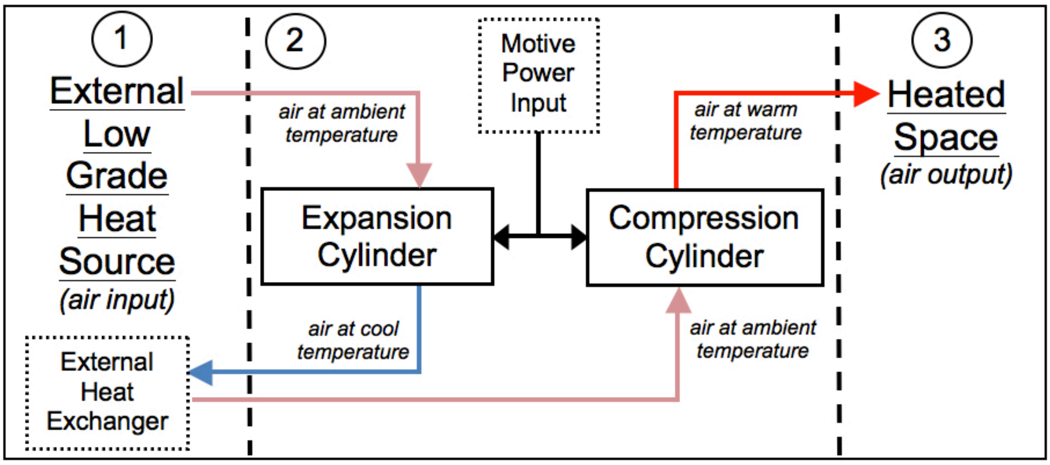

Figure 2.2: Principles of the heat pump design as proposed by Lord Kelvin, 1852.

External ambient air (1) is drawn in to the heat pump (2) and expanded within the powered expansion cylinder. This creates a drop in pressure that cools the air as energy is released. The expanded cool air is passed through a heat exchanger that is in contact with the ambient air. The expanded cool air is heated by this interaction as it travels through the heat exchanger, and then compressed in the powered compression cylinder. This increases the air temperature beyond that of the initial air input and the warm air is used to heat a space (3). The process operating within the heat pump can be considered an open system (Cantor, 2011).

It is on Lord Kelvin's design that the modern day heat pump is based. The component arrangement is modified to adopt a vapour compression cycle within the system. This exploits the characteristics of phase change associated with an appropriate working fluid. In all cases, this is a refrigerant with a low boiling point as air is inefficient at heat transfer (Butler et al., 2001; Petchers, 2003). All heat pumps currently on the market use the vapour compression cycle (Cantor, 2011) (figure 2.3).

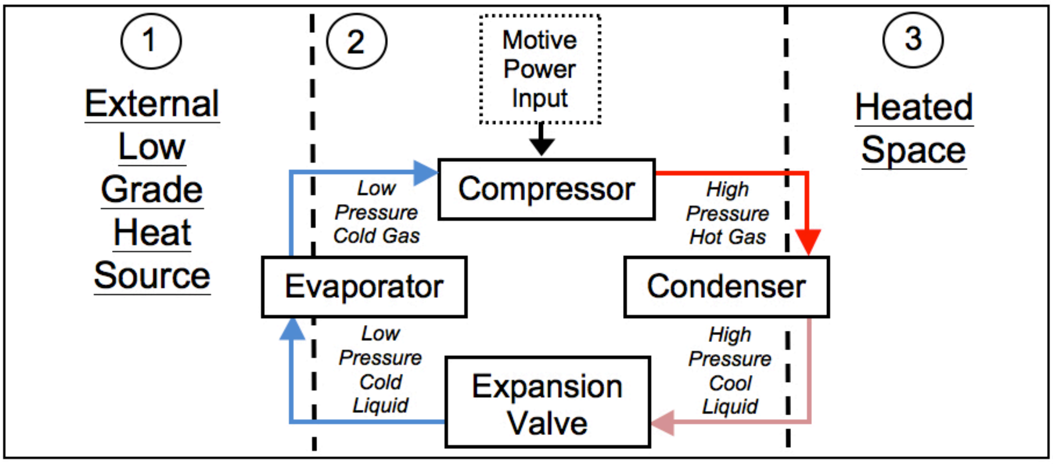

Figure 2.3: Principles of a modern day heat pump.

An external low-grade heat source (1) is placed in contact with a heat exchanger known as the evaporator that is part of the heat pump (2). Refrigerant circulates in a loop within the heat pump and has a low boiling point. Energy is transferred from the external low-grade heat source (1) to the refrigerant loop within the heat pump as both pass through the evaporator. The refrigerant changes phase to a gas, and is drawn into the powered compressor. The compression action further increases the temperature of the refrigerant, which is then passed through another heat exchanger known as the condenser. A centralised heating circuit within the heated space (3) is placed into contact with the condenser, and it is the fluid within this secondary circuit that is heated and used to heat the required space. The refrigerant is cycled through an expansion cylinder where temperature and pressure drop and the cycle begins again. The process operating within the heat pump can be considered a closed system (Cantor, 2011). All heat pump installations are reverse-cycle refrigeration systems – in simple terms, refrigeration systems working in reverse (Dincer & Kanoglu, 2010).

2.2.1 Ground Source Heat Pumps

As the temperature within the ground is relatively stable all year round (Banks, 2008) it is possible to use this as the source of external low-grade heat (1) shown in figure 3. Coupling the ground to the heat pump in this way completes the ground source heat pump system.

Groundwater can be extracted in an 'open loop' configuration of the external side of the heat pump process (1) shown in figure 2.3. Groundwater is abstracted through a buried inlet pipe, which is then drawn through the evaporator of the heat pump to heat the refrigerant. In a 'closed loop' configuration, an anti-freeze mixture is circulated in a closed loop of buried pipes and thermal energy is conducted from the ground through the walls of the pipe loop (Florides & Kalogirou, 2007). Water is an excellent fluid choice with good thermal properties, however the freezing point of water is 0°C. This means that water alone cannot be used for conditions below this temperature in the ground loop. This is also a fundamental limit, since the highest heat demand for the heated space will be on the coldest winter day. A water glycol mixture has a lower freezing point than water and so is often to the closed ground loop configuration at the external heat source to prevent freezing (Silberstein, 2016).

2.2.2 Coefficient of Performance

A wide range of literature exists that introduces ground source heat pumps, their applications, and the mechanics of 'moving heat' (Sanner et al., 2003; Florides & Kalogirou, 2007; Omer, 2008; Banks, 2009; Banks, 2012). Crucial to this process is a ratio called the coefficient of performance (CoP) (Banks, 2009). The CoP is a measure of output energy relative to the motive work required to output that energy. In this case the energy output is as heat. If the CoP ratio for a given GSHP system is too low, this can indicate that heat may not be being obtained in the most cost effective way. Energy should only be harnessed if the balance between the heat delivery from the heat pump and the electrical input to run the heat pump is sufficiently advantageous (Banks, 2009). Typical GSHP systems are recorded as having CoPs of between 3 and 4 (De Carli et al., 2015; Safa et al., 2015). An example CoP calculation (1) for a typical residential heat pump system with peak heating load of $6kW_t$ would be:

$$\text{Coefficient of Performance} = \frac{\text{Heating Energy Output of the Heat Pump (kW)}}{\text{Motive Power Input to drive the Heat Pump (kW)}} = \frac{6}{2} = 3 \quad (1)$$

In this example, the heat pump is sized to meet 100% of the residential heat load, and has an electrical input of $2kW_e$ to power the compressor within the heat pump.

The CoP for a heat pump is dimensionless (El-Meniawy et al., 1981; Devotta & Holland, 1985). A higher CoP indicates how much more effective the heat pump is at supplying heat than if the original input energy was used directly for heat instead (Devotta & Holland, 1985). The example CoP calculation (1) gives a CoP of 3 for a $6kW_t$ heat pump where $2kW_e$ of energy is consumed by the heat pump. The user therefore obtains 6kW of space heating, with 4kW directly obtained from geothermal heating (Banks, 2009). In simple terms, two thirds of the required energy to heat a space can be drawn from the environment (Ochsner, 2007).

Beyond the CoP, a more accurate way of recording performance is the Seasonal Performance Factor (SPF) of a heat pump. This is calculated in a similar way to the CoP, however takes account of seasonal variations in temperature of the surroundings (Banks, 2008). For GSHPs, the main fluctuations will be temperature changes in the ground over time in tandem with temperature changes in the space to be heated. These changes can affect the working efficiency of a heat pump, leading to a lower than expected CoP, and increased running costs of the heat pump system. The SPF compensates for these temperature fluctuations by measuring the total heat output over the total energy input, over one year (Cantor, 2011). The SPF, or Seasonal Coefficient of Performance (SCOP), is based on flow temperatures within the heating system (MCS, 2016). The SCOP is used in the UK to regulate RHI payments for accredited installations, and is determined using official conversion tables accredited by the regulator (MCS, 2016).

2.2.3 Opportunities and Limitations

The main benefits of a heat pump installation include a reduction in greenhouse gas emissions (Omer, 2008) in tandem with energy bill savings for households (Cantor, 2011). Simcock et al. (2014) show that one of the largest influencing factors on end users for energy related information is financial cost. Therefore, understanding cost barriers and opportunities associated with GSHP installations can be more relevant to improve uptake of the technology.

2.2.3.1 Installation Costs against Energy Cost Savings

Construction costs and operating costs are shown to be important at all stages, in any engineering project (Kim et al., 2010). Heat pump installation costs are no different and vary due to equipment sizing against building size. The UK's complex geology also presents difficulty when attempting to standardise installation costs (Busby et al. 2009). GSHPs are often shown with installation cost ranges. Installation costs for a standard domestic property fall within the range of £8,000 to £16,000 (Cantor, 2011), however could be as much as £20,000 (Energy Saving Trust, 2016a).

The Energy Saving Trust (2016a) has estimated cost savings when displacing a current heating system with that of a GSHP system (table 2.2). Also shown is the RHI payment amount based on the renewable portion of heat that is produced, which varies by end user habits and installation size. Retrofitting heat pumps in this way is particularly relevant when two-thirds of the properties already in existence will still be standing in 2050 (Boardman et al., 2005). Additionally, DECC (2013) show that increasing GSHP system size to cater for multiple homes is shown to decrease the cost per unit of heat generated. This enhances the flexibility of a GSHP installation.

Table 2.2: Cost savings associated with a GSHP system when displacing a current heating system.

Existing system	Fuel bill savings (£/year)	Renewable Heat Incentive (RHI) payment (£/year) 1 April 2015 to 31 March 2016	Renewable Heat Incentive (RHI) payment (£/year) 1 March 2016 to 30 June 2016	Carbon dioxide savings (kgCO2/year)
Gas older (non-condensing)	£440 to £660	£2,555 to £3,955	£2,590 to £4,005	2,100 to 3,300 kg
Electric (old storage heaters)	£790 to £1,425			6,700 to 11,700 kg
Oil older (non-condensing)	£130 to £220			3,000 to 4,700 kg
LPG older (non-condensing)	£960 to £1,500			2,800 to 4,500 kg
Coal	£590 to £990			7,600 to 12,100 kg

Excluding the variability in capital costs associated with a GSHP installation, it is shown that operating a GSHP system can compete favourably with other methods of heat generation. The primary domestic heating source in the UK is natural gas which 63% of domestic properties use (DECC, 2015). Electricity is the second largest means of domestic heating generation, used in 25% of UK properties (DECC, 2015)., GSHPs can compete even with the use of natural gas and electricity but the largest yearly savings of £790 to £1,425 are realised when displacing electric storage heaters.

2.2.3.2 Policy Considerations

The costs of boreholes, heat pumps, heat exchangers, technology lifespan, and the variation in energy prices over time, however, are all important aspects that can adversely affect this viability (Kim et al., 2010). Although installation costs can be as much as £20,000 (Energy Saving Trust, 2016a), the Government run Renewable Heat Incentive (RHI) scheme in the UK makes cash back payments to producers of renewable heat. This aims to alleviate the high capital costs incurred when installing a renewable technology, and incentivises renewable heating to strengthen the UK energy mix. For a typical domestic GSHP installation, payments are made quarterly over 7 years. Even if taking the maximum anticipated GSHP installation cost of £20,000 with the lowest yearly RHI payment amount of £2,555 (table 2.2), the payback period is close to the 7 year period over which RHI payments are made. In addition, there is also the fuel bill savings per year that should be considered. This scheme is open to all persons interested in installing and operating a GSHP installation. Even with these financial benefits, GSHPs occupy less than 1% of the overall renewables market (DECC, 2014). The RHI is important in overcoming barriers to renewable heating technology deployment, and its application is discussed further in Chapter 3.

Links with other policy also support the potential use of GSHPs. This includes the Scottish Government's goal to decarbonise the heating system in Scotland by 2050 (Scottish Government, 2014c),. In addition, space constraints associated with the installation of ground loops and boreholes (Hughes, 2008) could be supported through links with spatial planning. This includes the Scottish Government's third National Planning Framework (NPF3) which looks for new and beneficial uses for previously developed land (Scottish Government, 2014b). Land use and land availability is also important for the long term operation of GSHPs. Fry (2009) & Pulat et al. (2009) show that the proximity of GSHP installations can cause concern for thermal interference between boreholes, and that inadequate heat exchanger spacing can impact on the performance of a GSHP system. Chapter 4 presents opportunities for using GSHPs on brownfield land in areas where space may already be an inhibiting constraint. Chapter 5 discuses how these effects can be mitigated through optimal heat extraction to maintain stable ground temperatures over time.

Social policies can also support the use of GSHPs. Fuel poverty occurs when a household spends more than 10% of household income on energy costs (Boardman, 2010). High-energy costs can be due to issues including, but not limited to, sub-standard building fabric or inadequate heating methods. This means that less money is available for other household expenses, such as food, leading to serious consequences for human health (Liddell & Morris, 2010). This includes dangers such as developmental effects in children from over crowding in warmer rooms of a household, and broader issues related to living in cold, damp conditions.

The UK is the only country to have agreed a definition of fuel poverty (NEA et al., 2009). However, the low household income levels and household energy costs that define it are dynamic factors. The lack of a definition in other parts of the world means that no integrated policies exist to address it. For example, the USA has the same factors that can impact on fuel poverty (low income levels against energy costs) however the lack of a definition means that no policies exist to address it (Power, 2006). A similar situation exists for countries in Europe, through the EU is showing an increased understanding of the problem based on the UK fuel poverty definition (NEA et al., 2009).

The UK has been working since the early 1990's to design policies to address fuel poverty. This includes Scotland's ambitious target of eradicating fuel poverty, as far as is reasonable practicable, by November 2016 (Scottish Executive, 2002). Current fuel poverty policy for Scotland considers area-based schemes that target fuel poor households (Scottish Government, 2014a). However, these measures are often limited to insulation options to improve the thermal performance of buildings. The most recent housing condition survey for Scotland has shown that more than 34% of households still remain in fuel poverty (Scottish Government, 2015), so work still has to be done to achieve the target set for November 2016.

Fuel poverty is also shown to have a heterogeneous spatial distribution. Morrison & Shortt (2008) explain that the ability to map fuel poverty is important to assist in developing robust community profiles, which can then be taken to aid the targeting of resources. Maantay (2013) shows that deprivation correlates with brownfield land, whilst Bambra et al. (2014) identify a link between brownfield land and morbidity and mortality. If GSHPs are used on brownfield land, then deployment here can be supported across policy to meet fuel poverty aspirations. Saunders et al. (2012) highlight that renewable energy can play an important role in reducing fuel poverty where improved outcomes are shown for low-income households through coordinated support mechanisms. This research identifies fuel poverty as an important driver for the use of renewable energy technologies and this is discussed in chapter 4.

2.3 Other Renewable Technologies suitable for Space Heating

Alongside heat pumps, other technologies are available for space heating. These are also classed as renewable and have the potential to lower energy bills and reduce greenhouse gas emissions. Providing a background to these other renewable heating options highlights the technology potential. Table 2.3 presents an evaluation of other technologies that are suitable for space heating.

Table 2.3: Renewable heating technology options

Renewable heating technology option	Features	Advantages or opportunities	Disadvantages or constraints	References
Solar Water Heating	- Water heated via sunlight using a solar collector, then transferred to the building using a small electrical input.	- Classed as renewable so eligible for UK Government subsidy. - Could limit exposure to rising energy prices by offsetting some gas or electricity use. - Can be mounted on rooftops, however such installations would not assist brownfield land redevelopment.	- Solar is at its weakest at times of high heat demand (winter), so supplementary heating system is needed. - Solar arrays would fullly occupy the available land so sterilises future redevelopment. - Requirements to mitigate against vandalism (important if located on ground) and allowances for required maintenance.	*Department of Trade and Industry, 2006.* *Energy Saving Trust, 2016b.* *Energy Saving Trust, 2017a.* *Li, et al., 2014.* *Rosenbloom & Meadowcroft, 2014.* *Trainer, T., 2010.*
Solar PV	- Electricity created via sunlight using photovoltaic (PV) cells.	- Classed as renewable so eligible for UK Government subsidy. - Could limit exposure to rising energy prices by offsetting some or all electricity use. - Can be ground mounted instead of on rooftops, however such installations would not assist brownfield land redevelopment.	- Solar is at its weakest at times of high lighting electricity demand (evenings & dark winter periods), so a supplementary electricity system may be needed. - Solar arrays would fully occupy the available land so sterilises future redevelopment. - Requirements to mitigate against vandalism (important if located on ground) and allowances for required maintenance.	*Department of Trade and Industry, 2006.* *Energy Saving Trust, 2016b.* *Energy Saving Trust, 2017b.* *Li, et al., 2014.* *Trainer, T., 2010.*
Biomass	- Biomass cultivated on site, then harvested for combustion in furnace to generate heat, or fermented to biogas for heating.	- Classed as renewable so eligible for UK Government subsidy. - Could limit exposure to rising energy prices by subsituting for gas or electricity use. - Could be used to supply district heating systems using biomass. - Could be used to provide greenspace, visual improvement and ecosystem servces.	- Biomass material is normally processed at an offsite facility so transport losses are incurred. - Often used for grid generation, so then offers developer little direct benefit. - Seasonal growth so may require storage.	*Energy Saving Trust, 2017a.* *Li, et al., 2014.* *Rentizelas, et al., 2009.*
Heat Pumps *(this study)*	- Heat pump systems use the thermal energy in the ground to heat water for space heating and for use as domestic hot water.	- Classed as renewable so eligible for UK Government subsidy. - Limits exposure to rising energy prices compared to all electric or all gas heating systems. - Little or no visual impact or footprint so land could be further devloped after installation if vertical systems used.	- GSHPs require below ground excavation which increases costs. - Technical expertise is limited but growing. - Future landuse is sterilised if horizontal arrays used.	*Andersson-Sköld, et al., 2014.* *Energy Saving Trust, 2017a.* *Environment Agency, 2009.* *NIBE, 2010.*

2.4 Challenges for the use of Brownfield Land for Energy

Whilst the Scottish Government (2014b) encourages new and beneficial uses for previously developed land (brownfield land), it cannot be assumed that subsurface conditions on any site will be geologically homogenous and consequently favourable. This is a challenge when considering the re-use of brownfield land.

2.4.1 Variable Subsurface Conditions

Brownfield land comes the physical legacy of its own previous use (Syms, 2001). This can include the presence of foundations, underground structures (such as culverts and voids), machinery, and redundant services (such as cabling and pipes) (Adams & Watkins, 2002). Brownfield land can also hold the threat of contamination (Syms, 2001) and all of these factors may be unknown at the planning stage. A detailed site investigation is recommended by many developers which aims to highlight these potential obstacles at an early stage (Adelaja, et al., 2010). The use of geophysical techniques can also help to characterise subsurface features prior to any intrusive investigation (RSK Geophysics, 2013).

2.4.2 Soil properties and heat flow performance

The performance of a heat pump system is strongly dependent on the moisture content of the soil and also the soil type (Leonga et al., 1998). For a horizontal ground collector installation, specific heat extraction rates range from 10-15 $W.m^{-2}$ for dry sandy soils to 30-35 $W.m^{-2}$ for ground with groundwater; for a vertical ground collector installation, specific heat extraction rates range from

20-40 W.m for dry sandy soils to 70-90 W.m for a groundwater bearing layer (Viessmann, 2006). Without site investigation, it is difficult to predict what soil will be encountered and what the specific heat extraction rate will be. Within the context of this study, it is important to have an awareness of this uncertainty as a potential issue. This also extends to the clean up of contamination on site, should it be required once the site investigation begins. Any disruption to the subsurface may also create different pathways for contaminant migration (Hollander, et al., 2010), which could complicate redevelopment. This largely contributes to cost uncertainty (Adelaja, et al., 2010).

In turn, this has limitations on computer models of ground heat exchangers and heat pump systems which require accurate predictions of heat transfer rates. The British Geological Survey (BGS) provides superficial thickness maps based on borehole data from across the UK (Busby et al., 2009). This helps accurate predictions of heat transfer rates but cannot provide exact data. This means that there is a degree of uncertainty within modelled systems. Chapter 5 uses a modelled heat pump system and should be treated with consideration in this respect.

2.5 Summary

This chapter has described the background and context for the research undertaken in the thesis. The following chapters (3-5) each take the form of independent papers that have been prepared for journal publication. Chapter 3 (*Sustainable Energy Technologies and Assessments, vol. 7, pp. 30-33*) investigates how the RHI operates in practice when using GSHPs as the renewable heating technology option. Chapter 4 (*Renewable Energy, vol. 116, pp. 344-355*) explores the relationship between social housing, deprivation, and brownfield land and presents a new method for the targeting of GSHPs. Chapter 5 is a case study that uses the method designed in chapter 4 to model the viability of a GSHP installation for a social housing low-rise tower block. These chapters were designed to answer the question of how best ground source heat pumps can be deployed in a public sector context. A final chapter summarises the findings and conclusions and highlights opportunities for further research.

2.6 References

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3. Challenges for the Implementation of the Renewable Heat Incentive – An Example from a School Refurbishment Geothermal Scheme

3.1 Preface

To fully answer the research question '*how best can ground source heat pumps be deployed in a public sector context?',* it is reasonable to first examine renewable heat policy in the UK. This determines if policy support is available for renewable heat that matches the UK Government aspirations on climate change. Chapter 3 was published in the peer-reviewed journal *Sustainable Energy Technologies and Assessments* in April 2014 (appendix 1). In this chapter, the author participated in the planning, design and build stages of a school refurbishment that was to make use of ground source heating. This account illustrates current practice at the time with a view to maximising opportunities for renewable heating deployment under the UK Government Renewable Heat Incentive (RHI) policy scheme. This scheme makes cash back payments to producers of renewable heat to retrospectively assist with capital costs. Dr. Richard Lord, Department of Civil & Environmental Engineering, University of Strathclyde, United Kingdom is co-author for this research article. The article was prepared by Ross Donaldson, and Dr. Richard Lord reviewed and revised the article.

3.2 Summary

The school refurbishment discussed in this chapter was one of the first builds in the UK that planned to use the new RHI scheme, and presents a unique opportunity to understand how UK heat policy is positioned in a real world build. Whilst this chapter found the RHI to be clear and transparent in a policy context, it was found that implementation at the planning and subsequent construction phase of the refurbishment was lacking. This could be improved by better guidance and more structured awareness of the importance of the RHI in making projects viable. To improve the uptake of renewable heat on a broader scale, this chapter concludes that universal integration strategies should also be considered that could widen opportunities for renewable heating deployment. In tandem, this integration could also be championed by new and innovative projects which assist and supports heat policy development.

Thus, the integration of renewable heat policy across other policy areas is investigated in subsequent chapters. This includes land use strategies and also that of fuel poverty reduction (chapter 4). Opportunities for renewable heat deployment within an innovative project setting, as recommended here, are also examined (chapter 5).

3.3 Introduction

Renewable energy and the link to climate change targets is a discussion that today tops the bill across many sectors. The UK Government has a legally binding target of achieving 15% of its energy consumption through renewable means by 2020 (European Commission, 2009), as well as reducing greenhouse gas emissions by 34% on 1990 levels (Climate Change Act (2008)).

Unfortunately, interim targets so far have not been met – for example, the previous UK Government's target of reducing carbon dioxide emissions by 20% by 2010 was not achieved (Christian Aid, et al., 2011) – which makes meeting 2020 targets across EU Climate Change policies particularly challenging. A cost effective and efficient balance between economic and industrial growth, whilst incorporating a reduction in greenhouse gas emissions, must soon be developed; that is, a transition to a low carbon economy.

3.3.1 Carbon Reduction

For carbon dioxide, the greenhouse gas that is most notably attributed as the main human driver behind climate change, the European Commission (EC) is recommending that emissions on 1990 levels be reduced by 25% by 2020, and 40% by 2030, to make the transition to a low carbon economy cost efficient (European Commission, 2011). Taking the UK's groundwork on interim 2010 targets into account, a lot has to be done in this area to make these EC figures a reality.

As of 2010, the UK Government has managed to reduce their own carbon emissions by 14%, however carbon emissions as a whole for the UK grew for the year 2010, then reduced for 2011 (Black, 2011). Linked to the recession, the economy showed a moderate recovery for 2010 followed by the recession taking hold again in 2011. This recent downturn in the economy is a good development for reducing carbon emissions, but in the long term provides no certainty for securing a definite reduction in carbon emissions on 1990 levels.

3.3.2 Heating

Of the UK energy usage mix, heating is the single biggest sector in terms of energy consumption, with heating and electricity together forming the biggest sector in terms of carbon emissions (DECC, 2012). As electricity and heating are so closely linked – that is, we use in part electricity to heat our homes, offices, and industrial spaces, and likewise use electricity to cool them – an approach that considers heating as a critical mass within the energy debate should therefore net a two-fold win in meeting climate change targets as we move towards 2020.

3.3.3 Incentive Schemes

Feed-In Tariffs (FITs) are already commonplace, where domestic and industrial producers of renewable electricity are paid in part for the electricity that they produce, even if they use it themselves (Energy Savings Trust, 2012). Other Government programmes such as the Carbon Emissions Reduction Target (CERT) and the Community Energy Saving Programme (CESP) aim to incentivise energy efficiency, reduce carbon emissions, and tackle fuel poverty, and have so far proven to be highly successful in development within these areas (DECC, 2012).

By measuring energy produced instead of electricity fed in, heat can also be produced inline with a scheme such as the FITs (Ownergy Plc, 2012). It is clear that considering heat within this framework is critical in order to see successful improvements in a sector that requires significant reform if it is to be aligned with emissions targets and the future UK energy portfolio.

3.4 The Renewable Heat Incentive

FITs were introduced as part of the Energy Act (2008) and at the same time a provision was also made to allow the Secretary of State to establish a financial support programme for renewable heat – this is known as the Renewable Heat Incentive (RHI) scheme (DECC, 2012).

A world first for renewable heat generation, the Government run RHI scheme aims to tackle head on the issues surrounding the reduction of carbon emissions and meeting climate change targets by incentivising the uptake of renewable heat across the UK. Open to non-domestic applications in December 2011, with the domestic regime to follow in spring 2014, the scheme allows cash back payments to be made to producers of renewable heat, where heat is derived from technologies including solid biomass, ground and water source heat pumps, solar thermal, solid biomass in Municipal Solid Waste (MSW), biogas and biomethane injection (Ofgem, 2012). Ultimately, the RHI is aiming to provide a maximum rate of return of 12% on the additional capital costs of installing the renewables to combat investor hurdles (DECC, 2011a). This varies by technology, for example in the case of solar thermal where the rate of return is 6% (DECC 2011b, cited in Abu-Bakar, et al., 2013, p.373), mirroring installation and deployment costs associated with the specified technology.

The RHI largely has the potential to generate the returns on investment that are required to make many projects viable with payback periods that are satisfactory (Abu-Bakar, et al., 2013).

3.4.1 Policy and Process

Policy and regulations concerning the RHI are managed by the Department of Energy and Climate Change (DECC), with administration for the scheme being handled by the Office of Gas and Electricity Markets (Ofgem) (Ofgem, 2012). This builds on Ofgem's successful achievements such as that for the administration for the FITs.

The process of applying for the RHI is two fold. Firstly, the applicant must be the owner of the installation (as defined as eligible by Ofgem), and the installation must be installed prior to the application being submitted (Ofgem, 2012). The application is submitted online via Ofgem's website, and is to include details of the installation, commissioning certificates, as well as schematic diagrams. Ofgem will then accredit the installation or enquire further about the nature of the project if clarification is required. If approved, quarterly heat readings are submitted online by the applicant and quarterly payments are received accordingly inline with the RHI tariffs and the amount of renewable heat produced (Glasgow City Council, 2010).

3.4.2 Initial Analysis after Implementation

The administration and implementation of the RHI is designed to be straightforward, as anything overly complex is likely to go against the aim of incentivising the uptake of renewable heat. However, there are some issues that may cause confusion as the RHI scheme progresses. The RHI has been received well – as of March 2012, applications amounted to 300 – however only 15 of these had been approved and fully accredited, to allow payments to be made to the applicants (R. Gibson[1] 2012, pers. comm., 20 March). With timescales of 4 weeks claimed for simple systems and 6 weeks for complex systems, for an £860million scheme the rate of accreditation should have been higher. One year on, applications rose to 1710 as of 28th February 2013, with 603 installations fully accredited and having received a payment (DECC, 2013) – a marked increase after an evidently slow start.

An initial performance review however highlights a slight misalignment of the process of obtaining permission and the accreditation for a renewable heat installation. For example, planning permission for certain technologies has to be sought before the RHI is applied for, and before the installation is accredited by

[1] Ruth Gibson is Technical Development Manager (RHI) at Ofgem, and is involved with administration of the RHI.

Ofgem – but this process is extremely risky for the installation owner as there is no guarantee that their installation will be accredited even after the costly planning application is submitted (M. Drummond[2] 2012, pers. comm., 20 March).

Also, whilst pre-approval for technologies above 200kW exists, no pre-approval process exists for smaller projects – that is, smaller installations have to be in place before the RHI is applied for, and before the installation is accredited by Ofgem (M. Drummond 2012, pers. comm., 20 March). This could be seen as a huge risk for smaller project installers in terms of initial costs and no guarantee of receiving the accreditation required in order to receive the RHI payments.

March 2012 also saw DECC issue a consultation on interim cost control for the RHI which would suspend the scheme until the next financial year should the budget of £860million be under threat through application numbers and accreditation rates (Williamson, 2012). At a critical point when the scheme was just initiated, this was an unusual move having the potential to make prospective applicants nervous.

It is evident that these issues may limit the RHI's effectiveness in incentivising the uptake of renewable heat for both small-scale and large-scale producers across the UK. From an environmental aspect, it is also notable that there is no

[2] Morag Drummond is Senior Manager, Business Operations (RHI) at Ofgem, and is involved with administration of the RHI.

minimum efficiency directive for installations within the RHI, and there are no specific criteria for the calorific value of the fuel to be used (as, for example, in solid biomass facilities that generate heat) (R. Gibson 2012, pers. comm., 20 March).

3.4.3 Domestic and Non-Domestic installations

The distinction between domestic installations (which is open for applications as of spring 2014) and non-domestic installations is also not entirely clear within the administration framework of the RHI. Ofgem have stated that the RHI is currently open for applications from the non-domestic sector, however a critical element not fully explored or emphasised by Ofgem is that two or more private dwellings using heat from the one renewable heat facility is currently eligible for RHI payments (R. Gibson 2012, pers. comm., 20 March). This means that, even though households can currently receive one off payments under the Renewable Heat Premium Payment scheme (RHPP), administered by the Energy Saving Trust to assist in installing renewable heat technologies, many individual private properties may be missing out on the RHI as it currently stands. As the expected deployment date for the RHI scheme in the domestic sector is now spring 2014 after some delays, this is worth considering as multiple domestic installations could be operating, owners could be receiving payments, and movement could be being made towards meeting climate change targets. Given that the cost of installation for any given renewable heat technology can run into many thousands of pounds, with lengthy payback timescales, many community groups and co-operative organisations – that is, those most likely to benefit from renewable heat technologies but who lack the formal business arrangement – may be missing out as well.

Fundamentally, the definition of domestic and non-domestic as supplied by Ofgem is not clear, and may result in many individuals and groups not exploring the RHI until much later in 2014 when the domestic sector is expected to come into force.

3.5 A School Geothermal Case Study

A project has arisen that is soon to make use of the benefits that the RHI offers, both in terms of environmental and monetary savings, whilst adopting a novel approach to renewable heat. Glasgow City Council, Scotland, is in the advanced stages of a programme to modernise strategic learning establishments, specifically primary, special education needs schools, and pre 5 establishments (Glasgow City Council, 2010). Part of this programme has seen the commencement in January 2012 of the refurbishment of a Victorian primary school in Glasgow's West End.

Dowanhill Primary School, built in 1894, has a prime location within the Glasgow West End community. Situated off Byres Road - a main thoroughfare for shoppers and residents and close to Glasgow University, the historic building commands much admiration for the Victorian architecture. As such, Glasgow City Council saw it necessary to modernise, not demolish, at a cost of £9million, whilst staying inline with their development policies (Glasgow City Council, 2010). The school will have 14 new classrooms spanning 5 floors, a new extension wing housing nursery facilities and general-purpose areas, and will service a heat requirement of 400kW.

Ultimately, Glasgow City Councils aims are to create a multi-use, multi-purpose facility (including a nursery and community space) that considers social, economic, and environmental goals, whilst incorporating sustainable architecture and construction into the design and management of the build (Glasgow City Council, 2010). It is understood that planning constraints often inhibit the ability to expand into one's own space, so the school is designed with this flexibility in mind whereby modifications and extensions can be completed without adverse environmental and social effects (Glasgow City Council, 2010).

3.5.1 Geothermal Heating and the RHI

The renewable technology element of the project in Glasgow's West End considers a novel approach to renewable heat, not yet applied anywhere in the UK. Two 100m test boreholes found the school grounds to be preferential to the use of ground source heat - groundwater was present within the bedrock and the thermal conductivity of the boreholes were 75% and 78% higher than anticipated for shale and sandstone (Glasgow City Council, 2010). Ground Source Heat Pumps (GSHPs), of reasonable capacity, would therefore be entirely viable. GSHPs connected to eighteen 110m boreholes laid out in the surrounding car park and adjoining playground are to supply heat for the school in combination with a Combined Heat and Power (CHP) facility (Glasgow City Council, 2010). During times of extreme cold, the CHP is to be used to protect the boreholes by sending heat down them if this facility is needed. In displacing the original oil fired boilers, this tandem approach crucially protects the asset, as far as is reasonably practical, from rising energy costs in the future.

GSHPs do however require a relatively small electrical input for their operation. Grid electricity can be considered as poor thermal efficiency energy transfer into electrical energy at the power station, and using this generated electricity for running the GSHPs would not contribute to the lowest possible cost and lowest carbon emissions (Glasgow City Council, 2010). Generating onsite electricity, using gas fired CHP, is considered a viable option whereby running costs for the GSHPs and overall emissions are minimized, whilst taking advantage of the lower price for mains gas. Onsite biomass facilities were also considered, however space constraints and infrastructure issues made this unfeasible. GSHPs provide the viable mechanism to explore this build within the RHI.

3.5.2 The RHI in Practice

The RHI is therefore set to form a large part of the school refurbishment project in demonstrating the cost effectiveness and environmental viability of the build. To further support the project, a series of fortnightly mechanical service meetings were arranged by the principal contractor and held on site for the duration of the build, bringing together team members involved in ventilation, sprinklers, heating, controls such as the Building Management System (BMS), as well as plumbing and overall mechanical and electrical matters. Issues and general progress are communicated and discussed between all team members present, ensuring swift work-arounds from problem to solution as and when they arise.

Whilst the mechanical workshops held onsite are successful in identifying problems and maintaining progress, it is revealing to see that the RHI does not fall neatly within the construction phase of the build. The calculations for determining what element of the heat produced is truly renewable are fairly straightforward, as gas fired CHP is not classed as 'renewable'. Ofgem advises that the quantity of heat placed back into the ground, to protect the boreholes, should simply be subtracted from the quantity of heat extracted from the ground, which ensures a minimisation of heat meters (R. Gibson 2012, pers. comm., 20 March) (figure 3.1).

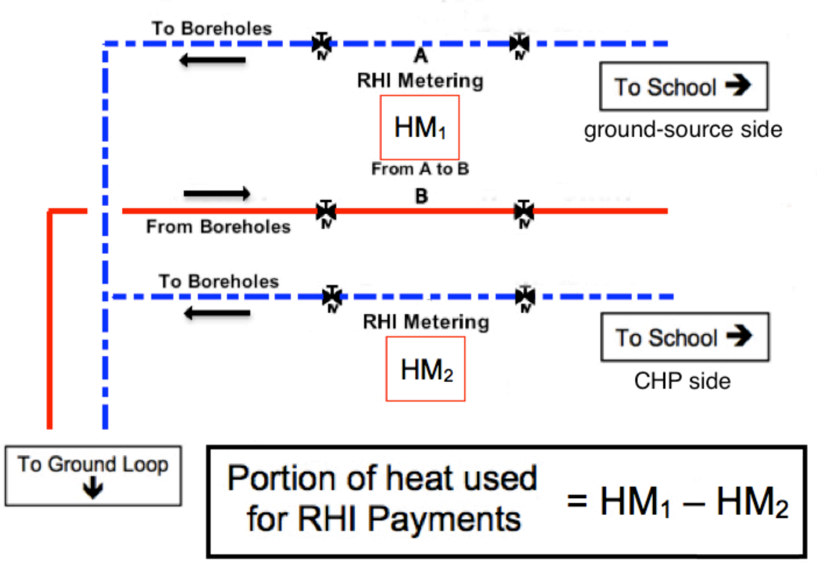

Figure 3.1: Layout of RHI meters in Glasgow school geothermal project.

However, there exists uncertainty for the contractor as to where the heat meters are to be positioned and when the RHI accreditation will be achieved. This is compounded by there existing little to no framework for where the RHI fits within a build, yet it is this crucial incentive scheme that aims to make many projects viable. For this specific project, the RHI meters and metering were a consistent unknown. Quite simply, if the RHI is to succeed, it has to find a recognised and universally accepted place within planning guidelines.

3.6 Conclusions

Examining the RHI framework and exploring the options for renewable heat through a real world project, it is apparent that the RHI scheme has some way to go if it is to incentivise the uptake of renewable heat towards meeting climate change targets. Effective implementation of the RHI scheme should take issues, such as planning and accreditation, into account before they cause a hindrance, as more installations come online ready for RHI accreditation. Implementation of renewable heat on a broader scale should also consider universal integration strategies to allow a wider uptake of renewable heat technologies.

Whilst the RHI is clear and transparent within a policy context, at a construction level phase there needs to be a significant improvement in how the RHI is managed and supported in order to fully aid implementation. This could be through more accessible guidance on the RHI for those working on construction sites, or alternatively a broader awareness on the importance of the RHI within an entire project. In many cases, the RHI is, and should be seen as, the crucial component that makes many projects viable.

In a broader sense, the RHI also represents an opportunity to transform the heating market across varying technologies, continual reduction of carbon emissions, and integrated control measures towards a resilient and secure 'future-proof' energy economy. This gives a significant advantage for those willing to innovate, such as in the geothermal refurbishment project in Glasgow. However, if the RHI is not integrated correctly, project success may be compromised, instead hindering the heating market and the technologies that are adopted.

For renewable heat to succeed, innovative projects are crucial to test feasibility and cost, revenue, and also the management of risk. Without pioneering examples, the move towards meeting EU Climate Change targets will be slow – however, for those willing to overcome what may be viewed as risks, significant benefits and valuable experience can be attained. Innovative projects such as that in Glasgow's West End are supported by the RHI, though the lack of clarity in how the RHI is integrated in the build, and how the RHI functions out with policy and in the real world, is not fully supporting the implementation of a scheme that has the potential to transform the heating market.

It could be that it is too early to comment on the RHI giving its lifetime of 20 years – however, when multi-million pound developments can either succeed or fail based on RHI support, issues such as those identified here are shown to be significant, and should be addressed for future renewable heating projects.

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4. Can Brownfield Land Be Reused for Ground Source Heating to Alleviate Fuel Poverty?

4.1 Preface

As we look to determine the best deployment strategy for ground source heat pumps within a public sector context, this chapter focuses on two key areas identified earlier within this research. This comprises the overcoming of space constraints associated with heat pump deployment (chapter 2) as well as a link with drivers across other policy areas (alleviating fuel poverty) that are directly related with the provision of energy (also chapter 2). As recommended within chapter 3, we look to now identify an innovative land use strategy that has the potential for fuel poverty reduction.

An amended version of chapter 4 (this chapter) was published in the peer-reviewed journal *Renewable Energy* in September 2017. This is included in appendix 2. In this chapter, the author identifies likely incidences of fuel poverty within Glasgow, Scotland with a view to meeting that heat demand using neighbouring land for the heat exchanger system. These two variables are combined to identify zones of opportunity for heat pump deployment within this context. Dr. Richard Lord, Department of Civil & Environmental Engineering, University of Strathclyde, United Kingdom is co-author for this research article. The article was prepared by Ross Donaldson, and Dr. Richard Lord reviewed and revised the article.

4.2 Summary

The land use strategy discussed and developed in this chapter uses collated data on vacant land availability (specifically vacant and derelict land) and determines incidences of fuel poverty based on numerous variables (discussed later). This is completed for Glasgow, Scotland where spatial zones of opportunity are identified that account for high vacant land availability and high likely incidences of fuel poverty. Thus, this gives rise to spatial zones of opportunity that may be suitable for heat pump deployment with the city. This aims to address both land use constraints and policy objectives. Whilst the proposed land use strategy is fully developed for Glasgow, Scotland, vacant land data was obtained and collated for all of Scotland. This gave rise to a noteworthy discovery where, once collated, more land was showing as 'available' than was publicly recorded. This means that the energy potential for Scotland (in terms of renewables deployed on land) could be higher than previously anticipated once this land is considered.

The proposed land use strategy alongside a more complete understanding of vacant land availability therefore form important contributions to the field of research.

4.3 Introduction

The move towards increased renewable energy provision has seen a transformation in the way energy is managed and generated. In the UK, the drive to meet mandated climate change targets (Climate Change Act (2008)) as well as regional devolved targets (Climate Change (Scotland) Act (2009)) has seen carbon-heavy fossil fuel generation gradually replaced by a greater reliance on dispersed renewables, such as wind technology (DECC, 2014a). Closures of generating facilities up to 2025 (Energy UK, 2013), as well as stricter UK Government emission controls (UK Government, 2013a), mean that it is an ever-increasing challenge to develop a strong, secure, and resilient "energyscape" (Howard, et al., 2012) in the move towards a low carbon economy.

How this step change in energy supply and demand is implemented in towns and cities is an important factor in determining what renewable energy options are viable (Takebayashi, et al., 2014). For example, the rollout of smart meters from 2015 (UK Government, 2014), is giving energy suppliers and energy users an unprecedented view of how energy is distributed and consumed, as well as supporting the transformation to "smart" cities (UK Government, 2013b). It is important that solutions are also affordable and reflect end-user needs. In particular, when energy costs fluctuate and rise, irrespective of static household income, this can contribute to greater incidences of the growing phenomenon of fuel "poverty" (Boardman, 1991), which has serious potential impacts on public health and is a growing consideration in energy policy (Scottish Government, 2017).

Strategies for the built environment (Scottish Government, 2010; UK Government, 2011a) provide a strong basis for a low carbon economy, but require a diverse portfolio of renewables (UK Government, 2011a), interconnected flows of information (IBM, 2011), energy affordability and security of supply (Scottish Government, 2010). Moreover, socially motivated energy provision could also simultaneously serve to enhance other policy and decision-making (Batel, et al., 2013), such as the alleviation of fuel poverty, and the regeneration of socially and economically deprived zones within cities (Scottish Government, 2013). Here we consider novel ways of reusing "brownfield" land to achieve these ambitions.

The aim of this paper is thus to identify the quantity of land that could be available for the provision of renewable energy for heating using Glasgow (Scotland) as an example, to determine its distribution and how it could be used for ground source heat pumps as part of an integrated approach to reusing brownfield sites.

4.3.1 Brownfield Land

Due in part to the frequent use of the term "brownfield" in various contexts, a variety of possible definitions exist. According to Alker et al. (2000) brownfield land is "any land or premises which has previously been used or developed and is not currently fully in use, although it may be partially occupied or utilised. It may also be vacant, derelict or contaminated". For the UK, brownfield land is usually synonymous with "previously developed land" which is "land that is or was occupied by a permanent structure and any associated fixed surface infrastructure" (UK Government, 2011b). It is anticipated that many such sites are also contaminated (Simons, 1998; Alberini, et al., 2004) although minor levels of contamination may not always need remediation, depending on the type of reuse (Alker, et al., 2000). The definitions used in the UK serve to promote a pragmatic approach to reusing a brownfield site, where contamination may not be present, known or disproved until it is fully investigated. The USA definition presumes contamination, since brownfield land is classed as "real property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant" (US EPA, 2002). Both UK and US definitions serve to show that, following previous use of a brownfield site, contamination may or may not be present, so it can be assumed that some form of investigation and possible remedial action may be required before redevelopment can take place, whether that be simple site clearances or more detailed contaminant remediation.

The potential for contamination can be a disincentive to redevelopment of brownfield land, even with incentive schemes (Thornton, et al., 2006), meaning many sites across the UK remain vacant long after they have gone into disuse, in some cases for up to 30 years (Maantay, 2013; Scottish Government 2014). Due partly to the differing availability of sites across the country, no overall targets were originally set for the regeneration of brownfield land in the UK in the 2012 UK National Planning Policy Framework (UK Government, 2012), through which local councils and communities were encouraged instead to assess where is best for local development to occur. In 2016 the concept of brownfield registers was launched as a pilot in 73 council areas in England, with the aim of providing 1 million more homes and having planning permission in place on 90% of suitable brownfield sites (UK Government, 2016a). Planning is a devolved issue, however, meaning individual countries within the UK have their own decision-making powers. Furthermore, planning is directed towards sustainable development, so is not only focused on reusing brownfield land, but should include regard to other policy issues.

4.3.2 Fuel Poverty

Boardman (1991; 2010) was the first to recognize fuel poverty as an issue, and defined it as "when a household is unable to provide sufficient energy services for 10% of income". This means that when a household is classed as being in fuel poverty they spend a disproportionate percentage of their income on the cost of energy. In this instance energy means all heat and power that is used to constitute a suitable living environment i.e. utility costs for heating, lighting, and general electrical power use, but excluding transport costs. Thus fuel poverty is also inextricably linked to income, energy prices, building fabric or its energy efficiency, and energy use habits.

In Scotland fuel poverty is determined by comparing the cost of household energy against total income available before housing costs (Scottish Parliament 2012). This means that deductions such as council tax, income tax, and national insurance (i.e. local and national taxes, social security charges) come off the available income before it is compared to energy costs, whereas rental or mortgage payments (i.e. housing costs) do not. The Scottish Executive's (2002) use of this definition of income mirrors its application at a national level within Scotland for fuel poverty calculations. Households that fall within the definition of fuel poverty are predicted to experience a standard of living that is unacceptable. This could be in the form of cold, damp, overcrowded rooms, or health effects on individuals that are linked to being fuel poor (Boardman, 2010; Liddell & Morris, 2010).

With so many interrelated factors, locating the fuel poor is also difficult. Social housing has a long history of helping low-income households, traditionally housing vulnerable persons and those that are disadvantaged within society (Carley, 1990). Here prerequisites such as low income will serve to compound incidences of fuel poverty. Although fuel poverty is also found in privately rented/owned properties, this sector is more difficult to evaluate due to the mixture of rental and owner-occupiers in many private housing estates and apartment buildings.

Fuel poverty is not solely a UK phenomenon, but is now on the agenda in other parts of the world, although here the focus may be on broader energy poverty or simply low household income (Power, 2006). Such is the current concern in the

UK that the Government and devolved administrations had set a target to eradicate fuel poverty, as far as was reasonably practicable, by 2016 (2018 for Wales) (DECC, 2009). The target for 2016 was not met.

The seriousness of fuel poverty cannot be overlooked. For England alone, it is estimated that cold related ill-health costs the National Health Service £1.36 billion per year (Age UK, 2012; Public Health England, 2014). The human cost of this is an estimated 26,700 excess winter deaths every year (Boardman, 2010). It is also estimated that people spend a higher proportion of the day at home than away from it (Boardman, 2010). Targeting space heating for the poorest households makes many of these adverse consequences preventable, being a direct result of low household incomes and/or poor building energy efficiency.

Whilst household income can be increased through accessing government benefits (where eligible), there is no support that directly helps with the costs of fuel (Boardman, 2010). With energy prices rising faster than income levels for the poorest households (Office for National Statistics, 2014), the provision of low-cost renewable energy for space heating is a strategic opportunity to address public health and the impacts on healthcare systems caused by fuel poverty.

4.3.3 Reusing Brownfield Land for Energy Provision

It is possible that reusing brownfield land partly as an energy resource during regeneration and local development could provide low-cost energy to help alleviate fuel poverty. To determine whether this integrated approach has the ability to simultaneously meet brownfield land regeneration and fuel poverty intentions, the availability and energy potential of brownfield land in proximity to energy users must be considered. In moderate climates, such as the UK, space heating accounts for more than 50% of total energy consumption (DECC, 2012) in the domestic sector. If appropriate renewables are directed towards brownfield land, such as heat pumps or locally used biomass, there is the potential for large gains to be achieved in carbon reduction, as well as assisting individuals with lower heating costs. Thus two socio-economic issues could be addressed simultaneously with wider positive impacts for society (Adelaja, et al., 2010).

The consideration of environmental factors such as land condition within the fuel poverty debate could also serve to mitigate a lesser-known relationship between land quality and public health. Morrison et. al (2014) have shown that the chemical quality of soil is spatially linked with deprivation, being higher in deprived areas, specifically in Glasgow. For England, Bambra et. al (2014) have shown a significant relationship between brownfield land intensity and morbidity. Together, land condition is shown to have an important, often overlooked, contribution to public health.

4.3.4 Sources of Land Data in Scotland

4.3.4.1 Vacant and Derelict Land

The Scottish Vacant and Derelict Land Survey (SVDLS) exists to record progress on land reuse within Scotland, where Local Authorities report data to the Scottish Government directly (Scottish Government, 2014). Following the demise of the National Land Use Database (NLUD) for England (the most recent update being in 2010), the SVDLS is the most complete and accurate data that exists in determining land availability for renewable heating. Updated annually, the database provides a range of information on vacant sites, including derelict sites and contaminated sites (Adams & Watkins, 2002). The database is also freely available online, providing straightforward access to up to date data (http://data.gov.uk/dataset/scottish_vacant_and_derelict_land_survey).

In the SVDLS, the Scottish Government (2014) defines vacant land as “land which is unused for the purposes it is held and suitable for development”, and derelict land as “land which is damaged and requires significant rehabilitation before reuse”. Thus both vacant and derelict land identified in the SVDLS fall under previously developed or brownfield land according to the UK definitions, where land is classified into five main categories within the National Land Use Database (UK Government, 2009):

- Previously developed land, now vacant.
- Vacant buildings.
- Derelict land and buildings.
- Previously developed land or buildings currently in use and allocated. in local plan or with planning permission.
- Previously developed land or buildings currently in use with redevelopment potential, but no planning allocation or permission.

4.3.4.2 Landfill Sites

Landfill sites represent a land type that is not normally considered within the regeneration framework for vacant and derelict land, since planning conditions typically specify restoration to an appropriate end use, such as agricultural, ecological, recreational, or woodland (DOENI, 2007). These sites may have areas of several 10s of hectares, so are relatively large compared to most brownfield sites, with locations on the outskirts of towns and cities (Wright, 1993). They are normally unavailable for use and cannot easily be redeveloped with buildings for many years due to landfill gas, and instability. Many will already have grid connections by virtue of existing landfill gas generation. As such, a considerable opportunity exists to develop these landfill sites further for renewable energy generation.

The Landfill Sites and Capacities Report, available freely from the Scottish Environmental Protection Agency (SEPA), provides up to date data on active or closed landfill sites, those under restoration and sites associated with waste such as waste transfer stations and waste holding facilities in Scotland licensed since its creation in 1996 (SEPA, 2012). Landfills are recorded in terms of deposited or available waste volume, whereas vacant and derelict land is recorded in terms of area, meaning that comparison between the two data sets requires further information.

Data for historic unlicensed former landfill sites or those with licenses held by local authorities before SEPA's creation is not held centrally but by the individual local councils concerned. Interacting with local council therefore presents an opportunity to harness more data on land use relevant to this study.

4.4 Methodology

4.4.1 Collation of Landfill Data (current and historic)

All 32 of the Local Authorities within Scotland were contacted in January 2013 in order to obtain known data such as site areas and grid coordinates of current and historical landfill sites. This was requested under the Freedom of Information Act (2000), which has within it a provision that allows local government data to be requested freely by members of the public, or under the Environmental Information Regulations (2004), a similar process but applicable to environmental queries that may incur a charge. Both types of request included:

- Site location i.e. address, National Grid Reference.
- The total area (in ha) of the landfill sites.
- The present status of each landfill site (whether it is active, closed or capped).
- The type of waste landfilled (if known).
- GIS data layer(s) showing site boundaries (if available).

Responses were combined with the Landfill Sites and Capacities Report data, available freely from the Scottish Environmental Protection Agency (SEPA). It was anticipated that responses would include sites already listed on the Landfill Sites and Capacities Report, together with additional historical sites. The area of each site, grid reference and whether the response originated from SEPA and/or the local authority allowed for checks on duplication or inconsistencies between data from different sources.

4.4.2 Estimating Site Areas

Where site areas were reported as unknown, these were estimated using drawn polygons with a GIS using satellite imagery and either basic site address information or, preferably, grid reference coordinates. Features used for visual identification of former landfill site areas included:

- Evidence of made ground or void filling.
- Changes in landform or vegetation over time (Figure 4.1).
- Site boundaries, fences or bordering land.
- Absence of current land use, such as for livestock.

Figure 4.1: Example of changes in a landfill site appearance over time.
Sources: http://earth.google.co.uk (left) & http://maps.bing.co.uk (right).

4.4.3 Combining Landfill Data and Vacant & Derelict Land Data

The data on landfill site areas from local authority responses and estimated site areas was combined with the vacant and derelict site data from the SVDLS to include:

- Site address.
- Site Area (and whether estimated or actual).
- Grid reference.

Grid references provided a means to check for sites that may appear on both lists, as it was anticipated that some historic landfill sites known to councils (for example in-filled quarries) could also appear on the SVDLS.

4.4.4 Selection of Study Area and Renewables Potential

4.4.4.1 Selection of Study Area

The Glasgow City Council area was chosen because it contains the greatest concentration of vacant and derelict land in Scotland (Scottish Government, 2014) where it totals 1195 hectares represented by 863 sites. Also, the Glasgow City council area contains the highest portion of data zones that are considered the most deprived in Scotland (Scottish Government, 2016). This represents a high likelihood of available land and a high likelihood of social issues such as fuel poverty. This is aligned with the research objectives in chapter 1.

4.4.4.2 Renewables Potential

The potential for renewables was then estimated using the total figures for vacant and derelict land and landfill sites in Scotland. As the focus was on renewable heating options, ground source heat pumps were selected as a technology option. This is also aligned with the research objectives in chapter 1. The maximum ground source energy yield was calculated per square metre of collector area for different scenarios that use ground source heat pumps. The total land used for the ground collector in each GSHP scenario was calculated and recorded on a per household basis, based on meeting 80% and 100% of a households heat demand respectively. Using the newly determined vacant and derelict land quantity for Glasgow, it was determined how many households could have their heat demand met using GSHPs.

4.4.5 Brownfield Land Distribution and Social Housing Distribution

The geographical distribution of brownfield land and social housing was compared for Glasgow. Social housing per capita was calculated using available population data (Glasgow City Council, 2011b) and housing data (Glasgow City Council, 2011a) for each electoral ward. The use of a per capita variable introduces density (in this context), and is the most commonly used measure in population statistics and when comparing large areas such as cities (Williams, 2009). This was then compared to the percentage of the electoral ward area classed as vacant and derelict land, using electoral ward geographical shape files (MapIt:UK, 2014) and vacant and derelict land data (Scottish Government, 2014). This mirrored the approach taken by Bambra et al. (2014) of comparing health indicators by ward to vacant and derelict land area and serves to identify if there is any measurable correlation.

4.4.5.1 Identification and Ranking of Opportunity Areas

The wards were ranked by the number of social housing units and by the quantity of vacant and derelict land, classified into quartiles to indicate relative intensity, then compared to assess any geographical coincidence. These variables were chosen because a central aim of this research is the targeted deployment of GSHPs on vacant and derelict land for use in social housing (chapter 1). Each ward therefore represents an area of opportunity for deployment according to its numbers of both social housing and vacant and derelict land. Using these variables, the following levels of opportunity have been created:

- High opportunity: The lowest value of the ranked dataset to the median of the first quartile (Q1) represents the highest level of opportunity.
- Moderate opportunity: The median of Q1 to the median of the third quartile (Q3) represents a moderate level of opportunity.
- Low opportunity: The median of Q3 to the highest value of the ranked dataset represents the lowest level of opportunity.

Mapping electoral wards which are in both the first quartile for social housing provision and for vacant and derelict land provides an alternative method of identifying geographical areas in which heat poverty is likely and opportunities exist to address it.

4.5 Results

4.5.1 Non-agricultural land in Scotland

Table 4.1 shows comparative results for licenced landfills and historical landfill sites derived from SEPA and Local Authority data respectively. Land areas were provided for 895 sites and estimated for 329. The areas of 193 (14%) remain unknown so are not yet included in the areas shown. No response was received from 1 local authority.

Table 4.1: Landfill data including historical landfill sites.

Landfill type/data source	Number of sites	Minimum area in hectares	
		Estimated	Provided
Licenced sites recorded as per SEPA list	364 sites	2786 ha	1324 ha
Unlicensed/historic sites (recorded by Local Authority*)	1053 sites	371 ha	2800 ha
		3157 ha	4124 ha
Total	1417 sites	7281 ha	

*Percentage response rate from Scottish Local Authorities 97%

Roughly three times as many historic sites have been identified as exist on SEPA's landfill capacities report. This adds an additional area of 3171 hectares so is nearly the same quantity of land again (77.14%) as is currently listed on the Landfill Sites and Capacities Report, a near doubling of the capacity that could be available for energy uses. Together with the 11,114 hectares of recorded vacant and derelict land for Scotland included in the SVDLS for 2013, the estimated total area of available non-agricultural land is 18,395 hectares. Thus landfills add an additional landbank equivalent to 66% of the V&D L area. In both cases, the land in question is largely open or vacant, and so could potentially be used for the provision of renewable energy including the provision of low-cost renewable heating.

4.5.2 Potential Brownfield Heat Yield for Glasgow, Scotland.

The Glasgow area contains the greatest concentration of vacant and derelict land in Scotland (Scottish Government, 2014) where it totals 1195 hectares represented by 863 sites. To this our study has added 367 hectares from 50 licensed and unlicensed landfills. Together these make up nearly 9% of the city area. In Glasgow an estimated 93,000 households are in fuel poverty (Scottish Parliament, 2012) of which 35,000 may be at high risk (G-Heat, 2014).

Taking an average household size of $92m^2$ (DCLG, 2014) a typical domestic heat load and heat pump unit capacity of $8kW_t$ was assumed (Banks, 2012). A (conservative) coefficient of performance (COP) of between 3 and 4 is also assumed (Banks, 2012; Worchester Bosch Group, 2014). Hence the electrical input to each heat pump (2) and the heat energy provided in return (3) can firstly be calculated:

Electrical Power Input to household GSHP

= Useful Heat Output/COP

= $8\ kW_t/3.3$ = $2.4\ kW_e$ (2)

&

Energy provided by household GSHP

= Useful Heat Output – Electrical Power Input

= $8\ kW_t - 2.4\ kW_e = 5.6\ kW_g$ (5600W) (3)

For horizontal GSH collector systems, an energy yield of $15W_g.m^{-2}$ (Banks, 2012; Worchester Bosch Group, 2014) can be assumed. For vertical GSH boreholes an energy yield of 40W.m (Banks, 2012; Worchester Bosch Group, 2014) can be assumed. This results in a smaller collector size footprint to meet the same domestic heat load at an increased capital cost. It should be noted that whilst the footprint of a vertical borehole is approximately $1m^2$, to avoid interference between boreholes a spacing of 6-10 m is required. This gives an effective footprint per borehole of 36-100 m^2 (Energy Saving Trust, 2007; Banks, 2012). The increased footprint theoretically serves to reduce the energy yield per unit area when this additional land is considered, and is an important point if comparing energy yields across scenarios 1 to 4. Thus, the potential heat that could be delivered by ground source heat pump systems on brownfield land under different scenarios can be determined (table 4.2). For calculation purposes, it is assumed that all available land is used for ground source heating, which is taken as 1,562 ha (page 107). However, it should be noted that sub-surface conditions (i.e. obstructions including, but not limited to, building foundations, voids, culverts, buried services) may impact on the land that is available for use.

Table 4.2: Potential brownfield heat yield for Glasgow, Scotland

Technology Option (scenario)	Maximum ground sourced energy yield per square metre of collector area	Land used per household		Number of households supplied	
		(a) for 100% of heat demand	(b) for 80% of heat demand	(a) for 100% of heat demand	(b) for 80% of heat demand
SCENARIO 1 GSHPs (horizontal array, using all land)	$15 W.m^{-2}$	$448 m^2$	$358 m^2$	34,866	43,631
SCENARIO 2 GSHPs (vertical borehole, 1 per site, 1 borehole per dwelling)	$0.33 W.m^{-2}$	$1 m^2$* ($100 m^2$)	$1 m^2$* ($100 m^2$)	913	913
SCENARIO 3 GSHPs (vertical borehole, 10 per hectare, 1 borehole per dwelling)	$5.6 W.m^{-2}$	$1 m^2$* ($100 m^2$)	$1 m^2$* ($100 m^2$)	15,620	15,620
SCENARIO 4 GSHPs (vertical borehole, 100 per hectare, 1 borehole per dwelling)	$56 W.m^{-2}$	$1 m^2$* ($100 m^2$)	$1 m^2$* ($100 m^2$)	156,200	156,200

*Actual footprint. For a site with multiple boreholes, a spacing of between 6-10m (i.e. 36-$100 m^2$) is required to avoid thermal interference (Energy Saving Trust, 2007; Banks, 2012) which reduces the energy yield per square metre and increases the effective footprint to $100 m^2$. Borehole lengths are calculated at 140m to meet 100% of a households heat demand, and 112m to meet 80% of a households heat demand.

4.5.2.1 Scenario 1: Horizontal array using all brownfield land

In a scenario using all available brownfield land, horizontal array ground source heat pumps are shown to potentially meet the full peak heat demand of 34,866 properties. If only 80% of the peak heat demand is to be met, as is typical in optimising such designs (Lind, 2011), the size of this figure increases to 43,631 properties, nearly half of the total in fuel poverty:

Maximum ground source energy yield per square metre of collector area

= $15W.m^{-2}$ (Banks, 2012) (4)

Land used per household for meeting 100% of heat demand (horizontal array)

= Ground source energy/energy yield

= 5600/15 (= $373.m^2$)

= 373 x 1.2 (to allow for a 20% buffer between arrays)

= $448.m^2$ (5)

Land used per household for meeting 80% of heat demand (horizontal array)

= Land used per household for 100% of heat demand x 0.8

= $373.m^2$ x 0.8 (= $298.m^2$)

= 298 x 1.2 (to allow for a 20% buffer between arrays)

= $358.m^2$ (6)

Number of households supplied for meeting 100% of heat demand (horizontal array)

= Area of vacant and derelict land in Glasgow/area of land used per household

= (1195 ha + 367 ha)/448.m^2

= 15620000.m^2/448.m^2

= 34866 properties (7)

Number of households supplied for meeting 80% of heat demand (horizontal array)

= Area of vacant and derelict land in Glasgow/area of land used per household

= (1195 ha + 367 ha)/358.m^2

= 15620000.m^2/358.m^2

= 43631 properties (8)

4.5.2.2 Scenario 2: One vertical borehole per site that each supply one dwelling

Indicative figures for more costly vertical borehole ground source heat pumps gives a decreased footprint per property over a horizontal array (scenarios 2 to 4). Here, one vertical borehole per site is used to meet the heating demand for one dwelling. The maximum ground source energy yield per square metre of collector area is 0.33W.m^{-2}, which is the GSHP energy yield per borehole averaged by site area. It has been calculated that 913 properties can have both 80% and 100% of their heating demand met, which is equal to the number of vacant and derelict land sites in Glasgow (913 sites), the latter being the principle constraint in this scenario. The land requirement for each borehole for meeting both 80% and 100% of a households' heating requirement is the same (100.m^2) as the buffer requirements do not change:

Maximum ground source energy yield per square metre of collector area

= Energy provided by each household GSHP/Average area per site

= 5600W/(Area of vacant and derelict land in Glasgow/Number of sites)

= $5600W/(15620000.m^2/913)$

= $5600W/17108.m^2$

= $0.33W.m^{-2}$ (9)

Land used per household for meeting 100% of heat demand (vertical borehole, 1 per site)

= Borehole surface area requirement

= $100.m^2$ (includes spacing between boreholes to limit thermal interference) (10)

Land used per household for meeting 80% of heat demand (vertical borehole, 1 per site)

= Borehole surface area requirement

= $100.m^2$ (includes spacing between boreholes to limit thermal interference) (11)

Number of households supplied for meeting 100% of heat demand (vertical borehole, 1 per site)

= Number of vacant and derelict sites in Glasgow

= 913 households (12)

Number of households supplied for meeting 80% of heat demand (vertical borehole, 1 per site)

= Number of vacant and derelict sites in Glasgow

= 913 households (13)

4.5.2.3 Scenario 3: Ten vertical boreholes per hectare that each supply one dwelling

The arrangement in this scenario scales up the borehole intensity previously outlined in section 4.5.2.2. Ten vertical boreholes per hectare (where a hectare is $10000.m^2$) each supply one dwelling. The maximum ground source energy yield per square metre of collector area increases to $5.6W.m^{-2}$ as more boreholes are placed on the same amount of land. It has been calculated that 15,620 properties can have both 80% and 100% of their heating demand met, when limited to ten boreholes per hectare. The land requirement for each borehole for meeting both 80% and 100% of a households' heating requirement is the same ($100.m^2$) as the buffer requirements do not change:

Maximum ground source energy yield per square metre of collector area

= Energy provided by each household GSHP x Number of boreholes per hectare

= 5600W x 10 (=56000W.ha)

= 56000W.ha/10000 (to convert to $W.m^2$)

= $5.6W.m^{-2}$ (14)

Land used per household for meeting 100% of heat demand (vertical borehole, 10 per hectare)

= Borehole surface area requirement

= $100.m^2$ (includes spacing between boreholes to limit thermal interference) (15)

Land used per household for meeting 80% of heat demand (vertical borehole, 10 per hectare)

= Borehole surface area requirement

= 100.m^2 (includes spacing between boreholes to limit thermal interference) (16)

Number of households supplied for meeting 100% of heat demand (vertical borehole, 10 per hectare)

= Area of vacant and derelict land in Glasgow x Number of boreholes per hectare

= 1562 ha x 10.ha

= 15620 households (17)

Number of households supplied for meeting 80% of heat demand (vertical borehole, 10 per hectare)

= Area of vacant and derelict land in Glasgow x Number of boreholes per hectare

= 1562 ha x 10.ha

= 15620 households (18)

4.5.2.4 Scenario 4: One hundred vertical boreholes per hectare that each supply one dwelling

This scenario scales up the borehole intensity further. One hundred vertical boreholes per hectare (where a hectare is 10000.m^2) each supply one dwelling. The maximum ground source energy yield per square metre of collector area increases to 56W.m^{-2} as more boreholes are placed on the same amount of land. It has been calculated that 156,200 properties can have both 80% and 100% of their heating demand met, when limited to one hundred boreholes per hectare.

The land requirement for each borehole for meeting both 80% and 100% of a households' heating requirement is the same ($100.m^2$) as the buffer requirements do not change. With a higher density approaching the minimum spacing (100 per hectare) the entire domestic heat load of fuel poor properties could be easily met. Where larger heat pumps are deployed to supply multiple properties, it is anticipated that economies of scale would make this advantageous (Fawcett, 2011) together with a more efficient use of the available land. Systems supplying multiple domestic units would also qualify for the Renewable Heat Incentive (RHI), a UK Government cash back payment made to producers of renewable heat (Donaldson & Lord, 2014):

Maximum ground source energy yield per square metre of collector area

= Energy provided by each household GSHP x Number of boreholes per hectare

= 5600W x 100 (=560000W.ha)

= 560000W.ha/10000 (to convert to $W.m^2$)

= $56W.m^{-2}$ (19)

Land used per household for meeting 100% of heat demand (vertical borehole, 100 per hectare)

= Borehole surface area requirement

= $100.m^2$ (includes spacing between boreholes to limit thermal interference) (20)

Land used per household for meeting 80% of heat demand (vertical borehole, 100 per hectare)

= Borehole surface area requirement

= 100.m^2 (includes spacing between boreholes to limit thermal interference) (21)

Number of households supplied for meeting 100% of heat demand (vertical borehole, 100 per hectare)

= Area of vacant and derelict land in Glasgow x Number of boreholes per hectare

= 1562 ha x 100.ha

= 156200 households (22)

Number of households supplied for meeting 80% of heat demand (vertical borehole, 100 per hectare)

= Area of vacant and derelict land in Glasgow x Number of boreholes per hectare

= 1562 ha x 100.ha

= 156200 households (23)

4.5.3 Brownfield Land as an Energy Resource for Social Housing

The relationship between brownfield land availability and social housing availability for Glasgow is shown in figure 4.2 where the number of social housing units per capita (Glasgow City Council, 2011a; Glasgow City Council, 2011b) is plotted against brownfield land per electoral ward (this study) (MapIt:UK, 2014; Scottish Government, 2014). These variables were chosen to test the hypothesis that the heating needs of the fuel poor living in public sector housing can be met using nearby vacant and derelict land. This investigates if the potential energy 'resource' (i.e. vacant and derelict land) is spatially related to the heating 'need' (i.e. low income social housing), so that the potential energy resource can be used to meet the heating need. The testing of the hypothesis in this way therefore did not involve iterative examination of other variables.

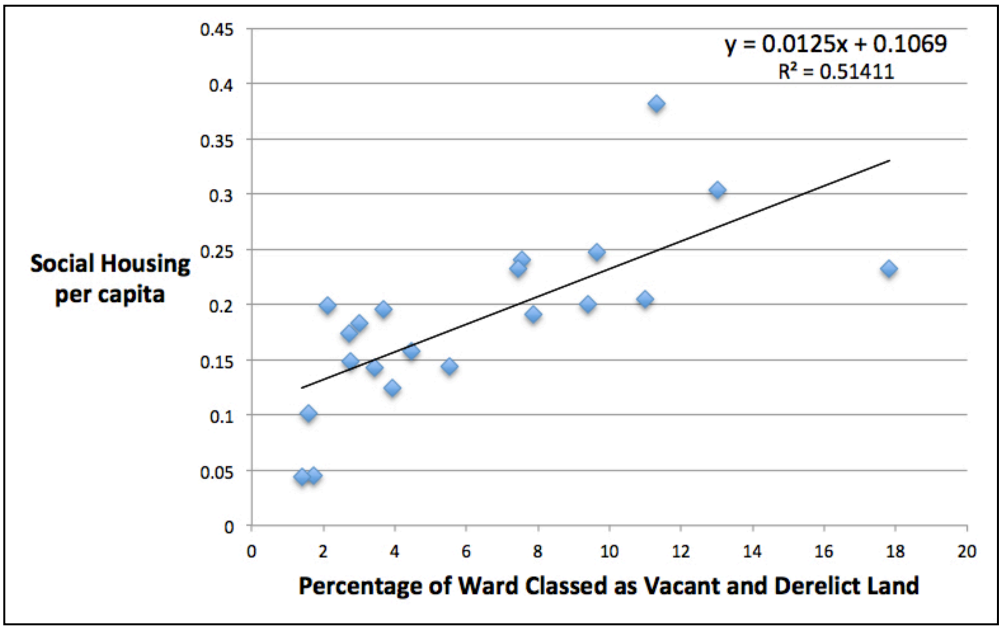

Figure 4.2: Social housing provision (housing units per capita) compared with brownfield land intensity by electoral ward.

Although there are two obvious outliers for the highest amounts of brownfield land and social housing respectively there is a moderately strong positive correlation between the intensity of social housing provision and brownfield land availability (r^2 = 0.51). This association is also illustrated in the distribution of the housing stock of the largest housing association within Glasgow (totaling 62,566 properties (GHA, 2010)) which compares well with that of the vacant and derelict land data from the SVDLS (figure 4.3).

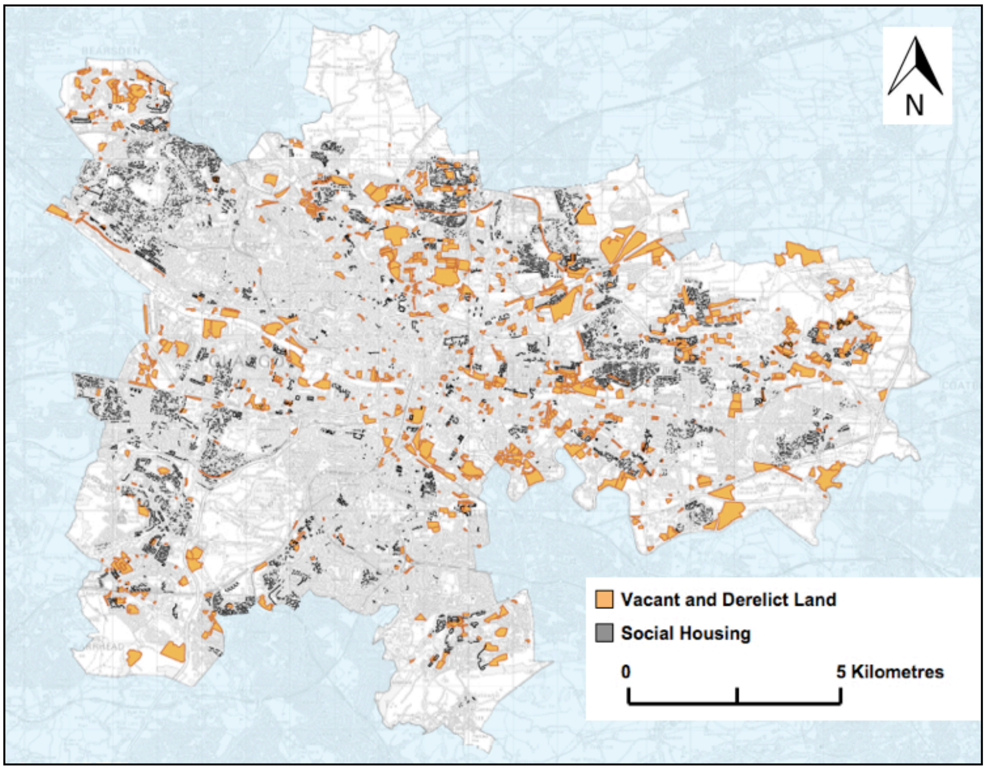

Figure 4.3: Vacant & derelict land and social housing distribution in Glasgow, Scotland.

Sources: http://www.glasgow.gov.uk (v&d land layer) & http://www.gha.org.uk (housing layer).

4.5 Discussion

4.5.1 Targeting Fuel Poverty through Brownfield Land Reuse

The spatial association of social housing and vacant urban brownfield land in Glasgow suggests that there is an opportunity to use this potential resource to address heat poverty. Meeting the heat demands of multi-occupier residential buildings through investment in ground source systems could provide renewable heating to those that may be fuel poor or more vulnerable through health or income inequalities, thus positively reinforcing the benefits of social housing provision (Batel, et al., 2013). It is widely accepted that three main variables contribute to fuel poverty, individually or in combination: household income, the energy efficiency of the property, and the energy costs required to provide an adequate standard of living for the household (Boardman, 1991; UK Government, 2016a), with heating playing a major role compared to power. Having the ability to control end-user energy costs per unit of heat by operating a renewable heating installation can also serve to mitigate the potential for fuel poverty in the face of rising energy bills. Thus, directing renewable heating solutions in this way towards households with low income, high energy bills, and low energy efficiency provides a starting point from which to alleviate fuel poverty.

4.5.2 Fuel Poverty Mapping

As the fuel poverty definition is exacerbated by low income and high energy bills, combining these two indicators in a Geographical Information Systems (GIS) could provide the basis of a fuel poverty map. However, data on household income and energy bills is incomplete and not recorded to a sufficient resolution. For example, DECC (2014b) records per capita gas and electricity use at an intermediate zone level, where each zone contains on average 4000 households. Focusing on income and energy bills alone also removes the causal effect of the building fabric, age and type which are attributes that contribute indirectly to fuel poverty through determining that building's, energy demands and heat loss characteristics. Examples of possible fuel poverty mapping approaches could include:

- Evidence of made ground or void filling.
- Identifying incidences of high per capita energy use and low income.
- Choosing areas that score high on deprivation indices, but with low income, or broader uptake of means tested benefits, showing where affordability might be an issue.
- Mapping other infrastructure such as gas connections, since electricity or oil will be more expensive alternative fuels.

Figure 4.4 shows a example of a fuel poverty map completed by Glasgow City Council for the IBM Smart Cities challenge (J. Arnott[3] 2013, pers. comm., 25 March), where fuel use has been compared to deprivation data to identify areas where high fuel use and implied costs occur in deprived areas. Note that it does not use actual energy costs per household, but instead assumes that high energy use is an indicator of high energy bills.

[3] James Arnott is Principal Officer, Development and Regeneration Services, at Glasgow City Council.

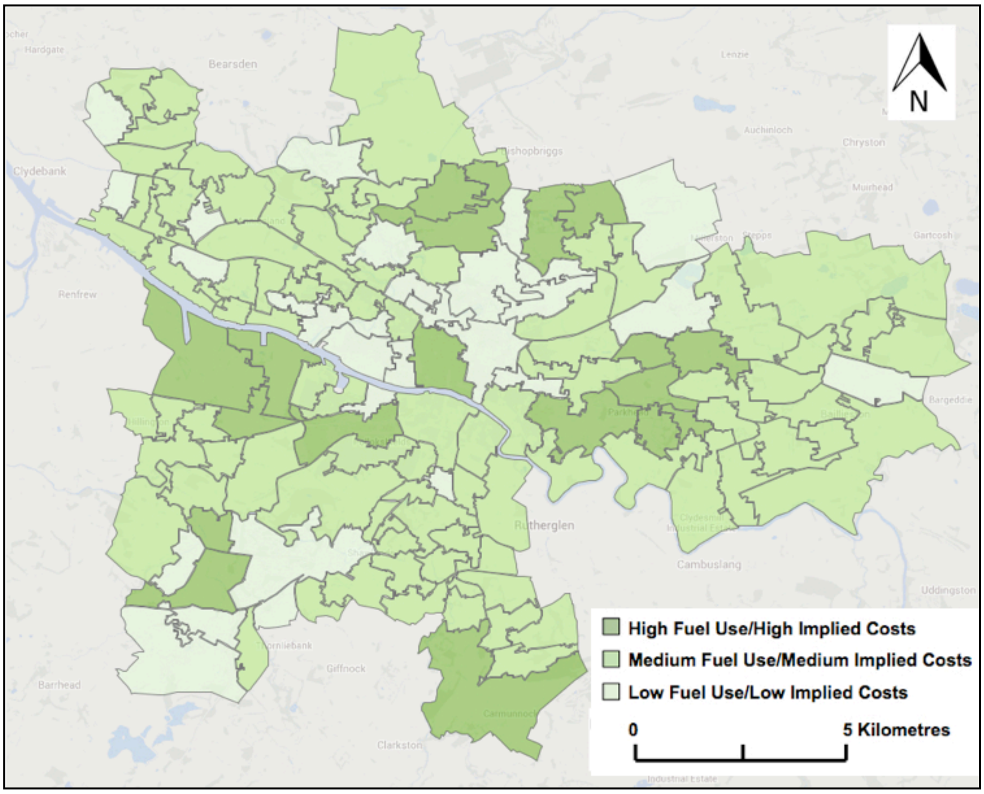

Figure 4.4: Fuel Use Map for Glasgow, Scotland.

Source: http://www.glasgow.gov.uk.

The numerous variables involved mean that fuel poverty mapping outputs vary, without necessarily being incorrect or invalid. For example, simply mapping deprivation levels or income, rather than high energy use relative to income, could exclude those experiencing fuel poverty through poor building fabric. What is also clear is that fuel poverty is dynamic, and as householders approach this point, self-regulation of energy use can mean actual incidences are avoided. This keeps many householders out of fuel poverty statistics according to the strict definition, even though had they used all of the energy needed to maintain a suitable living environment, their energy costs would indeed have exceed the 10% threshold. The consequences for living standards and health implications are still clearly unacceptable. Fuel poverty is thus a challenging and complex issue with many contributory factors, and as such, no one definitive fuel poverty mapping approach has yet been agreed (J. Arnott 2013, pers. comm., 25 March).

4.5.3 Deployment Opportunities through Social Housing

The nature of social housing means that it potentially supports large-scale rollout of communal heating systems by providing access to one landlord who can speak on behalf of many tenants. Social housing is provided for low-income households who cannot compete in the normal market place (Reeves, 1996). This suggests a type of housing where low income relative to energy bills, might be an issue. Examining the distribution of social housing provides a method whereby opportunities to address heat poverty can be identified.

Although the distributions are not quite identical, social housing as a market for heating energy is found clustered around vacant and derelict land (figure 4.3). This represents an opportunity to tackle fuel poverty by retrofitting existing social housing with communal heating schemes as part of area-level regeneration accompanying low energy new development with potential public health benefits from the resulting reduction of brownfield land (Bambra, et al., 2014). Mapping electoral wards which are in both the first quartile for social housing provision and for vacant and derelict land (figure 4.5) provides an alternative method of identifying geographical areas in which heat poverty is likely and opportunities exist to address it.

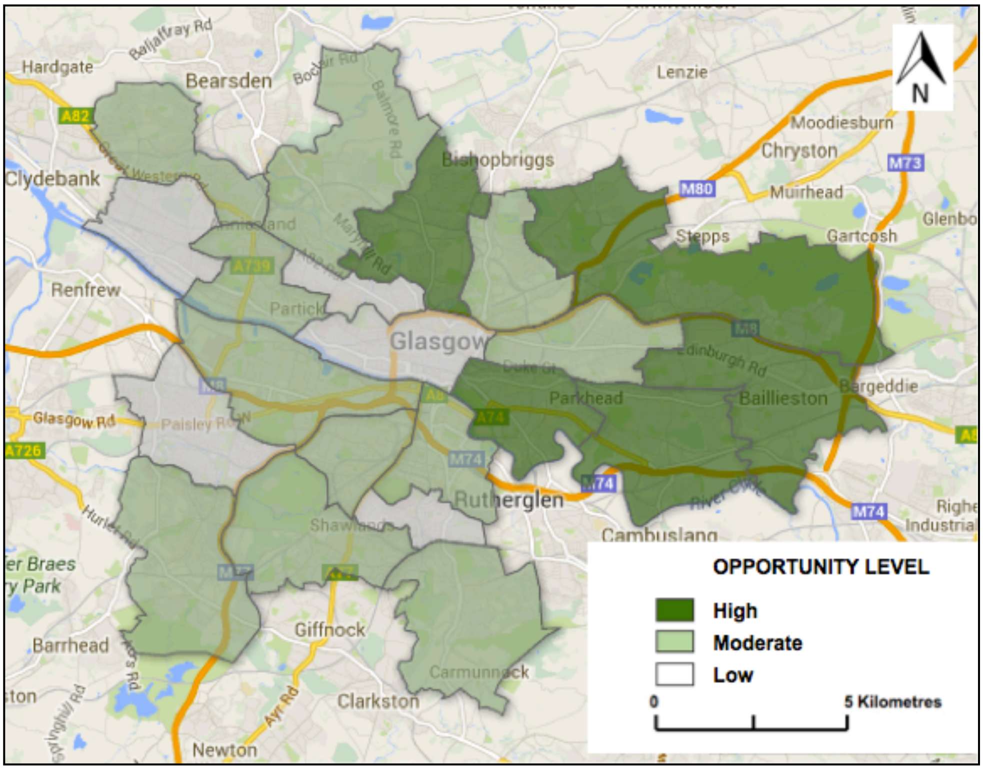

Figure 4.5: Social Housing and Vacant & Derelict Land Intensity by electoral ward for Glasgow, Scotland.

4.5.4 Challenges and Future Work

4.5.4.1 Challenges and Risks in Reusing Brownfield Land

Perhaps the greatest challenges in reusing brownfield land to alleviate fuel poverty come from the inherent nature of the land itself: Vacant and derelict land is not currently in use, implying that it is not currently needed, or perhaps not economically viable, for development. This lack of value can stem simply from the geographical location, or may be the effect of the potential cost of remediation. The potential presence of contamination and need for remediation is inherent in the various definitions of brownfield land (Alker, et al., 2000; UK Government, 2011b; US EPA, 2002), so there is a risk that the net value after the necessary treatment is completed could be negative. Without the financial incentives of development as a trigger, detailed site investigation to accurately constrain this risk may be unaffordable. Furthermore, in a risk-based approach to contaminated land management, such as that operating in the UK, the extent of remediation required to ensure “suitability for use” is dependent on having an identified end use. Moreover, additional precautions would be needed during installation on a potentially contaminated site, to include protecting personnel from exposure, preventing further dispersion by correct disposal of excavated spoil from burial of horizontal arrays, and preventing cross contamination of groundwater via pathways created along vertical boreholes; Previously-developed land may well retain ground obstacles derived from earlier structures, such as concrete floor slabs or foundations. Likewise, the definition of dereliction (Scottish Government, 2014) implies a cost for corrective measures to rehabilitate and to address damage; former landfilled areas will contain heterogeneous wastes with unknown properties, potential for contamination, gas or leachate generation. In more recent licensed landfills these could include a variety of engineered features, such as clay or geotextile liners, capping layers, gas or leachate collection pipework (Barry, et al., 2001), although these might also offer a way to exploit the enhanced temperatures generated by decomposition of biodegradable wastes (Coccia, et al., 2013). In urban areas, the spacing of wells and hydrogeological conditions may further limit the performance and sustainability of ground source heating systems (Younger, 2008). Other options for reusing brownfield land are compared in table 4.3. This illustrates the greater potential energy yield when used for ground source heating, with vertical systems still offering flexibility for future redevelopment.

A number of additional technical challenges might arise during the deployment of ground source heat pump systems on brownfield sites due to their history and possible ground conditions. Developers may also find other options more suitable by comparing the respective benefits or constraints (table 4.3).

Table 4.3: Comparative uses for brownfield land.

Proposed action or landuse	Energy yield	Features	Advantages or opportunities	Disadvantages or constraints	References
Do nothing	Zero	- Landuse unchanged.	- No investment required.	- Land remains brownfield, vacant or derelict. - No added value, incentive for future development, or contribution to regeneration needs. - Site remains a potential liability until investigated fully and or remediated.	South Cambridgeshire District Council, 2014. Alberini et al., 2004.
Reuse for public open space, green space, amenity etc.	Zero (or minimal from harvested biomass arisings)	- Land used for urban greenspace e.g. park or semi-natural area.	- Improved aesthetic or visual character. - Improved public access to green space may also improve public health. - Can also contribute to local area regene ration and improved eco-system service delivery. - Minimal investment in site investigation and or remediation required, compared to "hard" redevelopment for more sensistive landuses. - Opportunity to address contamination, e.g. by capping, or to use "gentle" remediation methods.	- Possibility of contamination may limit suitability for current or future use. - No revenue stream created, capital value unchanged, so requires grant aid for funding improvements.	De Sousa, 2003. CL:AIRE, 2009. Thompson et al., 2012. Harrison et al., 2014. Mathey et al., 2015. Sandifer et al., 2015 Parlimentiary Office of Science & Technology, 2016. Li et al., 2016. Onwubuya et al., 2009. Cundy et al., 2015.
Redevelop for commercial, industrial or housing use	Possibilty for limited embedded generation (e.g. roof top solar thermal or PV, ground source heating/cooling etc) depending on end use	- Requires detailed site investigation, planning approval, remediation to render site "suitable for use" if found to be contaminated.	- Visual appeal increased but ecosystem service provision may be reduced. - Can contribute to local area regeneration and any contamination is investigated and mitigated. - Opportunity to provide low-cost, energy efficient housing that meets current performance standards for comfort or efficiency, for sale or rental to meet market needs. - Capital value realised or revenue stream created, so may be self-funded as viable economic activity.	- Potential for contamination, liability, cost of remediation or project delay may deter investors. - Significant investment required, likely long term commitment. - Additional housing does not necesssarily benefit existing community. - Cost of remediation may outweigh economic value of cleaned site, so remains derelict.	Adams & Watkins, 2002. Alberini et al., 2004. De Sousa, 2003. CL:AIRE, 2006. Stein et al., 2007. CIWEM, 2016. UK Government, 2016b.
Redevelop for energy generation	Varied - see below	- Permanent reuse for energy, or temporary reuse ahead of development.	- Can deliver local, secure renewable energy, meeting Government strategies for use of renewables and energy security, with limited transmission losses if used locally. - Renewables are efficient and effective solutions. - Can contribute to local area regeneration. - Revenue stream created. - Can be used to create wider community benefits, either as community benefit fund or by subsidizing household energy costs. - Opportunity to integrate energy service provision with some eco-system service delivery.	- Likelihood of contamination may highlight liability concerns for developer, however if no public use then concerns should be low. - Significant investment required, likely mid to long term committment. - Limited renewable options if considering technologies for heating.	Alberini et al., 2004. Kalogirou, 2004. IEA, 2007. Dóci et al., 2015 Holland, 2016. Spiess & De Sousa, 2016.
- Solar Water Heating	*50 W.m $^{-2}$* *(Energy Saving Trust, 2016)*	*- Water heated via sunlight using a solar collector, then transferred to the building using a small electrical input.*	*- Classed as renewable so eligible for UK Government subsidy.* *- Could limit exposure to rising energy prices by offsetting some gas or electricity use.* *- Can be mounted on rooftops, however such installations would not assist brownfield land redevelopment.*	*- Solar is at its weakest at times of high heat demand (winter), so supplementary heating system is needed.* *- Solar arrays would fullly occupy the available land so sterilises future redevelopment.* *- Requirements to mitigate against vandalism (important if located on ground) and allowances for required maintenance.*	Department of Trade & Industry, 2006. Trainer, 2010. Li et al., 2014. Rosenbloom & Meadowcraft, 2014. Energy Saving Trust, 2016. Energy Saving Trust, 2017b.
- Solar PV	*11 W.m $^{-2}$* *(Energy Saving Trust, 2016)*	*- Electricity created via sunlight using PV cells.*	*- Classed as renewable so eligible for UK Government subsidy.* *- Could limit exposure to rising energy prices by offsetting some or all electricity use.* *- Can be ground mounted instead of on rooftops, however such installations would not assist brownfield land redevelopment.*	*- Solar is at its weakest at times of high lighting electricity demand (evenings & dark winter periods), so a supplementary electricity system may be needed.* *- Solar arrays would fully occupy the available land so sterilises future redevelopment.* *- Requirements to mitigate against vandalism (important if located on ground) and allowances for required maintenance.*	Department of Trade & Industry, 2006. Trainer, 2010. Li et al., 2014. Energy Saving Trust, 2016. Energy Saving Trust, 2017a.
- Biomass	*c.0.3 W.m $^{-2}$ (97 GJ.ha $^{-1}$.a $^{-1}$) (1)*	*- Biomass cultivated on site, then harvested for combustion in furnace to generate heat, or fermented to biogas for heating.*	*- Classed as renewable so eligible for UK Government subsidy.* *- Could limit exposure to rising energy prices by subsituting for gas or electricity use.* *- Could be used to supply district heating systems using biomass.* *- Could be used to provide greenspace, visual improvement and ecosystem servces.*	*- Biomass material is normally processed at an offsite facility so transport losses are incurred.* *- Often used for grid generation, so then offers developer little direct benefit.* *- Seasonal growth so may require storage.*	Energy Saving Trust, 2017b. Rentizelas et al., 2009.
- Heat Pumps	*Scenario (a) horizontal arrays: 15 W.m $^{-2}$* *Scenario (b) vertical well spacing 10m: 56 W.m $^{-2}$ (2)*	*- Heat pump systems use the thermal energy in the ground to heat water for space heating and for use as domestic hot water.*	*- Classed as renewable so eligible for UK Government subsidy.* *- Limits exposure to rising energy prices compared to all electric or all gas heating systems.* *- Little or no visual impact or footprint so land could be further devloped after installation if vertical systems used.*	*- GSHPs require below ground excavation which increases costs.* *- Technical expertise is limited but growing.* *- Future landuse is sterilised if horizontal arrays used.*	Energy Saving Trust, 2017b. Environment Agency, 2009. NIBE, 2010. Andersson-Sköld et al., 2014.

(1) Calculated from gross energy yield of harvestable reed canarygrass grown on brownfield land in N England [63]. Ignores effects of water content on calorific value, energy inputs for harvesting, and losses from effciency of boiler system.
(2) Gross heat output from heat pump including contribution from electrical power at an assumed coefficient of performance of 3.3, per square metre of land area based on 10m well spoacing (this study).

4.5.4.2 Future Work

Many of the technical challenges in 4.5.4.1 are directly analogous to the issues identified for the reuse of the various types of derelict, underutilised and neglected land for bioenergy (Lord, 2015) for which successful trials have been completed. For ground source heat pumps, future work should focus on similar demonstration projects to confirm the actual energy yields and so test the economic viability and societal benefits of using ground source heating arrays on derelict land adjacent to social housing units. To that end, chapter 5 examines how social housing and vacant & derelict land intensity by electoral ward (figure 4.5) can be used to identify a suitable case study site that falls within one of the areas of high opportunity, as determined by this study. This is to test the economic and social viability of using a ground source heating array on derelict land adjacent to social a housing unit which addresses a research objective as outlined in chapter 1.

The GIS analysis conducted within this chapter has created not only new knowledge but also a product of value. The methodology is designed in such a way that it can also be used beyond the current geographical location (i.e. Glasgow, Scotland). Whilst this study looks to address fuel poverty, mapping the urban environment in this way using previously unknown vacant land could also highlight opportunities for other energy technologies, new housing, meaningful greenspace, or broader regeneration aspirations.

4.6 Conclusions

Historic, unlicensed landfill sites are shown to increase the total residual landfill area within Scotland by more than 75% to 7,281ha. Together with vacant and derelict land, a total of 18,395 ha is available which could potentially be used for the deployment of renewables. Although representing less than a quarter of one percent of the total land area of Scotland, much of this potential resource is situated close to urban centres of heat demand.

Using ground source heat pumps on all vacant and derelict land as a renewable heating technology option for 80% of a property's peak averaged heat demand for Glasgow, Scotland could serve to heat 43,754 properties or 47% of those estimated to be in fuel poverty. This is a 'worst case scenario', based on horizontal arrays where all available vacant and derelict land is used. Using higher cost vertical boreholes instead would increase this figure greatly due to the decreased technology footprint and increased energy yield. Hypothetically, the demands of all properties in heat poverty could be met, however it is necessary for a balance to be drawn between installation costs, the technology footprint, and the number of properties whose heat demand could be met, to provide the most cost effective, sustainable solution.

A correlation between urban brownfield land and social housing, suggests these are appropriate targets for deploying and utilizing ground sourced heating. Social housing provision also reflects areas of low income and associated deprivation, so can be used as a proxy for fuel poverty. Relative concentrations of social housing and brownfield land by electoral ward areas give a means of identifying zones of opportunity.

Examining a city such as Glasgow illustrates the complex legacy of former industry, such as proximity to vacant or derelict land and the prevalence of poor health in the most deprived communities. It has also helped to create a product of value that that could be applied across other towns and cities by following the same methodology. It is clear that using brownfield land to provide ground source heating for social housing has the potential to contribute to alleviating fuel poverty as well as bringing significant opportunities for the restoration and reuse of vacant and derelict land.

4.7 References

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5. Modelling a Ground Source Heat Pump System to meet the Heating Energy Demand of a Residential Public Sector Building

5.1 Preface

The previous chapter created a synthesis where opportunity for heat pump deployment is mapped across a city. Opportunity is seen as an electoral ward in the first quartile for social housing provision and also vacant and derelict land availability. Chapter 5 now uses that information to target a case study in one of these electoral ward areas where ground source heat pumps could meet the heating energy demand of a modelled residential public sector building. This comprises of a dynamic energy simulation model for an 8-storey residential public sector building, which is then used to determine a suitable ground source heat pump system situated on adjacent vacant and derelict land that can meet the building space heating requirements. This approach tests the viability of ground source heat pumps as a suitable technology, and if the overall use of data on social housing provision and vacant and derelict land availability is a practical tool to target their deployment. The completed models are available through the University of Strathclyde's research data repository (http://dx.doi.org/10.15129/a1604de0-4e2d-4499-b101-dd51e7dec9bf) or directly from the author.

5.2 Summary

The case study developed within this chapter uses a real world residential public sector building that is modelled in order to accurately understand the buildings energy consumption. Specifically, it is the energy for space heating that this study looks to address where that energy requirement could be met through the design of a ground source heat pump system on adjacent vacant and derelict land. To select a study site, tower blocks were mapped in electoral ward areas that are within the first quartile for social housing provision and vacant and derelict land availability for Glasgow, Scotland, as determined by this study (figure 4.5). The electoral ward area with the largest number of tower blocks was selected, and a case study tower block chosen based on a) proximity to, and b) availability of, vacant and derelict land. A dynamic energy simulation was performed on the chosen tower block, and a ground source heat pump system designed to meet the space heating requirements of the building. The financial and technical viability of the proposal is discussed to complete the case study analysis.

5.3 Introduction

Previous chapters have considered the role of renewable energy technologies, and how they have the potential to meet household heating energy demand. This chapter uses a case study to test if this energy demand can be met using ground source heat pumps, using the theory put forward in previous chapters.

Chapter 2 showed how ground source heat pumps can be used to extract low-grade heat from the ground to heat a space and explored the common configurations for a heat pump system. Ground source heat pumps are shown to have some limitations with regards to high costs, however, have potential to address other policy issues. Chapter 3 described how the use of renewable energy in this way is supported by the UK Government Renewable Heat Incentive (RHI). Opportunities for increasing the use of ground source heat pumps are examined in Chapter 4. This proposed a new approach where vacant and derelict land can be used to meet the heating energy demand of those people most vulnerable to heat poverty in public sector housing. The economic viability and environmental impact of using of ground source heat pumps in this context remains largely unknown.

In order to investigate this further, results are presented from a ground loop modelling exercise using a dynamic energy simulation model for a 1960s 8-storey tower block. The first hypothesis tested is that a residential public sector building such as a tower block can be selected for the use of ground source heat pumps based on the coincidence of fuel poverty and proximity to areas of vacant and derelict land. The second hypothesis to be tested is that ground source heat pumps can meet the actual predicted heating demand of the building. The third hypothesis is that this can be accomplished using the locally available area of derelict land, whilst ensuring the system operation is sustainable over time.

5.4 Methodology

5.4.1 Experimental Set-up

5.4.1.1 Site Selection

A map of social housing provision and vacant and derelict land concentration by electoral ward was generated for Glasgow, UK (Chapter 4). For the highest-ranking electoral ward areas (Baillieston, Calton, Canal, North East, Shettleston) i.e. those in first quartile for social housing provision and for vacant and derelict land, the locations of residential tower blocks and vacant and derelict land were overlaid using aerial mapping. It is important to note that a map of tower blocks does not exist. Satellite imagery was used (1000m x 1000m resolution) to identify and record tower blocks using cast shadows. The tower block locations were then recorded. Of these electoral ward areas, Canal had the highest number of residential tower blocks (11 tower blocks) so was the electoral ward area selected to identify a suitable case study location.

Three separate locations with a total of 11 tower blocks were then considered. All locations were within 100m of vacant and derelict land. Of the three housing associations that own and manage the tower blocks (Glasgow Housing Association, ng homes, Queen's Cross Housing Association), ng homes was found to operate within the statistically most deprived area of the Canal electoral ward (Scottish Government, 2016). ng homes owns and manages a single tower block within the Canal electoral ward area at 70 Broadholm Street and was chosen for the case study (figure 5.1). The vacant and derelict land parcel adjacent to 70 Broadholm Street is 1.98 ha (19763m^2) in size.

Figure 5.1: 70 Broadholm Street and adjacent vacant and derelict land parcel.

5.4.1.2 Building Plans

The current owner, ng homes, granted the use of 70 Broadholm Street for the purpose of a case study but held no information on the building characteristics and geometry. This information was required to construct an accurate computer model of the building. Building plans of 70 Broadholm Street were obtained from the Glasgow City Archives.

5.4.1.3 Modelling Software

Licenses for two energy related modelling software packages were obtained. Firstly, IES Virtual Environment (Integrated Environmental Solutions, 2016), a suite of application packages used for the 3D model and dynamic energy simulation model of 70 Broadholm Street. Secondly, Gaia Geothermal's Ground Loop Design (Gaia Geothermal, 2016) which uses the calculated heating load data from IES-VE to design a ground loop system. The use of these software packages falls within the approved design methods and compliance for the installation of GSHP systems (GSHP Association, 2011; GSHP Association, 2014).

5.4.2 Modelling Regime and Methods

5.4.2.1 Virtual Modelling Environment Preparation

Measurement units within IES-VE were set to metric and grid spacing set to 1 centimetre. The site rotation was set to correctly orientate the model and the site location set to 55.89 ° N, 4.25 ° W. Room inner volumes options were left unchecked (not represented) as wall thickness would be represented when assigning thermal constructions. Imperial measurements from the original January 1969 building plans were converted to metric then rounded to the nearest centimetre to match the grid spacing. The viewing experience was set to 'plan'.

5.4.2.2 Wireframe 3D Model Creation

Using the Model-IT application package of IES-VE, a prism was drawn to represent the central point (lift shaft) of 70 Broadholm Street. This acted as an anchor from which all other rooms would radiate. The remaining internal spaces were drawn to create the ground floor (Figure 5.2). Windows and doors (internal and external) were added in line with locations on the original building plans. The North, South, East and West surfaces of the completed ground floor were examined to ensure correct alignment. A 40cm void was placed below the ground floor, to represent foundations. This void follows the construction lines of the ground floor.

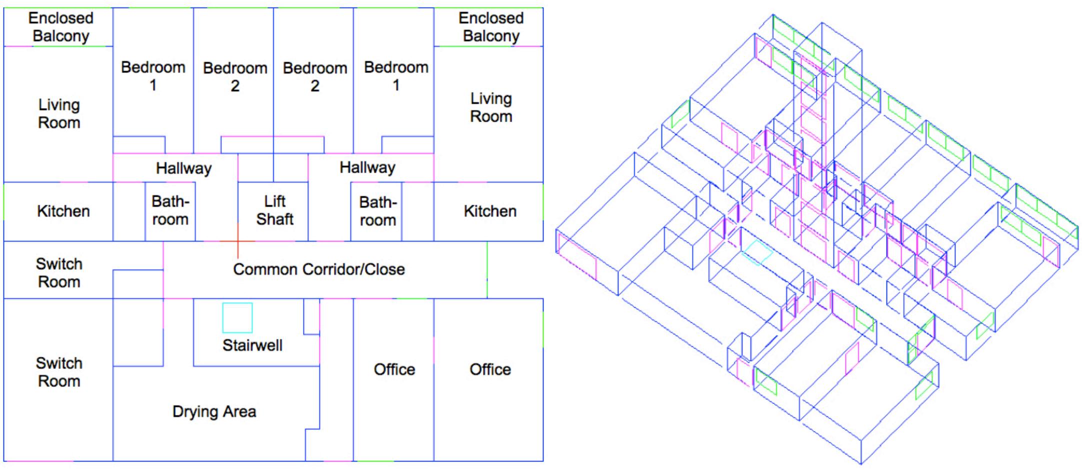

Figure 5.2: Ground floor representation of 70 Broadholm Street, Glasgow in plan view (L) and axonometric view (R).

The upper floors (floors 1 to 7) are uniform in construction. The main difference across all floors is on the ground floor which contains offices and switch rooms.

These areas are replaced by 1-bedroom apartments for the upper floors. The viewing experience was set to 'front', to view the front of the building and the ground floor was selected and copied to create the 1st floor. All rooms east of the central corridor on the 1st floor, including the corridor itself but excluding the east stairwell, were deleted. As before, prisms were created this time to represent the eastern spaces on the 1st floor. The North, South, East and West surfaces of the completed 1st floor were examined to ensure correct alignment. The completed first floor spaces were selected and copied seven times to create the remaining floors of the building. A single void space was added on top of the 8th floor to complete the construction process (Figure 5.3).

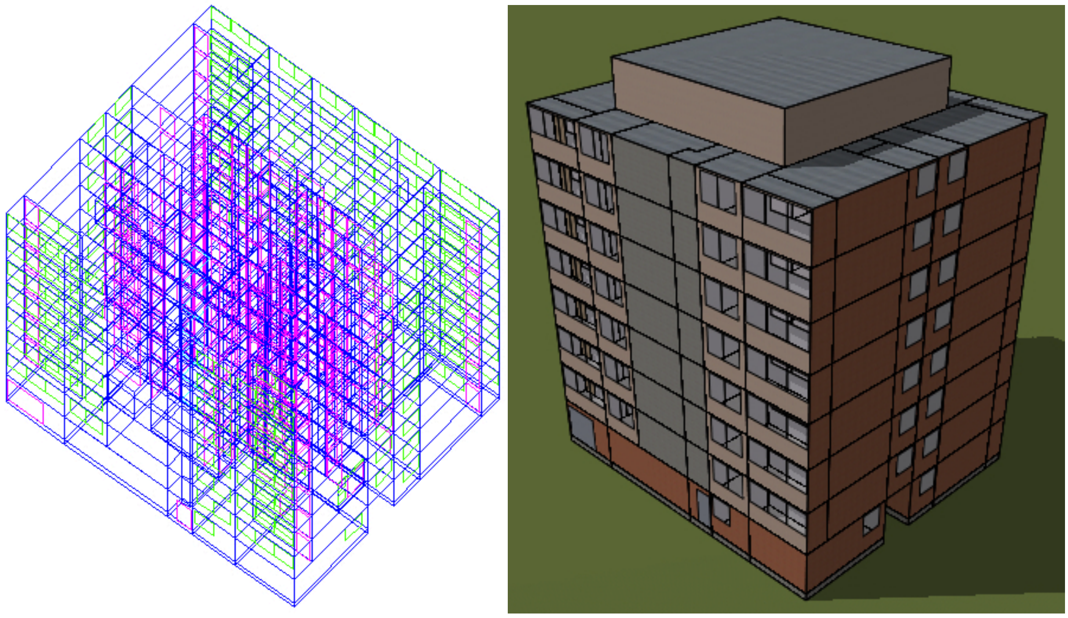

Figure 5.3: Completed model of 70 Broadholm Street, Glasgow in axonometric view (L) and with the inclusion of textures (R).

5.4.2.3 Thermal Construction Properties

The viewing experience was set to 'plan' and all ground floor spaces selected.

Wall thicknesses (ranging from approximately 150 to 300 mm depending on location) and wall construction properties were taken from the building plans. For each space, thermal constructions were assigned to each surface within the Model-IT application package of IES-VE. This included doors and windows. The assigned constructions selected from the project database matched as closely as possible the dimensions and materials used in the original building plans as detailed specifications were unknown (Table 5.1). At the same time, textures were assigned within Model-IT to enhance the visual experience. This process was repeated for each surface on each floor. The external walls were treated separately as these were known to be cladded with newer solid wall insulation, not represented on the original building plans. The modelled external walls were set to conform to a U-value of 0.3012 $W.m^{-2}.K^{\circ-1}$, in line with the Building (Scotland) Regulations 2002 (Scottish Executive, 2001). In general, a lower U-value means better insulation properties.

Table 5.1: Assigned constructions for 70 Broadholm Street, Glasgow.

Original construction type	Assigned construction type	Assigned construction type system U-value	Application
Plywood door	Timber flush panel hollow-core door	2.4408	Private living areas incl. cupboards
Wooden door	Plywood door	2.3025	Public areas i.e. drying areas.
Metal door	Metal door	4.0030	Lift doors, main entrance
Double glazing	Double glazing (domestic)	3.0330	Private living areas incl. offices
single leaf brick wall	115mm single leaf brick	2.0538	Partitions between rooms
double thickness brick wall	230mm single leaf brick	1.4872	Structural walls incl. partitions between rooms
External cavity wall	Standard wall construction (2002 Scotland Regs)	0.3012	External Walls
Ground floor	Solid ground floor (insulated to 1995 regs)	0.4112	Ground floor
Ceilings/floors	2013 Internal Ceiling/Floor	1.0693	All ceilings/floors
Roof	2013 Roof	0.1801	Exposed flat roof

5.4.2.4 Thermal Construction Properties

Profiles determine how the building is used under residential usage patterns. The profile database manager (APpro) is accessed via the Building Template Manager (BTM). The BTM is globally accessible from all IES-VE packages. For each of the livable space types (living room, bathroom, hall, bedroom 1, bedroom 2, kitchen, and office) a daily profile was created to indicate when the room is in use or not in 15-minute intervals of a 24-hour period (Figure 5.4). The daily profiles were extrapolated to create weekly profiles for each room. All profiles were created subjectively based on assumptions on how room types are likely to be used (Table 5.2).

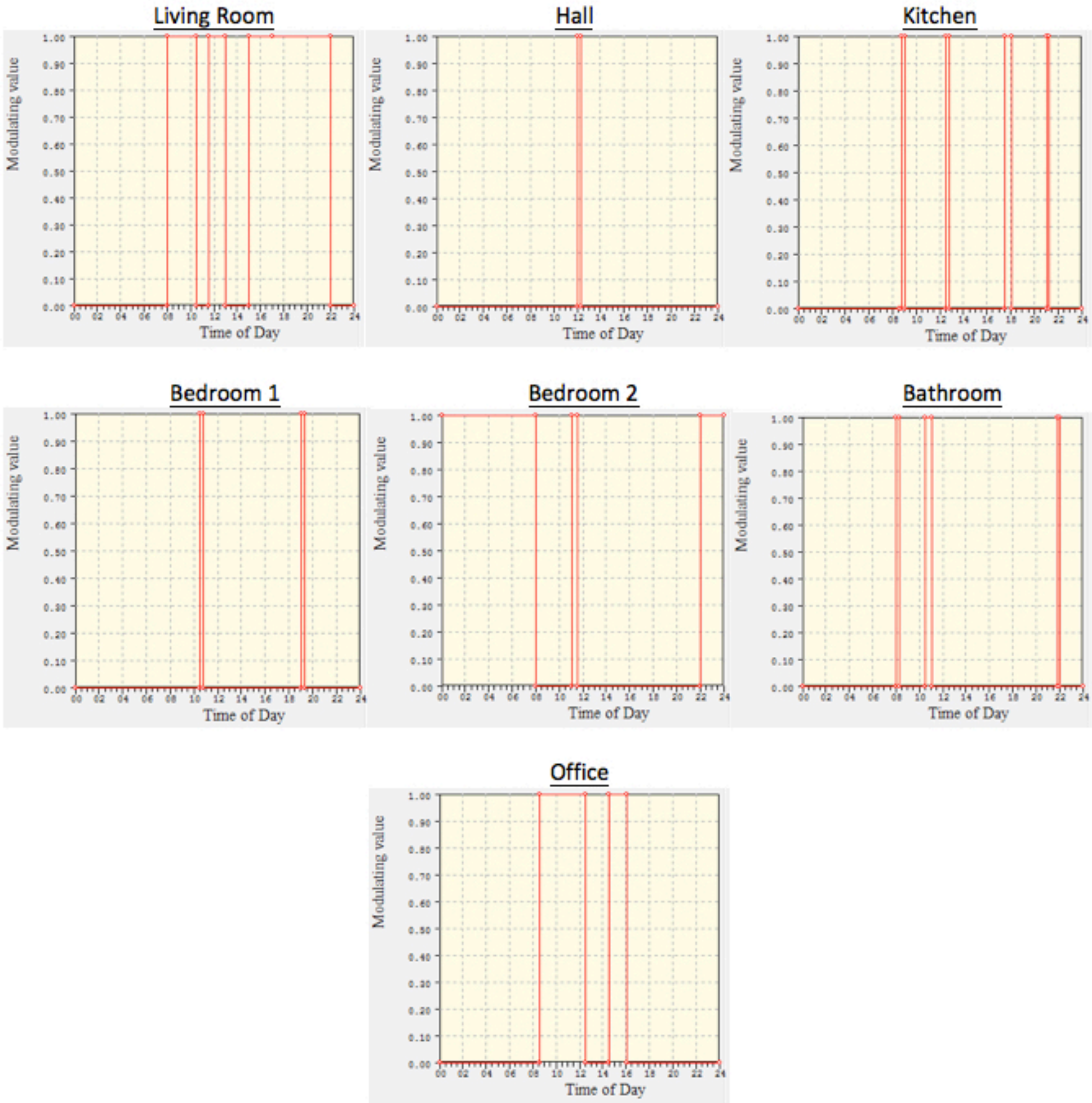

Figure 5.4: Daily profiles for each of the liveable spaces; a value of 1 indicates the room and appliances are in use.

Table 5.2: Assumptions linked to building use.

Variable	Details
Occupancy	Value = 2
Demographic	Elderly/vulnerable
Living room daily profile	It is assumed the living room is in constant use under normal conditions for the demographic.
Hall daily profile	It is assumed the hall is a transient area and a cumulative period of use has been recorded.
Kitchen daily profile	It is assumed the kitchen will be used under normal conditions (breakfast/lunch/dinner etc).
Bathroom daily profile	It is assumed the bathroom will be used under normal conditions (showers/personal hygiene etc).
Bedroom 1 daily profile	It is assumed bedroom 1 is used as a spare room, and is not in constant use.
Bedroom 2 daily profile	It is assumed bedroom 2 is the main bedroom and is used under normal conditions.
Office weekly profile	It is assumed the offices are used normally between Monday and Friday, and are not in use at weekends.
Other	It has been assumed the apartments will be vacant in the afternoon for a period of 2-3 hours to allow for occupant errands, and all profiles have been adjusted accordingly.

A thermal condition template was created in the BTM for each livable space. This contains set points for the heating regimes and recommended air changes per hour. The thermal condition templates follow the satisfactory regime for vulnerable households of 23°C for the living room and 18°C for all other rooms (Scottish Executive, 2002; Scottish Government, 2014) and industry-wide recommended air changes per hour (National Energy Services Ltd, 2012) (Table 5.3). For each thermal condition template by room type, the corresponding weekly profile was assigned and internal gains were assigned based on anticipated use. This includes gains for energy saving lighting (15-35 W), television equipment (250 W), cooking equipment (3000 W), and people (90 W/person).

Table 5.3: Assigned thermal conditions

Profile Type	Room Conditions		Air Changes per Hour
	Heating Set-point	Cooling Set-point	
Living room	23°C	25°C	6
Hall	18°C	25°C	3
Kitchen	18°C	25°C	15
Bathroom	18°C	25°C	10
Bedroom 1	18°C	25°C	2
Bedroom 2	18°C	25°C	4
Office	18°C	25°C	4

5.4.2.5 Dynamic Energy Simulation Model

Thermal calculations and simulations are conducted within the Apache application package of IES-VE. All spaces were grouped by type in the left pane, and the corresponding thermal condition templates were assigned to each selection set for heated spaces (258 in total). For the unheated spaces, heating and cooling points were set to off continuously within the Tabular Room Data function. Prior to performing the dynamic energy simulation model, a solar analysis was conducted within the SunCast package of IES-VE. This accounts for solar gains over a full calendar year, beginning January 1st and ending on December 31st.

A full calendar year dynamic energy simulation model was completed with the Apache package of IES-VE. This included a cross-link to the SunCast data file to account for solar gains in the output simulation file. For all livable spaces (258 in total), detailed output was requested. The simulation time step was set to 10 minutes, and the reporting interval was set to 60 minutes. The preconditioning period was set to the recommended interval of 10 days. Results were optimized for viewing in the VistaPro package of IES-VE. Data was extracted from VistaPro illustrating the 'Room Heating/Cooling Plant Sensible Load' (in kW), at 60 minute intervals for a full calendar year. The resulting heat load data file was converted to the .csv format accepted by the Ground Loop Design (GLD) package.

5.4.2.6 Ground Source Heat Pump System Model

The heat load data generated from the dynamic energy simulation model was imported into GLD using average block loads. The units were set to metric. An optimal heat pump type was selected based on maximum heating demand from the load data. The average block loads were linked to the borehole design project within GLD. Design parameters were set for the heat exchanger, including fluid characteristics set to ISO 13256. Propylene glycol was assumed as the transfer fluid. The undisturbed ground temperature was set at 10°C with a thermal conductivity of 2.9 $W.mK^{-1}$ and a thermal diffusivity of 0.115 m^2.day. This is correct for the geographical location and geological composition underlying Broadholm Street, which is limestone coal formation in the Clackmannan group parent unit (BGS, 2011; BGS, 2016). The undisturbed ground temperature is assumed as 10°C for temperate Europe, which includes the UK (Banks, 2008). This is approximately equal to the mean annual UK air temperature of 8-11°C (BGS, 2005).

The required vertical borefield size was calculated based on a modelled time period of 25 years. The process was repeated for a horizontal trench design project.

5.4.3 Data Analysis

The calculated heat load data was recast to estimate the heating consumption per square meter of livable floor space of the building. This allows the validity of the thermal characteristics and heating regime of the building to be checked average heating consumption for the existing UK building stock. This suggests a heat consumption of 100 $kWh.m^{-2}.year^{-1}$ for renovated buildings (Dowson et al., 2012).

The vertical borehole depths were checked to ensure they did not go beyond the upper limit of 300m. Large commercial borehole depths commonly fall within the range 200-300m (Gehlin et al., 2016). The horizontal trench depth was checked to ensure this did not go beyond 2m to ensure the design remains practical (Harvey, 2006).

5.5 Results and Discussion

5.5.1 Building Heat Load

The annual heat load calculated for 70 Broadholm Street is shown in table 5.4. This is the energy required to heat all of the livable spaces of the building to the designated heating regimes and set-points for one year. Also included is the annual cooling load. The cooling load is negligible at 2.76% of the total heating load, as heating is the dominant mode required in this geographical location. Natural ventilation also plays a role in the United Kingdom on the few occasions when cooling is required.

Table 5.4: Annual building heating and cooling loads for 70 Broadholm Street, Glasgow.

Heating Load ($kWh.year^{-1}$)	Cooling Load ($kWh.year^{-1}$)	Heating Load ($kWh.m^{-2}.year^{-1}$ of liveable space)
181,133	5,008	97

The heat load per square metre of livable space is $97kWh.m^{-2}.yr^{-1}$, based on a total livable area of $1,854m^2$. This is line with the average heating consumption for the existing UK building stock when renovated as shown in section 5.4.3 (100 $kWh.m^{-2}.year^{-1}$) and confirms that the calculated energy required to heat the livable spaces within the model is accurate. This also verifies any assumptions in the model so this heat load data is appropriate to design the GSHP heat exchanger system.

5.5.2 Ground Heat Exchanger Sizing

5.5.2.1 Vertical Borehole Design

The vertical borefield design options are shown in Table 5.5 and illustrated in Figure 5.5. These are designed to meet the calculated annual building heat load in section 5.5.1. The individual borehole diameter in all instances is 127mm, with spacing between boreholes of 10m to minimize interference. Included for reference are the indicative borehole drilling costs (Green Match, 2016), which form the largest portion of all GSHP project costs (DECC, 2016).

Table 5.5: Vertical borefield design options for 70 Broadholm Street, Glasgow.

Number of Boreholes	Borehole Depth (per borehole in metres)	Total Drilled Depth (metres)	Area of land required (m^2)	Indicative Installation Costs (£1500/kW*)
12	226	2712	621.78	£160,500
16	170	2720	930.74	£160,500
20	137	2740	1239.69	£160,500
24	114	2736	1548.65	£160,500

**includes cost of excavation and heat pumps, but excludes cost of internal distribution system (Energy Saving Trust, 2007).*

Figure 5.5: Indicative footprint of borefield design options by number of boreholes for 70 Broadholm Street, Glasgow.

As the depth of the boreholes increases, so the number of required boreholes and the overall footprint of the borefield decreases. At these depths costs are uniform as pricing is per installed kW (Energy Saving Trust, 2007) and the smallest borefield with fewest boreholes is within the normal borehole depth range for large commercial projects. The smallest borefield would also minimise downtime with fewer drilling rig moves and is a factor that can improve drilling efficiency (Cochener, 2010). The estimated ground temperature shows a maximum change of -0.4°C over 25 years, and stabilises 120 months (10 years) after commissioning. Total drilled cost and smallest operational footprint will likely inform decisions on how the vertical GSHP will be applied. However, the ground conditions may impact on drilled depth. In all cases, the borefield size options fit easily within the vacant and derelict land parcel constraints.

5.5.2.2 Horizontal Trench Design

The horizontal trench design is shown in Table 5.6. This is also designed to meet the calculated annual building heat load calculated in section 5.5.1. The proposed trenches are 0.9m wide and contain a slinky loop system, with a spacing between trenches of 10m to minimize interference. The cumulative trench length is shown, which is also smaller than the total length of drilling required for the borefield system.

Table 5.6: Horizontal trench design options for 70 Broadholm Street, Glasgow.

Total Excavated Area Required (m^2)	Total Trench Length (metres)	Percentage of Vacant and Derelict Land Parcel Used	Indicative Installation Costs (£1150/kW*)
17700	1770	90%	£123,050

**includes cost of excavation and heat pumps, but excludes cost of internal distribution system (Energy Saving Trust, 2007).*

However, the horizontal trench design requires a total area equivalent to 90%

of the available vacant and derelict land parcel. Trenches of parallel equal length are also not possible as the width and length of the vacant and derelict land parcel (40m & 350m respectively) would be exceeded. Therefore, any trench design would be highly variable in terms of trench length and direction. Although this option is much cheaper (c. 23% less than the cost of the borefield) future aspirations for the vacant and derelict land parcel will determine if this is possible, as the land would then be unavailable for further development in the future. It is worth nothing that the horizontal trench design also produces no change in ground temperature over the 25-year modelling period.

5.5.3 Design Viability and RHI Payback

Both vertical (all borefield sizes) and horizontal heat exchanger designs are shown to be viable for meeting the heat energy demand for 70 Broadholm Street. Whilst ground source heat pump installations within tower blocks are uncommon, a small number of projects have used GSHPs for tower block retrofits. This includes Walsall Housing Group where a vertical borehole system was installed consisting of 32x140m boreholes to service a 16-storey tower block of 65 social housing units at Austin House, Walsall (Renewable Energy Installer, 2013; RHILC, 2017). Similarly, Northwards Housing installed a vertical borehole system consisting of 22x150m boreholes to service a 12-storey tower block of 54 social housing units at Clifford Lamb Court, Manchester (Danbar Drilling Services, 2014; Housing Association Magazine, 2015). In both cases, the systems are shown to work correctly and meet the space heating requirements for each individual unit. The size and scale of these systems falls in line with the vertical borehole system options designed for 70 Broadholm Street.

As discussed in chapter 3, the RHI scheme offers cash back payments to those that are producing heat through the use of renewables, including ground source heat pumps. 70 Broadholm Street would be eligible under the non-domestic RHI Scheme. The RHI payments are the same for both vertical and horizontal heat exchanger systems as the rate in pence per kWh is the same for any GSHP system type. GSHP deployment remains low within the RHI (BEIS, 2017a), as such the tariff rate shown is unlikely to undergo degression. Note that cooling is ineligible for the RHI payment. Non-discounted RHI payments are shown in table 5.7.

Table 5.7: RHI payments for GSHP system at 70 Broadholm Street, Glasgow.

Ground Heat Exchanger Option	Heat Exchanger System Cost	Building Internal Distribution System Cost*	RHI Payment per Year (8.95p/kWh for heat load of 181,133 kWh)	RHI Payment over 20 year term
Vertical	£160,500	£67,500	£16,211.40	£324,228
Horizontal	£123,050	£67,500	£16,211.40	£324,228

**based on the installed cost per property of a wet distribution system (£3,000) minus the cost of a gas boiler (£750) (Staffell et al., 2015).*

For the non-domestic RHI scheme, RHI payments are made quarterly over a 20-year period. For both systems, the non-discounted RHI payment is £324,228. By comparison, the installation at Clifford Lamb Court, Manchester anticipates RHI contributions of over £400,000 over the 20 year RHI term (Housing Association

Magazine, 2015) however is a larger building with an increased space heating requirement. Although the RHI payments exceed investment in both cases for 70 Broadholm Street, no allowance is made here for the cost of capital, inflation, risk and changes in value of heat or power over time. These must be included in an analysis to illustrate if the proposed investment is worthwhile in real terms.

5.5.4 Net Present Value and Levelised Cost of Energy

The net present value (NPV) illustrates what the future value of an investment is worth today, where a discount factor is used to account largely for inflation and risk over time. A conservative discount factor of 4% is accepted as normal for energy system modelling (ECEEE, 2015). The financial benefit of a project over its lifetime is measured by its NPV (Wiesemann et al., 2009). The levelised cost of energy (LCoE) is the minimum cost per unit of energy that must be charged to the end user for the project to breakeven (Reichelstein & Yorston, 2013) and allows an energy generation system's value to be fairly compared against other means of energy generation. This is important as power generation methods and cost structures are often different (VGB Powertech, 2015). Considering the NPV and LCoE of the proposed energy system gives a more accurate representation of the financial benefits or not of undertaking the project. This has been examined for the vertical borehole GSHP model (table 5.8) which ensures that a majority the land parcel is saved for future redevelopment. Note that in this study it is assumed that end users are currently charged for heat at £0.1360/kWh, which is average variable unit price for domestic electricity for the UK in 2016 (BEIS, 2017b). The electricity used to run the GSHP system is chargeable to the project at £0.1208/kWh, which is the average price paid in 2016 by small non-domestic consumers in the UK. (BEIS, 2017c). The annual heating consumption for the building is 181,133 kWh/year and the electrical energy used to generate this heat is 45,283 kWh/year.

5.5.4.1 Levelised Cost of Energy

The LCoE is determined by comparing the full discounted costs (including capital expenditure, operation and maintenance costs) against the discounted energy that those investment costs generate over the full project lifetime (in this case 25 years) (DECC, 2013). Any financial support or incentives such as received through the RHI represent a revenue stream within the project and are also included. The LCoE for the proposed GSHP system is calculated at £0.0391/kWh and represents the minimum chargeable cost for the project to breakeven. This means that the cost per unit of energy charged to the end user should be no less than this figure. Figure 5.6 illustrates how the LCoE for this project compares with other specific means of energy generation that will play a large role going into the 2020s.

Table 5.8: NPV & LCoE determination - GSHP system with 4% discount rate.

USER INPUT VALUES	
Initial Capital Cost (Capex)	**£228,000**
Maintenance Costs (Opex) (/year)	**£1,000**
Maintanance Costs Escalation (/year)	**1%**
Renewable Heat Generated [total] (kWh/year)	**181,133**
Heat Pump COP	**4.0**
Electricity for Heat Pumps [total] (kWh/year)	45,283
Electricity Cost (£/kWh) *FOR REFERENCE*	**0.1208**
RHI Payment Rate (£/kWh) *FOR REFERENCE*	**0.0895**
Gas Cost (£/kWh) *FOR REFERENCE*	**0.0418**
Cost for Generated Heat (£/kWh)	**0.0418**
5% Increase on Generated Heat Cost (£/kWh)	0.0439
0% Increase on Generated Heat Cost (£/kWh)	0.0418
5% Discount on Generated Heat Cost (£/kWh)	0.0397

RESULTS

Project LCOE	£0.0391 / kWh

Heat Charged to End Users at 5% Increase on Gas Cost		**Heat Charged to End Users at same as Gas Cost**		**Heat Charged to End Users at 5% Discount on Gas Cost**	
with RHI		***with RHI***		***with RHI***	
NPV (25 years)	£13,586.81	NPV (25 years)	£7,672.79	NPV (25 years)	£1,758.76
Profitability Index	1.03	Profitability Index	1.02	Profitability Index	1.00
Heat Charged to End Users at 5% Increase on Gas Cost		**Heat Charged to End Users at same as Gas Cost**		**Heat Charged to End Users at 5% Discount on Gas Cost**	
no RHI		***no RHI***		***no RHI***	
NPV (25 years)	-£206,732.65	NPV (25 years)	-£212,646.67	NPV (25 years)	-£218,560.70
Profitability Index	0.34	Profitability Index	0.32	Profitability Index	0.31

Year	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Initial Cost		£228,000.00																									
Heat Output (kWh/year)			181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00	181,133.00
Heat Output (discounted) (kWh/year)			174,159.38	167,475.57	161,027.24	154,832.49	148,873.21	143,149.41	137,642.97	132,353.88	127,264.05	122,373.45	117,664.00	113,135.67	108,788.48	104,604.31	100,583.15	96,706.91	92,993.68	89,407.25	85,965.72	82,669.10	79,481.16	76,438.13	73,485.66	70,659.98	67,942.99
Electrical Input (kWh/year)			45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283.25	45,283	45,283	45,283	45,283
Electricity Cost (£0.139/kWh)			£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22	£5,470.22
Electricity Cost (discounted) (£0.139/kWh)			£5,259.61	£5,057.76	£4,863.02	£4,675.94	£4,495.97	£4,323.11	£4,156.82	£3,997.09	£3,843.37	£3,695.68	£3,553.45	£3,416.70	£3,285.41	£3,159.05	£3,037.61	£2,920.55	£2,808.41	£2,700.10	£2,596.16	£2,496.61	£2,400.33	£2,308.43	£2,219.27	£2,133.93	£2,051.88
RHI Payment (£0.0895/kwh)			£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£16,211.40	£0.00	£0.00	£0.00	£0.00	£0.00
RHI Payment (discounted) (£0.0895/kwh)			£15,587.26	£14,989.06	£14,411.94	£13,857.51	£13,324.15	£12,811.87	£12,319.05	£11,845.67	£11,390.13	£10,952.42	£10,530.93	£10,125.64	£9,736.57	£9,362.09	£9,002.19	£8,655.27	£8,322.93	£8,001.95	£7,693.93	£7,398.88	£0.00	£0.00	£0.00	£0.00	£0.00
Discount Factor (4%)	1.0400	1.0000	0.9615	0.9246	0.8890	0.8548	0.8219	0.7903	0.7599	0.7307	0.7026	0.6756	0.6496	0.6246	0.6006	0.5775	0.5553	0.5339	0.5134	0.4936	0.4746	0.4564	0.4388	0.4220	0.4057	0.3901	0.3751
Maintenance Costs incl. maintenance costs escalation			£1,010.00	£1,020.10	£1,030.30	£1,040.60	£1,051.01	£1,061.52	£1,072.14	£1,082.86	£1,093.69	£1,104.62	£1,115.67	£1,126.83	£1,138.09	£1,149.47	£1,160.97	£1,172.58	£1,184.30	£1,196.15	£1,208.11	£1,220.19	£1,232.39	£1,244.72	£1,257.16	£1,269.73	£1,282.43
TOTAL COSTS (discounted)		£228,000.00	£6,230.73	£6,000.95	£5,778.96	£5,565.45	£5,359.80	£5,162.03	£4,971.53	£4,788.33	£4,611.80	£4,441.96	£4,278.19	£4,120.51	£3,968.95	£3,822.87	£3,682.30	£3,546.59	£3,416.43	£3,290.52	£3,169.53	£3,053.50	£2,941.10	£2,833.70	£2,729.30	£2,629.25	£2,532.92

Revenue & NPV with RHI at varying heat costs to end users																											
Revenue (discounted, with RHI) *[when chargeable heat is 105% of gas cost]*	£0.00	£0.00	£23,231.12	£22,339.57	£21,479.42	£20,653.11	£19,858.20	£19,094.70	£18,360.20	£17,654.68	£16,975.75	£16,323.40	£15,695.20	£15,091.17	£14,511.30	£13,953.17	£13,416.79	£12,899.73	£12,404.43	£11,926.03	£11,466.97	£11,027.23	£3,488.43	£3,354.87	£3,225.29	£3,101.27	£2,982.02
NPV (with RHI) *[when chargeable heat is 105% of gas cost]*	£0.00	-£228,000.00	£17,000.39	£16,338.62	£15,700.46	£15,087.66	£14,498.40	£13,932.67	£13,388.66	£12,866.35	£12,363.95	£11,881.43	£11,417.01	£10,970.66	£10,542.34	£10,130.30	£9,734.49	£9,353.15	£8,988.00	£8,635.52	£8,297.43	£7,973.73	£547.32	£521.17	£495.99	£472.01	£449.10
Cumulative NPV (with RHI) *[when chargeable heat is 105% of gas cost]*	£0.00	-£228,000.00	-£210,999.61	-£194,660.99	-£178,960.53	-£163,872.87	-£149,374.47	-£135,441.80	-£122,053.14	-£109,186.78	-£96,822.83	-£84,941.40	-£73,524.39	-£62,553.73	-£52,011.39	-£41,881.09	-£32,146.60	-£22,793.45	-£13,805.46	-£5,169.94	£3,127.49	£11,101.22	£11,648.55	£12,169.71	£12,665.70	£13,137.71	£13,586.81
Revenue (discounted, with RHI) *[when chargeable heat is 100% of gas cost]*	£0.00	£0.00	£22,867.13	£21,989.54	£21,142.88	£20,329.51	£19,547.05	£18,795.52	£18,072.52	£17,378.06	£16,709.77	£16,067.63	£15,449.28	£14,854.71	£14,283.93	£13,734.55	£13,206.57	£12,697.62	£12,210.07	£11,739.17	£11,287.30	£10,854.45	£3,322.31	£3,195.11	£3,071.70	£2,953.59	£2,840.02
NPV (with RHI) *[when chargeable heat is 100% of gas cost]*	£0.00	-£228,000.00	£16,636.40	£15,988.60	£15,363.92	£14,764.06	£14,187.26	£13,633.49	£13,100.99	£12,589.73	£12,097.97	£11,625.67	£11,171.09	£10,734.20	£10,314.98	£9,911.67	£9,524.27	£9,151.03	£8,793.64	£8,448.65	£8,117.77	£7,800.95	£381.21	£361.41	£342.40	£324.33	£307.10
Cumulative NPV (with RHI) *[when chargeable heat is 100% of gas cost]*	£0.00	-£228,000.00	-£211,363.60	-£195,375.01	-£180,011.09	-£165,247.03	-£151,059.78	-£137,426.29	-£124,325.30	-£111,735.57	-£99,637.60	-£88,011.92	-£76,840.83	-£66,106.63	-£55,791.65	-£45,879.98	-£36,355.71	-£27,204.68	-£18,411.04	-£9,962.39	-£1,844.62	£5,956.33	£6,337.54	£6,698.95	£7,041.35	£7,365.69	£7,672.79
Revenue (discounted, with RHI) *[when chargeable heat is 95% of gas cost]*	£0.00	£0.00	£22,503.13	£21,639.52	£20,806.33	£20,005.91	£19,235.91	£18,496.34	£17,784.85	£17,101.45	£16,443.79	£15,811.87	£15,203.37	£14,618.26	£14,056.56	£13,515.92	£12,996.35	£12,495.50	£12,015.71	£11,552.31	£11,107.63	£10,681.67	£3,156.20	£3,035.36	£2,918.12	£2,805.91	£2,698.02
NPV (with RHI) *[when chargeable heat is 95% of gas cost]*	£0.00	-£228,000.00	£16,272.41	£15,638.57	£15,027.37	£14,440.46	£13,876.11	£13,334.30	£12,813.31	£12,313.11	£11,831.99	£11,369.91	£10,925.17	£10,497.75	£10,087.61	£9,693.05	£9,314.05	£8,948.91	£8,599.28	£8,261.79	£7,938.10	£7,628.17	£215.09	£201.66	£188.82	£176.65	£165.10
Cumulative NPV (with RHI) *[when chargeable heat is 95% of gas cost]*	£0.00	-£228,000.00	-£211,727.59	-£196,089.02	-£181,061.65	-£166,621.20	-£152,745.09	-£139,410.78	-£126,597.47	-£114,284.35	-£102,452.36	-£91,082.45	-£80,157.28	-£69,659.53	-£59,571.92	-£49,878.87	-£40,564.82	-£31,615.90	-£23,016.62	-£14,754.83	-£6,816.73	£811.44	£1,026.53	£1,228.19	£1,417.01	£1,593.66	£1,758.76

Revenue & NPV with no RHI at varying heat costs to end users																											
Revenue (discounted, no RHI) *[when chargeable heat is 105% of gas cost]*	£0.00	£0.00	£7,643.86	£7,350.50	£7,067.49	£6,795.60	£6,534.05	£6,282.83	£6,041.15	£5,809.01	£5,585.62	£5,370.97	£5,164.27	£4,965.52	£4,774.73	£4,591.08	£4,414.59	£4,244.47	£4,081.49	£3,924.08	£3,773.04	£3,628.35	£3,488.43	£3,354.87	£3,225.29	£3,101.27	£2,982.02
NPV (no RHI) *[when chargeable heat is 105% of gas cost]*	£0.00	-£228,000.00	£1,413.13	£1,349.56	£1,288.53	£1,230.15	£1,174.25	£1,120.80	£1,069.62	£1,020.68	£973.82	£929.01	£886.08	£845.01	£805.78	£768.21	£732.30	£697.88	£665.06	£633.57	£603.50	£574.85	£547.32	£521.17	£495.99	£472.01	£449.10
Cumulative NPV (no RHI) *[when chargeable heat is 105% of gas cost]*	£0.00	-£228,000.00	-£226,586.87	-£225,237.32	-£223,948.79	-£222,718.64	-£221,544.39	-£220,423.60	-£219,353.98	-£218,333.30	-£217,359.48	-£216,430.47	-£215,544.39	-£214,699.37	-£213,893.60	-£213,125.39	-£212,393.09	-£211,695.21	-£211,030.15	-£210,396.58	-£209,793.08	-£209,218.24	-£208,670.91	-£208,149.74	-£207,653.76	-£207,181.75	-£206,732.65
Revenue (discounted, no RHI) *[when chargeable heat is 100% of gas cost]*	£0.00	£0.00	£7,279.86	£7,000.48	£6,730.94	£6,472.00	£6,222.90	£5,983.65	£5,753.48	£5,532.39	£5,319.64	£5,115.21	£4,918.36	£4,729.07	£4,547.36	£4,372.46	£4,204.38	£4,042.35	£3,887.14	£3,737.22	£3,593.37	£3,455.57	£3,322.31	£3,195.11	£3,071.70	£2,953.59	£2,840.02
NPV (no RHI) *[when chargeable heat is 100% of gas cost]*	£0.00	-£228,000.00	£1,049.13	£999.53	£951.98	£906.55	£863.10	£821.61	£781.94	£744.06	£707.84	£673.25	£640.16	£608.56	£578.41	£549.59	£522.08	£495.76	£470.70	£446.71	£423.83	£402.07	£381.21	£361.41	£342.40	£324.33	£307.10
Cumulative NPV (no RHI) *[when chargeable heat is 100% of gas cost]*	£0.00	-£228,000.00	-£226,950.87	-£225,951.33	-£224,999.36	-£224,092.81	-£223,229.70	-£222,408.09	-£221,626.15	-£220,882.08	-£220,174.25	-£219,501.00	-£218,860.83	-£218,252.27	-£217,673.87	-£217,124.28	-£216,602.20	-£216,106.44	-£215,635.73	-£215,189.03	-£214,765.19	-£214,363.13	-£213,981.92	-£213,620.51	-£213,278.10	-£212,953.77	-£212,646.67
Revenue (discounted, no RHI) *[when chargeable heat is 95% of gas cost]*	£0.00	£0.00	£6,915.87	£6,650.45	£6,394.39	£6,148.40	£5,911.76	£5,684.46	£5,465.80	£5,255.77	£5,053.66	£4,859.45	£4,672.44	£4,492.62	£4,319.99	£4,153.84	£3,994.16	£3,840.23	£3,692.78	£3,550.36	£3,413.70	£3,282.79	£3,156.20	£3,035.36	£2,918.12	£2,805.91	£2,698.02
NPV (no RHI) *[when chargeable heat is 95% of gas cost]*	£0.00	-£228,000.00	£685.14	£649.51	£615.43	£582.95	£551.96	£522.43	£494.27	£467.44	£441.86	£417.49	£394.25	£372.11	£351.04	£330.97	£311.86	£293.64	£276.35	£259.84	£244.17	£229.29	£215.09	£201.66	£188.82	£176.65	£165.10
Cumulative NPV (no RHI) *[when chargeable heat is 95% of gas cost]*	£0.00	-£228,000.00	-£227,314.86	-£226,665.35	-£226,049.92	-£225,466.97	-£224,915.01	-£224,392.58	-£223,898.31	-£223,430.87	-£222,989.01	-£222,571.52	-£222,177.28	-£221,805.17	-£221,454.13	-£221,123.17	-£220,811.31	-£220,517.66	-£220,241.32	-£219,981.47	-£219,737.30	-£219,508.02	-£219,292.92	-£219,091.27	-£218,902.45	-£218,725.80	-£218,560.70

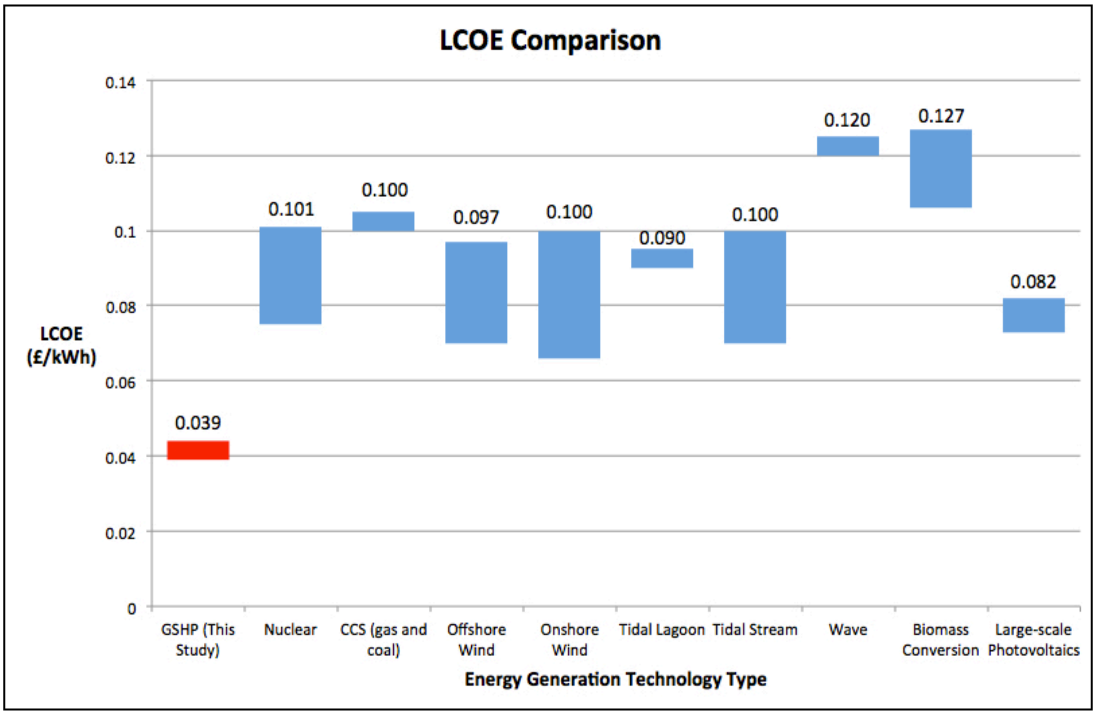

Figure 5.6: Levelised Cost of Energy comparison – this study against other technologies, rates shown with inclusion of subsidies where applicable. Not to be used as a definitive cost projection guide.

(Green Alliance, 2016).

A probabilistic analysis on all permutations of the electricity cost to run the GSHP system, incentive payments received through the RHI, and the GSHP system CoP illustrates the probability of the LCoE of £0.039/kWh occurring (figure 5.7). The values and assumed probabilities are shown in table 5.9.

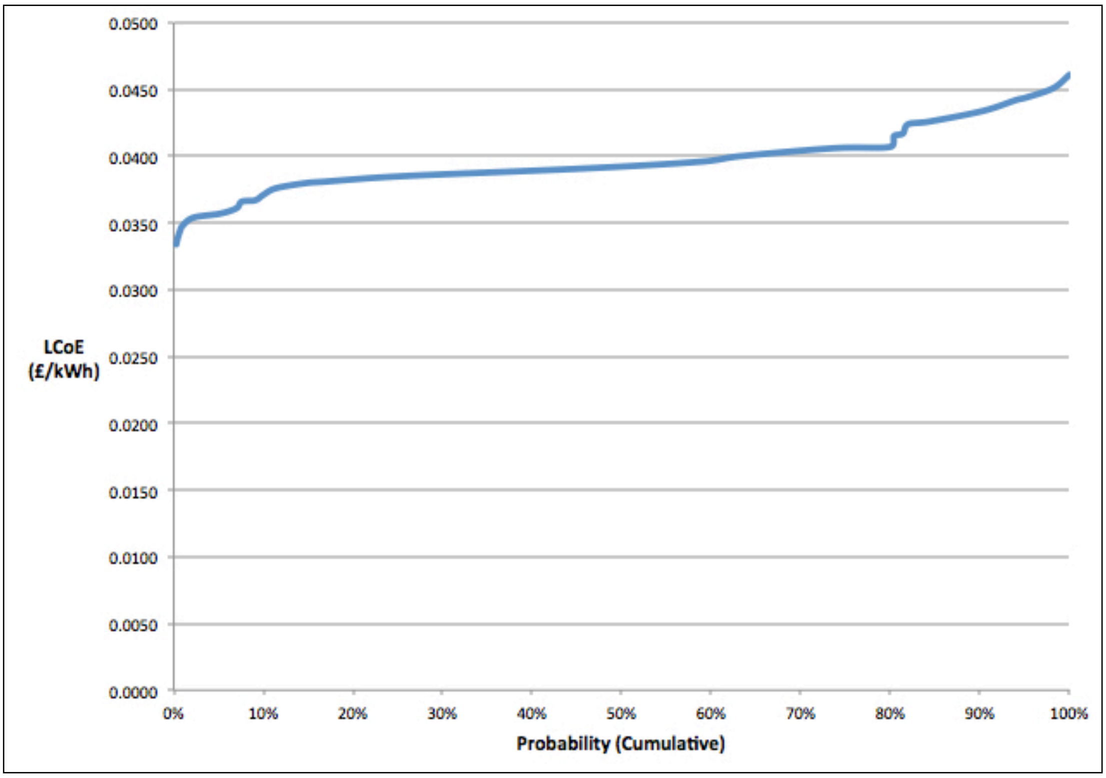

Figure 5.7: Probabilistic analysis – Levelised Cost of Energy against probability.

Table 5.9: Energy system values used within probabilistic analysis.

	Energy System Vales and Assumed Probability		
	Low	**Median (this Project)**	**High**
Electricity Cost (p/kWh)	0.1148	0.1208	£123,050
Probability	10%	60%	30%
RHI Rate (p/kWh)	0.0884	0.0895	0.906
Probability	10%	55%	35%
CoP of GSHP System	3.5	4.0	4.5
Probability	20%	70%	10%

5.5.4.1 Net Present Value

The net present value of the proposed GSHP system is calculated by quantifying capital expenditure costs and associated running costs over the 25 year project lifetime, offset against the revenue generated. Importantly, the NPV also considers financial support, such as that of the RHI. Table 5.8 fully illustrates the impact that the RHI has on the NPV, and includes a scenario where RHI payments are excluded from the NPV calculation.

The revenue generated by the project is determined by the unit price per kilowatt-hour of energy that is charged to the end users. This means that the NPV can change based on the predetermined price per unit of energy charged. The low price of natural gas is highly competitive (ICEF, 2016) and is used to heat over 80% of UK dwellings (Elwell, et al., 2015). A percentage variance from the domestic gas price presents a strong baseline on which to set the cost per unit of energy delivered from the GSHP system. Figure 5.8 illustrates 3 scenarios where the cost per unit of energy delivered from the GSHP system is set at 105%, 100% and 95% of the current gas price of £0.0418/kWh.

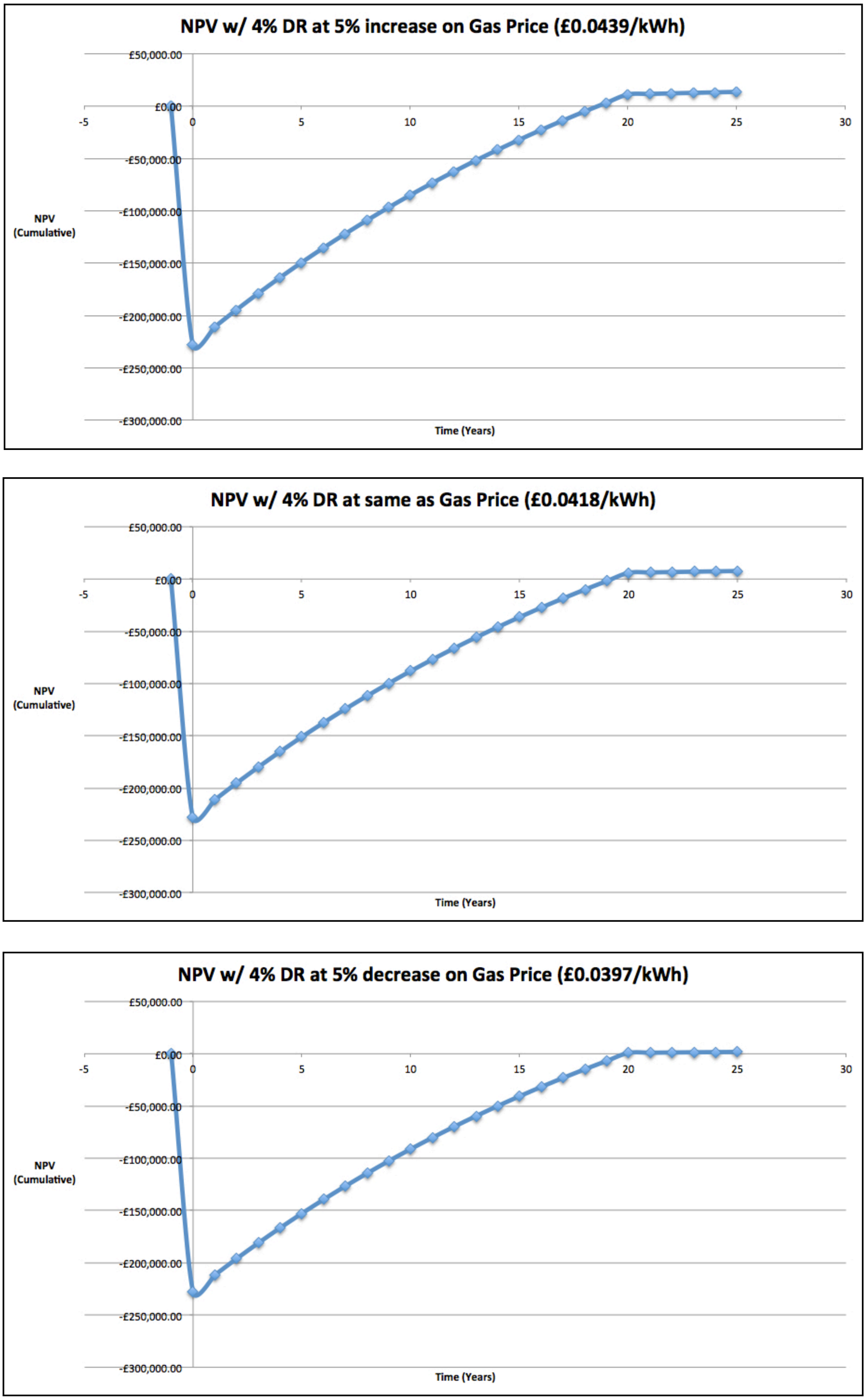

Figure 5.8: The impact of different rates for the chargeable energy cost from the GSHP system against cumulative NPV over the project lifetime (25 years).

In all scenarios, the initial capital investment is seen prior to year zero. The investment is repaid fully or in part by the RHI which gives an increasing cumulative NPV over the first 20 years. The RHI support ends at year twenty when the RHI payments stop and support then fully depends on any revenues received though additional tariffs set per unit of renewable energy generated by the GSHP system. Based on the fixed operational costs (for electricity), the tariff (for heat) can be set at 95% of the gas price, providing revenue includes the RHI. Table 5.10 illustrates the cumulative NPV at 25 years for each scenario, including scenarios if no RHI payments exist. The change in cost per unit of heat charged to the end user is shown to make little difference to project viability. All scenarios that include the RHI make a profit after 20 years, and the biggest difference is that a project charging at 105% of the current gas price is paid off 1 year earlier than the same project charging at 95% of the current gas price.

Table 5.10: Cumulative NPV based on predetermined tariff rates for chargeable heat for the GSHP system – a scenario based approach.

Cumulative NPV with RHI Payments			**Cumulative NPV without RHI Payments**		
Tariff = 105% of gas price (£0.0439 /kWh)	Tariff = 100% of gas price (£0.0418 /kWh)	Tariff = 95% of gas price (£0.0397 /kWh)	Tariff = 105% of gas price (£0.0439 /kWh)	Tariff = 100% of gas price (£0.0418 /kWh)	Tariff = 95% of gas price (£0.0397 /kWh)
£13,586.81	£7,672.79	£1,758.76	-£206,732.65	-£212,646.67	-£218,560.70

5.6 Conclusions

Although the horizontal trench design had the lowest cost, using this heat exchanger option is largely site dependent. That is, nearly all (90%) of the vacant and derelict land parcel in the present case study would be required, leaving little option for future "hard" redevelopment of the site. Future use of the site could, however, include "soft" end uses, such as landscaping, recreation or public open space. The vertical borehole design uses a smaller portion of the available vacant and derelict land but has a higher upfront cost. This is also a common design used in other GSHP tower block installations. In both cases, this study has shown that the heating energy demand of residential public sector building can be met effectively using ground source heat pumps on derelict land. A detailed analysis of projected costs and revenue over the project lifetime also shows that the GSHP system is commercially viable, if tariffs are set correctly per unit of chargeable energy used. This study has found that setting the tariff to within 5% of the current gas price makes the GSHP system competitive with the RHI in place. However, this does not limit exposure to the possibility of reduced revenue should gas prices fall, or an increase in system running costs should electricity prices increase. The inclusion of the RHI is the strongest mechanism to recover capital costs associated with implementing the GSHP system. It is clear that the RHI is an essential component in making the GSHP system viable. However, with only a 5% reduction possible against the price of gas, it is a delicate balance between offering end users a discount over current means of heating energy generation, and not charging a premium for the decarbonisation of domestic heating. In either case, likely savings are considerable when the system being displaced is generating heat through electricity and when individual gas boilers are not allowed in tower blocks due to the possible consequences should a fault occur.

Overall, this study has shown that a residential public sector building such as a tower block can be selected for the use of ground source heat pumps based on the coincidence of fuel poverty and proximity to areas of vacant and derelict land. Ground source heat pumps are able to meet the actual predicted heating demand of the building. Locally available derelict land could be used, with the system designed to ensure its operation and legacy is sustainable over time.

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6. Conclusions and Recommendations for Future Work

This thesis aims to answer the research question '*how best can ground source heat pumps be deployed in a public sector context?'.* The hypothesis was that the use of ground source heat pumps is a viable option for addressing the heating needs of the fuel poor living in public sector housing, using nearby vacant and derelict land. In order to answer the research question, the main policy support mechanism for renewable heating was firstly examined (chapter 3). A suitable end use was identified based on the proximity of vacant and derelict land to social housing (chapter 4). This chapter also gave rise to a noteworthy discovery where, once land data was collated, more land was showing as 'available' than was publicly recorded. This means that the energy potential for Scotland (in terms of renewables deployed on land) could be higher than previously anticipated. The proposed land use strategy alongside a more complete understanding of vacant land availability therefore form important contributions to the field of research. By defining the important relationship between social housing provision and proximity to vacant and derelict land, this work has obtained results that show ground source heat pumps on vacant and derelict land are a viable option for meeting the heating energy needs of a residential public sector building (chapter 5). It is shown that this can be accomplished within strict financial constraints whilst providing lower heating energy bills for end users.

In the following sections, the key findings relevant to this approach are summarised. This highlights the extent to which the chosen methodology assists in answering the research question '*how best can ground source heat pumps be deployed in a public sector context?'*.

6.1 Key Findings

6.1.1 Support Mechanism to Encourage Renewable Heating Deployment

This research began prior to the main support mechanism for renewable heating in the UK (the RHI) being open for applications. This meant that no prior research existed on how the RHI operated within real world projects. As such, this research was aligned with one of the first construction projects in the UK where the RHI would be applicable. In the first instance, it was found that missed opportunities occurred where embedding the RHI within planning and accreditation could have eased issues on site during building refurbishment. Implementation of renewable heat on a broader scale should also consider universal integration strategies to allow a wider uptake of renewable heat technologies. This direction forms a core argument for linking renewable heating across other policy areas if deployment is to increase, in this case linking heating demand with fuel poverty and the use vacant and derelict land.

Whilst the RHI was found to be clear and transparent within a policy context, at a construction level phase it was found that there needs to be a significant improvement in how the RHI is managed and supported in order to fully aid implementation. This could be through more accessible guidance on the RHI for those working on construction sites, or alternatively a broader awareness on the importance of the RHI within an entire project. In many cases, the RHI is, and should be seen as, the crucial component that makes many projects viable. The modelled case study (chapter 5) confirms that this is the case.

The RHI therefore represents an opportunity to transform the heating market, which includes integrated control measures towards a resilient and secure 'future-proof' energy economy. This gives a significant advantage for those willing to innovate, such as in the geothermal school refurbishment project in Glasgow (chapter 3) or targeting fuel poverty in tandem with vacant and derelict land (chapter 4). Innovative projects are therefore crucial to test feasibility, cost, revenue, and also the management of risk within renewable heating deployment. Support does exist within the RHI, though the lack of clarity in how the RHI is integrated in a build, and how the RHI functions out with policy and in the real world, is found to not fully support the implementation of a scheme that has the potential to transform the heating market.

6.1.2 Opportunities for Ground Source Heat Pumps on Vacant and Derelict Land

Research has shown that opportunities for renewables exist on brownfield land. This includes broad renewable energy potential on brownfield sites (Adelaja et al, 2010; Greater London Authority, 2011) or more specific uses of brownfield sites that include the use of biomass crops (Lord, 2015) or solar PV (Sangiorgio & Falconi, 2015). There has however been limited data available that examines the use of ground source heat pumps on vacant and derelict land. Chapter 4 explores this and identifies a correlation between urban brownfield land and social housing, suggesting these are appropriate targets for deploying and utilising ground sourced heating. Social housing provision also reflects areas of low income and associated deprivation, so can be used as a proxy for fuel poverty. Relative concentrations of social housing and brownfield land by electoral ward areas give a means of identifying zones of opportunity.

Historic, unlicensed landfill sites are shown to increase the total residual landfill area within Scotland by more than 75% to 7,281ha. Together with vacant and derelict land, a total of 18,395 ha is available which could potentially be used for the deployment of renewables. Although representing less than a quarter of one percent of the total land area of Scotland, much of this potential resource is situated close to urban centres of heat demand. The addition of previously unknown vacant and derelict land serves to increase Scotland's potential renewable energy resource further.

Using ground source heat pumps on all vacant and derelict land as a renewable heating technology option for 80% of a property's peak averaged heat demand for Glasgow, Scotland could serve to heat 43,754 properties or 47% of those estimated to be in fuel poverty. This is a 'worst case scenario', based on horizontal arrays where all available vacant and derelict land is used. Using higher cost vertical boreholes instead would increase this figure greatly due to the decreased technology footprint and increased energy yield. Hypothetically, the demands of all properties in heat poverty could be met, however it is necessary for a balance to be drawn between installation costs, the technology footprint, and the number of properties whose heat demand could be met, to provide the most cost effective, sustainable solution.

6.1.3 Modelling a Ground Source Heat Pump System for Public Sector Housing using Vacant and Derelict Land

Two design options for a heat pump system were identified in chapter 5. This included a horizontal trench system and a vertical borehole system that would meet the modelled heating energy demand (181,133 kWh) of a public sector building that is in close proximity to vacant and derelict land.

It was found that the horizontal trench design would use nearly all (90%) of the vacant and derelict land parcel. This would leave little option for future "hard" redevelopment of the site which may inhibit area regeneration opportunities. This is an important factor to consider when striving to 'future-proof' any design proposals. The vertical borehole design used a smaller portion of the available vacant and derelict land but at a higher upfront (23% more than the cost of the horizontal trench design). However, in both cases, the study has shown that the heating energy demand of residential public sector building can be met effectively using ground source heat pumps on the available vacant and derelict land.

Analysis of projected costs and revenue over the project lifetime also shows that the GSHP system is commercially viable, if tariffs are set correctly per unit of chargeable energy used. It has been calculated that the chargeable energy tariff to end users can be set to 5% below the current domestic gas price, making the GSHP system favourable and also competitive. However, if this tariff is fixed it has been acknowledged that his does not limit exposure to the possibility of reduced competitiveness should gas prices fall, or an increase in system running costs should commercial electricity prices increase. In a similar way, end-users of the GSHP system will benefit from a lower cost per unit of heat energy delivered should gas prices rise, and an immediate reduction in cost over the current means of heat generation.

Chapters 2 and 5 show that inclusion of the RHI is critical to recovering any capital costs associated with implementing the GSHP system. It is clear that the RHI is an essential component in making the GSHP system viable. Whilst it is necessary to assign RHI payments to cover the capital cost of installation, the end users still benefit through a large reduction in the price paid per unit of energy delivered for heating. This is particularly compelling when the system being displaced is generating heat through electricity as options for heating in tower blocks are limited do not include the use of individual gas boilers.

6.2 Future Research Opportunities

This study presents a comprehensive approach to the deployment of ground source heat pumps. This includes addressing technology barriers whilst meeting the heating energy needs of end-users to provide a system that is sustainable over time. The pathways highlighted in this study also opens up opportunities for future research. Possible future deployment challenges have also been identified.

6.2.1 Future Deployment Challenges

The contamination levels for each vacant and derelict land parcel are highly variable. This includes the possibility of soil contamination and also the presence of legacy structures that may exist above or below the ground level. This presents an investment risk but perhaps also an opportunity for further investigation to determine the specific level of clean up required during the installation of a ground source heat pump system. It is anticipated this would follow a risk-based approach. If remediation is necessary for the installation of a ground source heat pump system on land that is found to be contaminated, an investigation into opportunities that exist to draw down funding associated with contaminated land would be worthwhile. This would be in addition to the Renewable Heat Incentive and would strengthen the case for ground source heat pumps on vacant and derelict land.

This thesis also focuses on the refurbishment of a residential public sector building, specifically a tower block. Focusing on refurbishment is particularly important when two-thirds of the dwellings standing in 2050 are already in existence. However, there are only a handful of studies where ground source heat pump systems have been installed within tower blocks (British Gas, 2013; Oakray, 2016). The nature of these installations will present technical challenges in the above ground HVAC installation, where the use of risers and voids in tower blocks will play a role in delivering heat to individual dwellings. This will require further investigation so financial costs and the technical possibilities for the installation of GSHP systems in these types of buildings can be better understood.

6.2.2 Future Research Opportunities

The results within this research are dependent on a chosen definition of fuel poverty. Social housing was used as a derived indicator where low-income relative to energy bills might be an issue. However, it has been discussed that using other variables within a fuel poverty definition are equally as valid. This is possible because there is no one definition that exists for fuel poverty. Examples of other options for identify the fuel poor could include:

- Incidences of high per capita energy use and low income.
- Areas that score high on deprivation indices, but with low income, or broader uptake of means tested benefits, showing where affordability might be an issue.
- Determining where infrastructure such as gas connections exist, since homes supplied on electricity or oil will be more expensive to heat.

Changes such as these could realise a greater or fewer number of end-users determined as being fuel poor. This will impact on likely hot spots for fuel poverty, and may result in different outcomes both in terms of land availability and the buildings determined as being in close proximity to that land. This represents a clear avenue for future research investigating how changes in the determinants of a fuel poverty definition can increase or decrease fuel poverty incidences, in turn affecting how and where energy systems are deployed.

The driving elements within this thesis also include Government priorities for the direction of renewable heating, the use of vacant and derelict land, and addressing fuel poverty. This thesis attempted to harness all of these elements to form the targeted, integrated approach to renewable heating deployment that has been discussed. The Scottish Government (2014) has identified vacant and derelict land as an 'opportunity' for investment, where new and beneficial uses are needed for this land. Most recently, the Scottish Government (2017) has stated that integrated approaches are required for energy systems going forward, where end-users must be 'at the heart' of these approaches. This calls for local solutions meeting local needs, on an area-by-area basis. However, towards the end of this research, national fuel poverty eradication targets were not met and have been moved from 2016 to 2021. The fight against fuel poverty still exists, and integrating renewable heating in this socio-economic context presents opportunities for future research through investigating how far this is supported in real terms, and across other policy areas not limited to the RHI.

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7. Appendices

7.1 Appendix 1

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Technical Note

Challenges for the Implementation of the Renewable Heat Incentive – An example from a school refurbishment geothermal scheme

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ABSTRACT

The Government run UK Renewable Heat Incentive (RHI) scheme allows cash back payments to be made to producers of renewable heat. As a world first for renewable heat, it aims to tackle head on the issues surrounding emissions, energy use, and climate change targets. However, whilst the scheme goes a long way towards meeting these climate change targets, issues have been identified that may compromise its effectiveness. This paper aims to examine the progress of the RHI since its launch in November 2011, and avenues towards a more effective deployment.

Introduction

Renewable energy and the link to climate change targets is a discussion that today tops the bill across many sectors. The UK Government has a legally binding target of achieving 15% of its energy consumption through renewable means by 2020 [1], as well as reducing greenhouse gas emissions by 34% on 1990 levels [2].

Unfortunately, interim targets so far have not been met – for example, the previous UK Government's target of reducing carbon dioxide emissions by 20% by 2010 was not achieved [3] – which makes meeting 2020 targets across EU Climate Change policies particularly challenging. A cost effective and efficient balance between economic and industrial growth, whilst incorporating a reduction in greenhouse gas emissions, must soon be developed; that is, a transition to a low carbon economy.

Carbon reduction

For carbon dioxide, the greenhouse gas that is most notably attributed as the main human driver behind climate change, the European Commission (EC) is recommending that emissions on 1990 levels be reduced by 25% by 2020, and 40% by 2030, to make the transition to a low carbon economy cost efficient [4]. Taking the UK's groundwork on interim 2010 targets into account, a lot has to be done in this area to make these EC figures a reality.

As of 2010, the UK Government has managed to reduce their own carbon emissions by 14%, however carbon emissions as a whole for the UK grew for the year 2010, then reduced for 2011 [5]. Linked to the recession, the economy showed a moderate recovery for 2010 followed by the recession taking hold again in 2011. This recent downturn in the economy is a good development for reducing carbon emissions, but in the long term provides no certainty for securing a definite reduction in carbon emissions on 1990 levels.

Heating

Of the UK energy usage mix, heating is the single biggest sector in terms of energy consumption, with heating and electricity together forming the biggest sector in terms of carbon emissions [6]. As electricity and heating are so closely linked – that is, we use in part electricity to heat our homes, offices, and industrial spaces, and likewise use electricity to cool them – an approach that considers heating as a critical mass within the energy debate should therefore net a twofold win in meeting climate change targets as we move towards 2020.

Incentive schemes

Feed-In Tariffs (FITs) are already commonplace, where domestic and industrial producers of renewable electricity are paid in part for the electricity that they produce, even if they use it themselves [7]. Other Government programmes such as the Carbon Emissions Reduction Target (CERT) and the Community Energy Saving Programme (CESP) aim to incentivise energy efficiency, reduce carbon emissions, and tackle fuel poverty, and have so far proven to be highly successful in development within these areas [8].

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2213-1388/

By measuring energy produced instead of electricity fed in, heat can also be produced inline with a scheme such as the FITs [9]. It is clear that considering heat within this framework is critical in order to see successful improvements in a sector that requires significant reform if it is to be aligned with emissions targets and the future UK energy portfolio.

The Renewable Heat Incentive

FITs were introduced as part of the Energy Act (2008) and at the same time a provision was also made to allow the Secretary of State to establish a financial support programme for renewable heat – this is known as the Renewable Heat Incentive (RHI) scheme [10].

A world first for renewable heat generation, the Government run RHI scheme aims to tackle head on the issues surrounding the reduction of carbon emissions and meeting climate change targets by incentivising the uptake of renewable heat across the UK. Open to non-domestic applications in December 2011, with the domestic regime to follow in spring 2014, the scheme allows cash back payments to be made to producers of renewable heat, where heat is derived from technologies including solid biomass, ground and water source heat pumps, solar thermal, solid biomass in Municipal Solid Waste (MSW), biogas and biomethane injection [11]. Ultimately, the RHI is aiming to provide a maximum rate of return of 12% on the additional capital costs of installing the renewables to combat investor hurdles [12]. This varies by technology, for example in the case of solar thermal where the rate of return is 6% [13], mirroring installation and deployment costs associated with the specified technology.

The RHI largely has the potential to generate the returns on investment that are required to make many projects viable with payback periods that are satisfactory [14].

Policy and process

Policy and regulations concerning the RHI are managed by the Department of Energy and Climate Change (DECC), with administration for the scheme being handled by the Office of Gas and Electricity Markets (Ofgem) [11]. This builds on Ofgem's successful achievements such as that for the administration of the FITs.

The process of applying for the RHI is twofold. Firstly, the applicant must be the owner of the installation (as defined as eligible by Ofgem), and the installation must be installed prior to the application being submitted [11]. The application is submitted online via Ofgem's website, and is to include details of the installation, commissioning certificates, as well as schematic diagrams. Ofgem will then accredit the installation or enquire further about the nature of the project if clarification is required. If approved, quarterly heat readings are submitted online by the applicant and quarterly payments are received accordingly inline with the RHI tariffs and the amount of renewable heat produced [15].

Initial analysis after implementation

The administration and implementation of the RHI is designed to be straightforward, as anything overly complex is likely to go against the aim of incentivising the uptake of renewable heat. However, there are some issues that may cause confusion as the RHI scheme progresses. The RHI has been received well – as of March 2012, applications amounted to 300 – however only 15 of these had been approved and fully accredited, to allow payments to be made to the applicants (R. Gibson[1], 2012, pers. comm., 20 March). With timescales of 4 weeks claimed for simple systems and 6 weeks for complex systems, for an £860million scheme the rate of accreditation should have been higher. One year on, applications rose to 1710 as of 28th February 2013, with 603 installations fully accredited and having received a payment [16] – a marked increase after an evidently slow start.

An initial performance review however highlights a slight misalignment of the process of obtaining permission and the accreditation for a renewable heat installation. For example, planning permission for certain technologies has to be sought before the RHI is applied for, and before the installation is accredited by Ofgem – but this process is extremely risky for the installation owner as there is no guarantee that their installation will be accredited even after the costly planning application is submitted (M. Drummond[2], 2012, pers. comm., 20 March).

Also, whilst pre-approval for technologies above 200 kW exists, no pre-approval process exists for smaller projects – that is, smaller installations have to be in place before the RHI is applied for, and before the installation is accredited by Ofgem (M. Drummond, 2012, pers. comm., 20 March). This could be seen as a huge risk for smaller project installers in terms of initial costs and no guarantee of receiving the accreditation required in order to receive the RHI payments.

March 2012 also saw DECC issue a consultation on interim cost control for the RHI which would suspend the scheme until the next financial year should the budget of £860million be under threat through application numbers and accreditation rates [17]. At a critical point when the scheme was just initiated, this was an unusual move having the potential to make prospective applicants nervous.

It is evident that these issues may limit the RHI's effectiveness in incentivising the uptake of renewable heat for both small-scale and large-scale producers across the UK. From an environmental aspect, it is also notable that there is no minimum efficiency directive for installations within the RHI, and there are no specific criteria for the calorific value of the fuel to be used (as, for example, in solid biomass facilities that generate heat) (R. Gibson, 2012, pers. comm., 20 March).

Domestic and non-domestic installations

The distinction between domestic installations (which is open for applications as of spring 2014) and non-domestic installations is also not entirely clear within the administration framework of the RHI. Ofgem have stated that the RHI is currently open for applications from the non-domestic sector, however a critical element not fully explored or emphasised by Ofgem is that two or more private dwellings using heat from the one renewable heat facility is currently eligible for RHI payments (R. Gibson, 2012, pers. comm., 20 March). This means that, even though households can currently receive one off payments under the Renewable Heat Premium Payment scheme (RHPP), administered by the Energy Saving Trust to assist in installing renewable heat technologies, many individual private properties may be missing out on the RHI as it currently stands. As the expected deployment date for the RHI scheme in the domestic sector is now spring 2014 after some delays, this is worth considering as multiple domestic installations could be operating, owners could be receiving payments, and movement could be being made towards meeting climate change targets. Given that the cost of installation for any given renewable heat technology can run into many thousands of pounds, with lengthy payback timescales, many community groups and co-operative organisations – that is, those most likely

[1] Ruth Gibson is Technical Development Manager (RHI) at Ofgem, and is involved with administration of the RHI.

[2] Morag Drummond is Senior Manager, Business Operations (RHI) at Ofgem, and is involved with administration of the RHI.

to benefit from renewable heat technologies but who lack the formal business arrangement – may be missing out as well.

Fundamentally, the definition of domestic and non-domestic as supplied by Ofgem is not clear, and may result in many individuals and groups not exploring the RHI until much later in 2014 when the domestic sector is expected to come into force.

A school geothermal heat case study

A project has arisen that is soon to make use of the benefits that the RHI offers, both in terms of environmental and monetary savings, whilst adopting a novel approach to renewable heat. Glasgow City Council, Scotland, is in the advanced stages of a programme to modernise strategic learning establishments, specifically primary, special education needs schools, and pre 5 establishments [18]. Part of this programme has seen the commencement in January 2012 of the refurbishment of a Victorian primary school in Glasgow's West End.

Dowanhill Primary School, built in 1894, has a prime location within the Glasgow West End community. Situated off Byres Road – a main thoroughfare for shoppers and residents and close to Glasgow University, the historic building commands much admiration for the Victorian architecture. As such, Glasgow City Council saw it necessary to modernise, not demolish, at a cost of £9million, whilst staying inline with their development policies [18]. The school will have 14 new classrooms spanning 5 floors, a new extension wing housing nursery facilities and general-purpose areas, and will service a heat requirement of 400 kW.

Ultimately, Glasgow City Councils aims are to create a multi-use, multi-purpose facility (including a nursery and community space) that considers social, economic, and environmental goals, whilst incorporating sustainable architecture and construction into the design and management of the build [18]. It is understood that planning constraints often inhibit the ability to expand into one's own space, so the school is designed with this flexibility in mind whereby modifications and extensions can be completed without adverse environmental and social effects [18].

Geothermal heating and the RHI

The renewable technology element of the project in Glasgow's West End considers a novel approach to renewable heat, not yet applied anywhere in the UK. Two 100 m test boreholes found the school grounds to be preferential to the use of ground source heat – groundwater was present within the bedrock and the thermal conductivity of the boreholes were 75% and 78% higher than anticipated for shale and sandstone [15]. Ground Source Heat Pumps (GSHPs), of reasonable capacity, would therefore be entirely viable. GSHPs connected to eighteen 110 m boreholes laid out in the surrounding car park and adjoining playground are to supply heat for the school in combination with a Combined Heat and Power (CHP) facility [15]. During times of extreme cold, the CHP is to be used to protect the boreholes by sending heat down them if this facility is needed. In displacing the original oil fired boilers, this tandem approach crucially protects the asset, as far as is reasonably practical, from rising energy costs in the future.

GSHPs do however require a relatively small electrical input for their operation. Grid electricity can be considered as poor thermal efficiency energy transfer into electrical energy at the power station, and using this generated electricity for running the GSHPs would not contribute to the lowest possible cost and lowest carbon emissions [15]. Generating onsite electricity, using gas fired CHP, is considered a viable option whereby running costs for the GSHPs and overall emissions are minimised, whilst taking advantage of the lower price for mains gas. Onsite biomass facilities were also

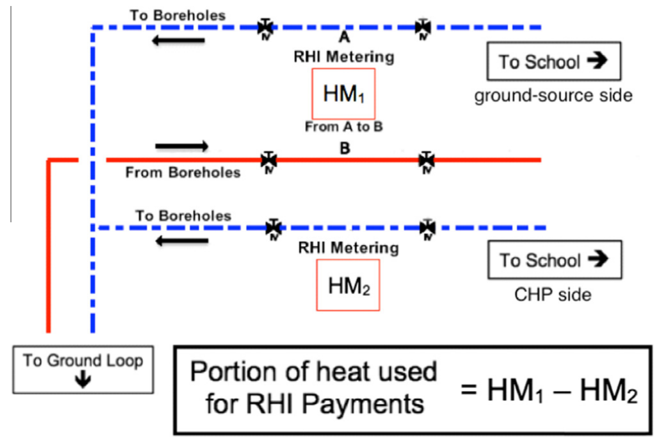

Fig. 1. Layout of RHI meters.

considered, however space constraints and infrastructure issues made this unfeasible. GSHPs provide the viable mechanism to explore this build within the RHI.

The RHI in practice

The RHI is therefore set to form a large part of the school refurbishment project in demonstrating the cost effectiveness and environmental viability of the build. To further support the project, a series of fortnightly mechanical service meetings was arranged by the principal contractor and held on site for the duration of the build, bringing together team members involved in ventilation, sprinklers, heating, controls such as the Building Management System (BMS), as well as plumbing and overall mechanical and electrical matters. Issues and general progress are communicated and discussed between all team members present, ensuring swift work-arounds from problem to solution as and when they arise.

Whilst the mechanical workshops held onsite are successful in identifying problems and maintaining progress, it is revealing to see that the RHI does not fall neatly within the construction phase of the build. The calculations for determining what element of the heat produced is truly renewable are fairly straightforward, as gas fired CHP is not classed as 'renewable'. Ofgem advises that the quantity of heat placed back into the ground, to protect the boreholes, should simply be subtracted from the quantity of heat extracted from the ground, which ensures a minimisation of heat meters (R. Gibson, 2012, pers. comm., 20 March) (Fig. 1).

However, there exists uncertainty for the contractor as to where the heat meters are to be positioned and when the RHI accreditation will be achieved. This is compounded by there existing little to no framework for where the RHI fits within a build, yet it is this crucial incentive scheme that aims to make many projects viable. For this specific project, the RHI meters and metering were a consistent unknown. Quite simply, if the RHI is to succeed, it has to find a recognised and universally accepted place within planning guidelines.

Conclusions

Examining the RHI framework and exploring the options for renewable heat through a real world project, it is apparent that the RHI scheme has some way to go if it is to incentivise the uptake of renewable heat towards meeting climate change targets. Effective implementation of the RHI scheme should take issues, such as planning and accreditation, into account before they cause a hindrance, as more installations come online ready for RHI accreditation. Implementation of renewable heat on a broader scale should also consider universal integration strategies to allow a wider uptake of renewable heat technologies.

Whilst the RHI is clear and transparent within a policy context, at a construction level phase there needs to be a significant improvement in how the RHI is managed and supported in order to fully aid implementation. This could be through more accessible guidance on the RHI for those working on construction sites, or alternatively a broader awareness on the importance of the RHI within an entire project. In many cases, the RHI is, and should be seen as, the crucial component that makes many projects viable.

In a broader sense, the RHI also represents an opportunity to transform the heating market across varying technologies, continual reduction of carbon emissions, and integrated control measures towards a resilient and secure 'future-proof' energy economy. This gives a significant advantage for those willing to innovate, such as in the geothermal refurbishment project in Glasgow. However, if the RHI is not integrated correctly, project success may be compromised, instead hindering the heating market and the technologies that are adopted.

For renewable heat to succeed, innovative projects are crucial to test feasibility and cost, revenue, and also the management of risk. Without pioneering examples, the move towards meeting EU Climate Change targets will be slow – however, for those willing to overcome what may be viewed as risks, significant benefits and valuable experience can be attained. Innovative projects such as that in Glasgow's West End are supported by the RHI, though the lack of clarity in how the RHI is integrated in the build, and how the RHI functions out with policy and in the real world, is not fully supporting the implementation of a scheme that has the potential to transform the heating market.

It could be that it is too early to comment on the RHI giving its lifetime of 20 years – however, when multi-million pound developments can either succeed or fail based on RHI support, issues such as those identified here are shown to be significant, and should be addressed for future renewable heating projects.

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7.2 Appendix 2

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Can brownfield land be reused for ground source heating to alleviate fuel poverty?

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A B S T R A C T

Brownfield land is a legacy of industrial retraction in many towns and cities worldwide, where land remains vacant long after it has gone into disuse, and is often a barrier to redevelopment. Using this land for renewable energy generation is one option that can support development of a low carbon economy and also stimulate regeneration. Fuel poverty is an increasingly pertinent social issue due to rising energy costs. This is particularly true for space heating, accounting for nearly half of all the energy consumed in North European climates. Addressing fuel poverty has become a key consideration in Scotland's internationally leading renewables policy. This article considers how deployment of renewables on brownfield land can be targeted towards addressing heat poverty in social housing. Using Glasgow as a case study, the quantity of available derelict land is calculated, then the spatial association of social housing and urban brownfield land is demonstrated. Technology options for meeting household heat requirements from brownfield land are presented, including scenarios using vertical or horizontal ground source heat pumps. The results suggest that the available urban land could easily supply the needs of all households in fuel poverty, if this scale of investment and non-market intervention was justified.

1. Introduction

The move towards increased renewable energy provision has seen a transformation in the way energy is managed and generated. In the UK, the drive to meet mandated climate change targets [1] as well as regional devolved targets [2] has seen carbon-heavy fossil fuel generation gradually replaced by a greater reliance on dispersed renewables, such as wind technology [3]. Closures of generating facilities up to 2025 [4], as well as stricter UK Government emission controls [5], mean that it is an ever-increasing challenge to develop a strong, secure, and resilient "energyscape" [6] in the move towards a low carbon economy.

How this step change in energy supply and demand is implemented in towns and cities is an important factor in determining what renewable energy options are viable [7]. For example, the rollout of smart meters from 2015 [8], is giving energy suppliers and energy users an unprecedented view of how energy is distributed and consumed, as well as supporting the transformation to "smart" cities [9]. It is important that solutions are also affordable and reflect end-user needs. In particular, when energy costs fluctuate and rise, irrespective of static household income, this can contribute to greater incidences of the growing phenomenon of fuel "poverty" [10], which has serious potential impacts on public health and is a growing consideration in energy policy [11].

Strategies for the built environment [12,13] provide a strong basis for a low carbon economy, but require a diverse portfolio of renewables [13], interconnected flows of information [14], energy affordability and security of supply [12]. Moreover, socially motivated energy provision could also simultaneously serve to enhance other policy and decision-making [15], such as the alleviation of fuel poverty, and the regeneration of socially and economically deprived zones within cities [16]. Here we consider novel ways of reusing "brownfield" land to achieve these ambitions.

1.1. Brownfield land

Due in part to the frequent use of the term "brownfield" in various contexts, a variety of possible definitions exist. According to Alker et al. (2000) brownfield land is "any land or premises which has previously been used or developed and is not currently fully in use, although it may be partially occupied or utilised. It may also be vacant, derelict or contaminated" [17]. For the UK, brownfield land

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is usually synonymous with "previously developed land" which is "land that is or was occupied by a permanent structure and any associated fixed surface infrastructure" [18]. It is anticipated that many such sites are also contaminated [19,20] although minor levels of contamination may not always need remediation, depending on the type of reuse [17]. The definitions used in the UK serve to promote a pragmatic approach to reusing a brownfield site, where contamination may not be present, known or disproved until it is fully investigated. The USA definition presumes contamination, since brownfield land is classed as "real property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant" [21]. Both UK and US definitions serve to show that, following previous use of a brownfield site, contamination may or may not be present, so it can be assumed that some form of investigation and possible remedial action may be required before redevelopment can take place, whether that be simple site clearances or more detailed contaminant remediation.

The potential for contamination can be a disincentive to redevelopment of brownfield land, even with incentive schemes [22], meaning many sites across the UK remain vacant long after they have gone into disuse, in some cases for up to 30 years [23,24]. Due partly to the differing availability of sites across the country, no overall targets were originally set for the regeneration of brownfield land in the UK in the 2012 UK National Planning Policy Framework [25], through which local councils and communities were encouraged instead to assess where is best for local development to occur. In 2016 the concept of brownfield registers was launched as a pilot in 73 council areas in England, with the aim of providing 1 million more homes and having planning permission in place on 90% of suitable brownfield sites [26]. Planning is a devolved issue, however, meaning individual countries within the UK have their own decision-making powers. Furthermore, planning is directed towards sustainable development, so is not only focused on reusing brownfield land, but should include regard to other policy issues.

1.2. Fuel poverty

Boardman (1991) was the first to recognize fuel poverty as an issue, and defined it as "when a household is unable to provide sufficient energy services for 10% of income" [10,27]. This means that when a household is classed as being in fuel poverty they spend a disproportionate percentage of their income on the cost of energy. In this instance energy means all heat and power that is used to constitute a suitable living environment i.e. utility costs for heating, lighting, and general electrical power use, but excluding transport costs. Thus fuel poverty is also inextricably linked to income, energy prices, building fabric or its energy efficiency, and energy use habits.

In Scotland fuel poverty is determined by comparing the cost of household energy against total income available before housing costs [28]. This means that deductions such as council tax, income tax, and national insurance (i.e. local and national taxes, social security charges) come off the available income before it is compared to energy costs, whereas rental or mortgage payments (i.e. housing costs) do not. The Scottish Executive's (2002) use of this definition of income mirrors its application at a national level within Scotland for fuel poverty calculations [29]. Households that fall within the definition of fuel poverty are predicted to experience a standard of living that is unacceptable. This could be in the form of cold, damp, overcrowded rooms, or health effects on individuals that are linked to being fuel poor [27,30].

With so many interrelated factors, locating the fuel poor is also difficult. Social housing has a long history of helping low-income households, traditionally housing vulnerable persons and those that are disadvantaged within society [31]. Here prerequisites such as low income will serve to compound incidences of fuel poverty. Although fuel poverty is also found in privately rented/owned properties, this sector is more difficult to evaluate due to the mixture of rental and owner-occupiers in many private housing estates and apartment buildings.

Fuel poverty is not solely a UK phenomenon, but is now on the agenda in other parts of the world, although here the focus may be on broader energy poverty or simply low household income [32]. Such is the current concern in the UK that the Government and devolved administrations had set a target to eradicate fuel poverty, as far as was reasonably practicable, by 2016 (2018 for Wales) [33]. The target for 2016 was not met.

The seriousness of fuel poverty cannot be overlooked. For England alone, it is estimated that cold related ill-health costs the National Health Service £1.36 billion per year [34,35]. The human cost of this is an estimated 26,700 excess winter deaths every year [27]. It is also estimated that people spend a higher proportion of the day at home than away from it [27]. Targeting space heating for the poorest households makes many of these adverse consequences preventable, being a direct result of low household incomes and/or poor building energy efficiency.

Whilst household income can be increased through accessing government benefits (where eligible), there is no support that directly helps with the costs of fuel [27]. With energy prices rising faster than income levels for the poorest households [36], the provision of low-cost renewable energy for space heating is a strategic opportunity to address public health and the impacts on healthcare systems caused by fuel poverty.

1.3. Reusing brownfield land for energy provision

It is possible that reusing brownfield land partly as an energy resource during regeneration and local development could provide low-cost energy to help alleviate fuel poverty. To determine whether this integrated approach has the ability to simultaneously meet brownfield land regeneration and fuel poverty intentions, the availability and energy potential of brownfield land in proximity to energy users must be considered. In moderate climates, such as the UK, space heating accounts for more than 50% of total energy consumption [37] in the domestic sector. If appropriate renewables are directed towards brownfield land, such as heat pumps or locally used biomass, there is the potential for large gains to be achieved in carbon reduction, as well as assisting individuals with lower heating costs. Thus two socio-economic issues could be addressed simultaneously with wider positive impacts for society [38].

The consideration of environmental factors such as land condition within the fuel poverty debate could also serve to mitigate a lesser-known relationship between land quality and public health. Morrison et al. (2014) have shown that the chemical quality of soil is spatially linked with deprivation, being higher in deprived areas, specifically in Glasgow [39]. For England, Bambra et al. (2014) have shown a significant relationship between brownfield land intensity and morbidity [40]. Together, land condition is shown to have an important, often overlooked, contribution to public health.

The aim of this paper is to identify the quantity of land that could be available for the provision of renewable energy for heating using Glasgow (Scotland) as an example, to determine its distribution and how it could be used for ground source heat pumps as part of an integrated approach to reusing brownfield sites.

2. Methodology

In order to quantify the brownfield land available for energy provision in Scotland, all known existing data on vacant and derelict land areas was obtained and combined as follows.

2.1. Vacant and derelict land

In the Scottish Vacant and Derelict Land Survey (SVDLS), the Scottish Government (2014) defines vacant land as "land which is unused for the purposes it is held and suitable for development", and derelict land as "land which is damaged and requires significant rehabilitation before reuse" [24]. Thus both vacant and derelict land identified in the SVDLS fall under previously developed or brownfield land according to the UK definitions, where land is classified into five main categories within the National Land Use Database [41]:

- Previously developed land, now vacant
- Vacant buildings
- Derelict land and buildings
- Previously developed land or buildings currently in use and allocated in local plan or with planning permission
- Previously developed land or buildings currently in use with redevelopment potential, but no planning allocation or permission

The SVDLS exists to record progress on land reuse within Scotland, where Local Authorities report data to the Scottish Government directly [24]. Following the demise of the National Land Use Database (NLUD) for England (the most recent update being in 2010), the SVDLS is the most complete and accurate data that exists in determining land availability for renewable heating. Updated annually, the database provides a range of information on vacant sites, including derelict sites and contaminated sites [42]. The database is also freely available online, providing straightforward access to up to date data (http://data.gov.uk/dataset/scottish_vacant_and_derelict_land_survey).

2.2. Landfill sites

Landfill sites represent a land type that is not normally considered within the regeneration framework for vacant and derelict land, since planning conditions typically specify restoration to an appropriate end use, such as agricultural, ecological, recreational, or woodland [43]. These sites may have areas of several 10s of hectares, so are relatively large compared to most brownfield sites, with locations on the outskirts of towns and cities [44]. They are normally unavailable for use and cannot easily be redeveloped with buildings for many years due to landfill gas, and instability. Many will already have grid connections by virtue of existing landfill gas generation. As such, a considerable opportunity exists to develop these landfill sites further for renewable energy generation.

2.2.1. Current or closed SEPA licensed landfills

The Landfill Sites and Capacities Report, available freely from the Scottish Environmental Protection Agency (SEPA), provides up to date data on active or closed landfill sites, those under restoration and sites associated with waste such as waste transfer stations and waste holding facilities in Scotland licensed since its creation in 1996 [45]. Landfills are recorded in terms of deposited or available waste volume, whereas vacant and derelict land is recorded in terms of area, meaning that comparison between the two data sets requires further information. The number of licensed landfill sites (364) is limited when compared to the larger number of historic landfill sites (1053 found in this study) or to derelict and vacant sites recorded in the SVDLS (4053).

2.2.2. Historical landfill sites

Data for historic unlicensed former landfill sites or those with licenses held by local authorities before SEPA's creation is not held centrally but by the individual local councils concerned. Accordingly, all 32 of the Local Authorities within Scotland were contacted in January 2013 in order to obtain known data such as site areas and grid coordinates of current and historical landfill sites. This was requested under the Freedom of Information Act (2000), which has within it a provision that allows local government data to be requested freely by members of the public, or under the Environmental Information Regulations (2004), a similar process but applicable to environmental queries that may incur a charge. Both types of request included:

- Site location i.e. address, National Grid Reference
- The total area (in ha) of the landfill sites
- The present status of each landfill site (whether it is active, closed or capped)
- The type of waste landfilled (if known)
- GIS data layer(s) showing site boundaries (if available)

Responses were combined with the Landfill Sites and Capacities Report data. It was anticipated that responses would include sites already listed on the Landfill Sites and Capacities Report, together with additional historical sites. The area of each site, grid reference and whether the response originated from SEPA and/or the local authority allowed for checks on duplication or inconsistencies between data from different sources.

2.3. Estimating site areas

Where site areas were reported as unknown, these were estimated using polygons with a GIS using aerial mapping and either basic site address information or, preferably, grid reference coordinates. Features used for visual identification of former landfill site areas included:

- Evidence of made ground or void filling
- Changes in landform or vegetation over time (Fig. 1)
- Site boundaries, fences or bordering land
- Absence of current land use, such as for livestock or crops

2.4. Data processing

The data on landfill site areas from local authority responses and estimated site areas was combined with the vacant and derelict site data from the SVDLS to include:

- Site address
- Site Area (and whether estimated or actual)
- Grid reference

Grid references provided a means to check for sites that may appear on both lists, as it was anticipated that some historic landfill sites known to councils (for example in-filled quarries) could also appear on the SVDLS.

The potential for renewables was then estimated using the total figures for vacant and derelict land and landfill sites in Scotland. As the focus was on renewable heating options, ground source heat pumps were selected as a technology option using the Glasgow City Council area as a case study.

The geographical distribution of brownfield land and social housing was then compared for Glasgow. Social housing per capita was calculated using available population data [46] and housing

Fig. 1. Example of changes in a landfill site appearance over time.
Source: http://earth.google.co.uk (left) & http://maps.bing.co.uk (right)

data [47] for each electoral ward. This was then compared to the percentage of the electoral ward area classed as vacant and derelict land, using electoral ward geographical shape files [48] and vacant and derelict land data [24]. This mirrored the approach taken by Bambra et al. (2014) of comparing health indicators by ward to vacant and derelict land area [40]. The wards were ranked separately by the number of social housing units and by the quantity of vacant and derelict land, classified into upper and lower quartiles to indicate relative intensity, then compared to assess any geographical coincidence.

3. Calculations

In order to determine the potential heat delivered by ground source heat pump systems on brownfield land under different scenarios, including the quantity of land required, the following estimates were made. A typical domestic heat load and heat pump unit capacity of $8kW_t$ was assumed [49], assuming a (conservative) coefficient of performance (COP) of between 3 and 4 [49,50], and an (again conservative) energy yield for a horizontal collector system of $15W_g.m^{-2}$ [49,50]. Hence,

$$\text{Electrical Power Input to GSHP} = \text{Useful Heat Output/COP} = 8\text{ kWt}/3.3 = 2.4\text{ kWe} \quad (1)$$

and

$$\text{Energy provided by ground source} = \text{Useful Heat Output} - \text{Electrical Power Input} = 8\text{ kWt} - 2.4\text{ kWe} = 5.6\text{ kWg (5600W)} \quad (2)$$

$$\text{Collector size per unit} = \text{Ground Source Energy/energy yield} = 5600/15 = 373\text{ m}^2 \quad (3)$$

And

$$\text{Collector size per unit including 20\% buffer} = 373 \times 1.2 = 448\text{m}^2 \quad (4)$$

For vertical GSH boreholes an energy yield of 40 W.m [49,50] can be used resulting in a smaller collector size footprint to meet the same domestic heat load at an increased cost. The footprint of a vertical borehole is approximately 1 m^2 but to avoid interference between boreholes a spacing of 6–10 m is required, giving an effective footprint of 36–100 m^2 [49,53].

4. Results

4.1. Non-agricultural land in Scotland

Table 1 shows comparative results for licenced landfills and historical landfill sites derived from SEPA and Local Authority data respectively. Land areas were provided for 895 sites and estimated for 329. The areas of 193 (14%) remain unknown so are not yet included in the areas shown. No response was received from 1 local authority.

Roughly three times as many historic sites have been identified as exist on SEPA's landfill capacities report. This adds an additional area of 3171 ha so is nearly the same quantity of land again (77.14%) as is currently listed on the Landfill Sites and Capacities Report, a near doubling of the capacity that could be available for energy uses. Together with the 11,114 ha of recorded vacant and derelict land for Scotland included in the SVDLS for 2013, the estimated total area of available non-agricultural land is 18,395 ha. Thus landfills add an additional landbank equivalent to 66% of the V&D L area. In both cases, the land in question is largely open or vacant, and so could potentially be used for the provision of renewable energy including the provision of low-cost renewable heating.

4.2. Potential of brownfield land to meet heat demand in glasgow

The Glasgow area contains the greatest concentration of vacant and derelict land in Scotland [24] where it totals 1195 ha represented by 863 sites. To this our study has added 367 ha from 50 licensed and unlicensed landfills. Together these make up nearly 9% of the city area. In Glasgow an estimated 93,000 households are in fuel poverty [28] of which 35,000 may be at high risk [51]. Taking an average household size of 92 m^2 [52] a peak heat energy demand of $8kW_t$ can be assumed. Using these figures the potential contribution from non-agricultural land can be estimated (Table 2).

In a scenario using all available brownfield land, horizontal array ground source heat pumps are shown to potentially meet the full peak heat demand of 34,866 properties. If only 80% of the peak heat demand is to be met, as is typical in optimising such designs [54], the size of this figure increases to 43,754 properties, nearly half of the total in fuel poverty. Indicative figures for more costly vertical

Table 1
Landfill data including historical landfill sites.

Landfill type/data source	Number of sites	Minimum area in hectares	
		Estimated	Provided
Licenced sites recorded as per SEPA list	364	2786	1324
Unlicensed/historic sites (recorded by Local Authority[a])	1053	371	2800
		3157	4124
Total	1417	7281	

[a] Percentage response rate from Scottish Local Authorities 97%.

Table 2
Potential brownfield heat yield for Glasgow, Scotland.

Technology Option (scenario)	Maximum ground sourced energy yield per square metre of collector area	Land used per household		Number of households supplied	
		(a) for 100% of heat demand	(b) for 80% of heat demand	(a) for 100% of heat demand	(b) for 80% of heat demand
GSHPs (horizontal array, using all land)	15 $W.m^{-2}$	$448m^2$	$357m^2$	34,866	43,754
GSHPs (vertical borehole, 1 per site, 1 borehole per dwelling)	0.33 $W.m^{-2}$	$1m^2$[a] ($100m^2$)	$1m^2$[a] ($100m^2$)	913	913
GSHPs (vertical borehole, 10 per hectare, 1 borehole per dwelling)	5.6 $W.m^{-2}$	$1m^2$[a] ($100m^2$)	$1m^2$[a] ($100m^2$)	15,620	15,620
GSHPs (vertical borehole, 100 per hectare, 1 borehole per dwelling)	56 $W.m^{-2}$	$1m^2$[a] ($100m^2$)	$1m^2$[a] ($100m^2$)	156,200	156,200

[a] Actual footprint. For a site with multiple boreholes, a spacing of between 6 and 10 m (i.e. 36–100 m^2) is required to avoid thermal interference [49,53] which reduces the energy yield per square metre and increases the effective footprint to 100 m^2. Borehole lengths are calculated at 140 m to meet 100% of a households heat demand, and 112 m to meet 80% of a households heat demand.

borehole ground source heat pumps (either 1 per site or 10 per hectare across each site) gives a decreased footprint per property. With a higher density approaching the minimum spacing (100 per hectare) the entire domestic heat load of fuel poor properties could be easily met. Where larger heat pumps are deployed to supply multiple properties, it is anticipated that economies of scale would make this advantageous [55] together with a more efficient use of the available land. Systems supplying multiple domestic units would also qualify for the Renewable Heat Incentive (RHI), a UK Government cash back payment made to producers of renewable heat [56].

4.3. Brownfield land as an energy resource for social housing

The relationship between brownfield land availability and social housing availability for Glasgow is shown in Fig. 2 where the number of social housing units per capita [46,47] is plotted against brownfield land per electoral ward (this study) [24,48].

Although there are two obvious outliers for the highest amounts of brownfield land and social housing respectively there is a moderately strong positive correlation between the intensity of social housing provision and brownfield land availability ($r^2 = 0.51$). This association is also illustrated in the distribution of the housing stock of the largest housing association within Glasgow (totaling 62,566 properties [57]) which compares well with that of the vacant and derelict land data from the SVDLS (Fig. 3).

5. Discussion

5.1. Targeting fuel poverty through brownfield land reuse

The spatial association of social housing and vacant urban brownfield land in Glasgow suggests that there is an opportunity to use this potential resource to address heat poverty. Meeting the heat demands of multi-occupier residential buildings through investment in ground source systems could provide renewable heating to those that may be fuel poor or more vulnerable through health or income inequalities, thus positively reinforcing the benefits of social housing provision [15]. It is widely accepted that three main variables contribute to fuel poverty, individually or in combination: household income, the energy efficiency of the property, and the energy costs required to provide an adequate standard of living for the household [10,26], with heating playing a major role compared to power. Having the ability to control end-user energy costs per unit of heat by operating a renewable heating installation can also serve to mitigate the potential for fuel poverty in the face of rising energy bills. Thus, directing renewable heating solutions in this way towards households with low income, high energy bills, and low energy efficiency provides a starting point from which to alleviate fuel poverty.

5.2. Fuel poverty mapping

As the fuel poverty definition is exacerbated by low income and high energy bills, combining these two indicators in a Geographical Information Systems (GIS) could provide the basis of a fuel poverty

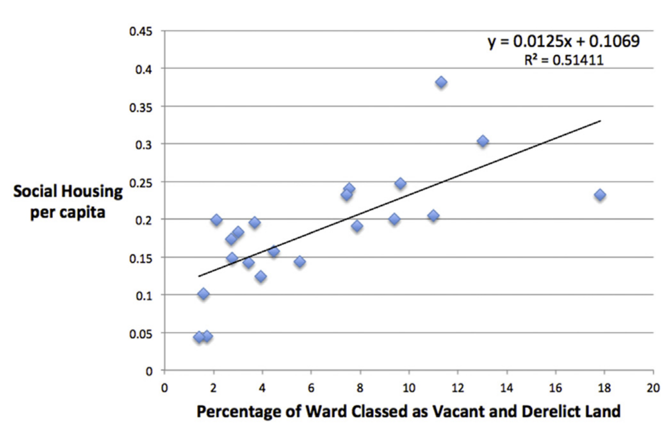

Fig. 2. Social Housing and the relationship to Brownfield Land.

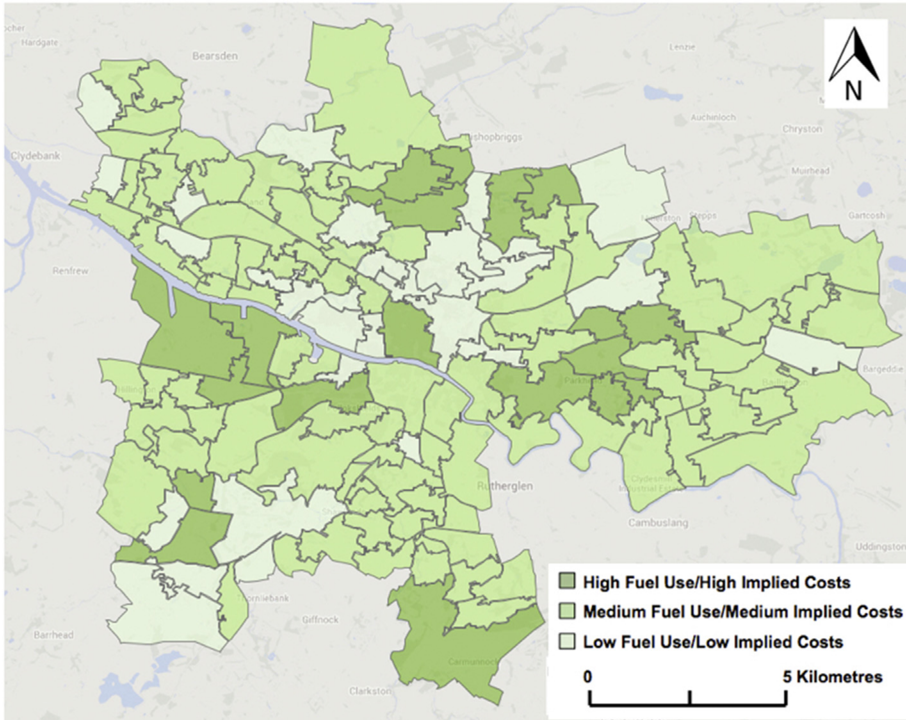

Fig. 3. Fuel use Map for Glasgow, Scotland.
Source: http://www.glasgow.gov.uk

map. However, data on household income and energy bills is incomplete and not recorded to a sufficient resolution. For example, DECC (2014) records per capita gas and electricity use at an intermediate zone level, where each zone contains on average 4000 households [58]. Focusing on income and energy bills alone also removes the causal effect of the building fabric, age and type which are attributes that contribute indirectly to fuel poverty through determining that building's, energy demands and heat loss characteristics.

Examples of possible fuel poverty mapping approaches could include:

- Identifying incidences of high per capita energy use and low income.
- Choosing areas that score high on deprivation indices, but with low income, or broader uptake of means tested benefits, showing where affordability might be an issue.
- Mapping other infrastructure such as gas connections, since electricity or oil will be more expensive alternative fuels.

Fig. 4 shows an example of a fuel poverty map completed by Glasgow City Council for the IBM Smart Cities challenge (J. Arnott 2013, pers. comm., 25 March), where fuel use has been compared to deprivation data to identify areas where high fuel use and implied costs occur in deprived areas. Note that it does not use actual energy costs per household, but instead assumes that high energy use is an indicator of high energy bills.

The numerous variables involved mean that fuel poverty mapping outputs vary, without necessarily being incorrect or invalid. For example, simply mapping deprivation levels or income, rather than high energy use relative to income, could exclude those experiencing fuel poverty through poor building fabric. What is also clear is that fuel poverty is dynamic, and as householders approach this point, self-regulation of energy use can mean actual incidences are avoided. This keeps many householders out of fuel poverty statistics according to the strict definition, even though had they used all of the energy needed to maintain a suitable living environment, their energy costs would indeed have exceed the 10% threshold. The consequences for living standards and health implications are still clearly unacceptable. Fuel poverty is thus a challenging and complex issue with many contributory factors, and as such, no one definitive fuel poverty mapping approach has yet been agreed (J. Arnott 2013, pers. Comm., 25 March).

5.3. Deployment opportunities through social housing

The nature of social housing means that it potentially supports large-scale rollout of communal heating systems by providing access to one landlord who can speak on behalf of many tenants. Social housing is provided for low-income households who cannot compete in the normal market place [59]. This suggests a type of housing where low income relative to energy bills, might be an issue. Examining the distribution of social housing provides a method whereby opportunities to address heat poverty can be identified.

Although the distributions are not quite identical, social housing as a market for heating energy is found clustered around vacant and derelict land (Fig. 3). This represents an opportunity to tackle fuel poverty by retrofitting existing social housing with communal heating schemes as part of area-level regeneration accompanying low energy new development with potential public health benefits from the resulting reduction of brownfield land [40]. Mapping electoral wards which are in both the upper quartile for social housing provision and for vacant and derelict land (Fig. 5) provides an alternative method of identifying geographical areas in which heat poverty is likely and opportunities exist to address it.

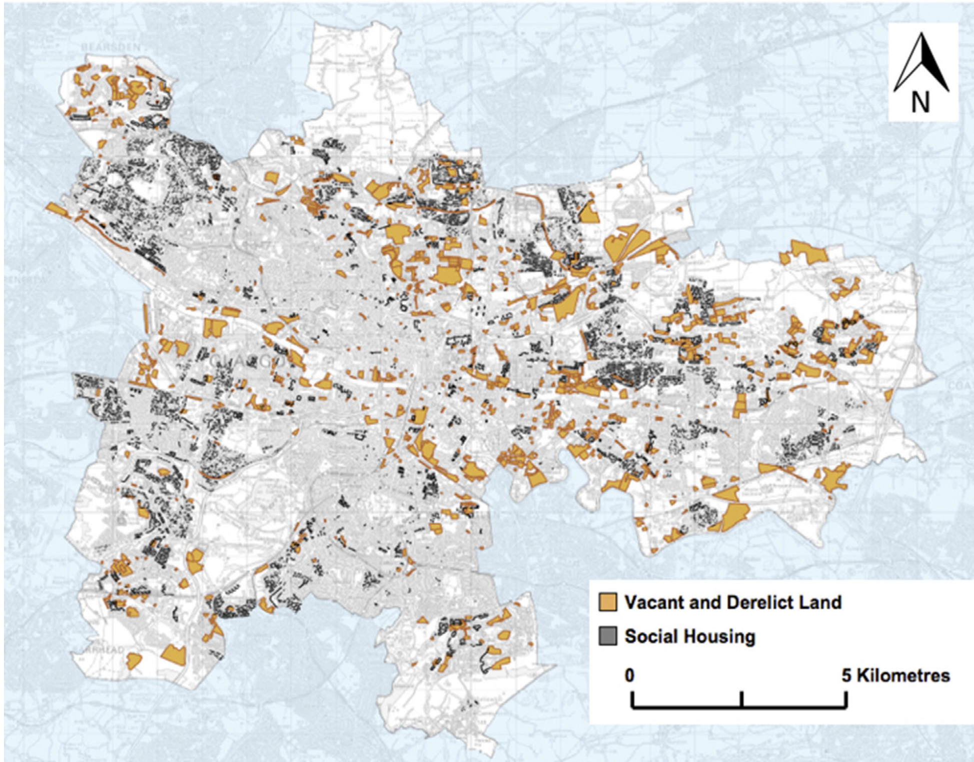

Fig. 4. Vacant & Derelict Land and Social Housing distribution in Glasgow, Scotland.
Sources: http://www.glasgow.gov.uk (V&D Land Layer) & http://www.gha.org.uk (housing layer)

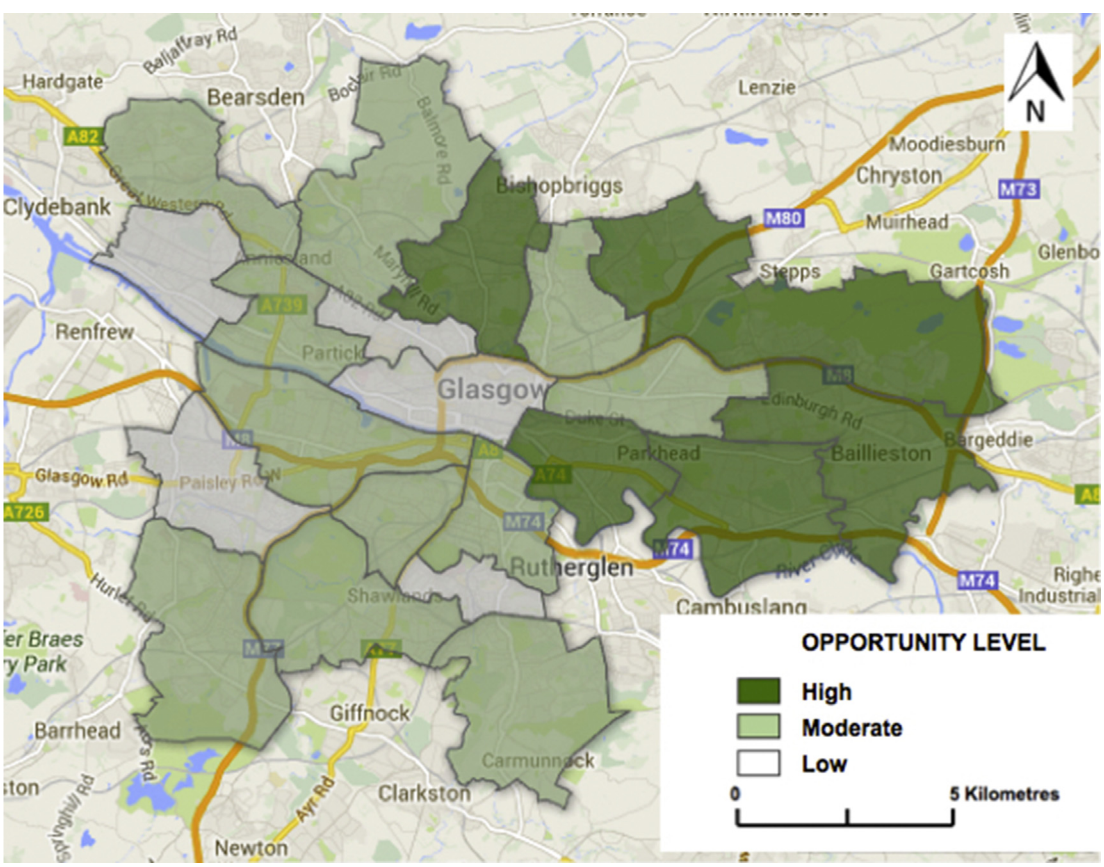

Fig. 5. Social Housing and Vacant & Derelict Land Intensity by electoral ward, Glasgow, Scotland.

Table 3
Comparative uses for brownfield land.

Proposed action or landuse	Energy yield	Features	Advantages or opportunities	Disadvantages or constraints	References
Do nothing	Zero	- Landuse unchanged.	- No investment required.	- Land remains brownfield, vacant or derelict. - No added value, incentive for future development, or contribution to regeneration needs. - Site remains a potential liability until investigated fully and or remediated.	[64,65]
Reuse for public open space, green space, amenity etc.	Zero (or minimal from harvested biomass arisings)	- Land used for urban greenspace e.g. park or semi-natural area.	- Improved aesthetic or visual character. - Improved public access to green space may also improve public health. - Can also contribute to local area regeneration and improved eco-system service delivery. - Minimal investment in site investigation and or remediation required, compared to "hard" redevelopment for more sensitive landuses. - Opportunity to address contamination, e.g. by capping, or to use "gentle" remediation methods.	- Possibility of contamination may limit suitability for current or future use. - No revenue stream created, capital value unchanged, so requires grant aid for funding improvements.	[66–75]
Redevelop for commercial, industrial or housing use	Possibility for limited embedded generation (e.g. roof top solar thermal or PV, ground source heating/cooling etc) depending on end use	- Requires detailed site investigation, planning approval, remediation to render site "suitable for use" if found to be contaminated.	- Visual appeal increased but ecosystem service provision may be reduced. - Can contribute to local area regeneration and any contamination is investigated and mitigated. - Opportunity to provide low-cost, energy efficient housing that meets current performance standards for comfort or efficiency, for sale or rental to meet market needs. - Capital value realised or revenue stream created, so may be self-funded as viable economic activity.	- Potential for contamination, liability, cost of remediation or project delay may deter investors. - Significant investment required, likely long term commitment. - Additional housing does not necessarily benefit existing community. - Cost of remediation may outweigh economic value of cleaned site, so remains derelict.	[42,65,66, 76–79]
Redevelop for energy generation	Varied - see below	- Permanent reuse for energy, or temporary reuse ahead of development.	- Can deliver local, secure renewable energy, meeting Government strategies for use of renewables and energy security, with limited transmission losses if used locally. - Renewables are efficient and effective solutions. - Can contribute to local area regeneration. - Revenue stream created. - Can be used to create wider community benefits, either as community benefit fund or by subsidizing household energy costs. - Opportunity to integrate energy service provision with some eco-system service delivery.	- Likelihood of contamination may highlight liability concerns for developer, however if no public use then concerns should be low. - Significant investment required, likely mid to long term commitment. - Limited renewable options if considering technologies for heating.	[65,80–84]
- Solar Water Heating	50 W m^{-2} [89]	- Water heated via sunlight using a solar collector, then transferred to the building using a small electrical input.	- Classed as renewable so eligible for UK Government subsidy. - Could limit exposure to rising energy prices by offsetting some gas or electricity use. - Can be mounted on rooftops, however such installations	- Solar is at its weakest at times of high heat demand (winter), so supplementary heating system is needed. - Solar arrays would fully occupy the available land so sterilises future redevelopment. - Requirements to mitigate against vandalism (important if located on	[85–90]

(continued on next page)

Table 3 (*continued*)

Proposed action or landuse	Energy yield	Features	Advantages or opportunities	Disadvantages or constraints	References
			would not assist brownfield land redevelopment.	ground) and allowances for required maintenance.	
- Solar PV	11 W m^{-2} [89]	- Electricity created via sunlight using PV cells.	- Classed as renewable so eligible for UK Government subsidy. - Could limit exposure to rising energy prices by offsetting some or all electricity use. - Can be ground mounted instead of on rooftops, however such installations would not assist brownfield land redevelopment.	- - Solar is at its weakest at times of high lighting electricity demand (evenings & dark winter periods), so a supplementary electricity system may be needed.Solar arrays would fully occupy the available land so sterilises future redevelopment. - Requirements to mitigate against vandalism (important if located on ground) and allowances for required maintenance.	[85–89,91]
- Biomass	c.0.3 W m^{-2} (97 GJ $ha^{-1}.a^{-1}$) [a]	- Biomass cultivated on site, then harvested for combustion in furnace to generate heat, or fermented to biogas for heating.	- Classed as renewable so eligible for UK Government subsidy. - Could limit exposure to rising energy prices by substituting for gas or electricity use. - Could be used to supply district heating systems using biomass. - Could be used to provide greenspace, visual improvement and ecosystem services.	- Biomass material is normally processed at an offsite facility so transport losses are incurred. - Often used for grid generation, so then offers developer little direct benefit. - Seasonal growth so may require storage.	[87,90,92]
- Heat Pumps	Scenario (a) horizontal arrays: 15 W m^{-2}. Scenario (b) vertical well spacing 10m: 56 W m^{-2} [b]	- Heat pump systems use the thermal energy in the ground to heat water for space heating and for use as domestic hot water.	- Classed as renewable so eligible for UK Government subsidy. - Limits exposure to rising energy prices compared to all electric or all gas heating systems. - Little or no visual impact or footprint so land could be further developed after installation if vertical systems used.	- GSHPs require below ground excavation which increases costs. - Technical expertise is limited but growing. - Future landuse is sterilised if horizontal arrays used.	[90,93–95]

[a] Calculated from gross energy yield of harvestable reed canarygrass grown on brownfield land in N England [63]. Ignores effects of water content on calorific value, energy inputs for harvesting, and losses from efficiency of boiler system.

[b] Gross heat output from heat pump including contribution from electrical power at an assumed coefficient of performance of 3.3, per square metre of land area based on 10m well spacing (this study).

5.4. Challenges and future work

Perhaps the greatest challenges in reusing brownfield land to alleviate fuel poverty come from the inherent nature of the land itself: Vacant and derelict land is not currently in use, implying that it is not currently needed, or perhaps not economically viable, for development. This lack of value can stem simply from the geographical location, or may be the effect of the potential cost of remediation; The potential presence of contamination and need for remediation is inherent in the various definitions of brownfield land [17,18,21], so there is a risk that the net value after the necessary treatment is completed could be negative. Without the financial incentives of development as a trigger, detailed site investigation to accurately constrain this risk may be unaffordable. Furthermore, in a risk-based approach to contaminated land management, such as that operating in the UK, the extent of remediation required to ensure "suitability for use" is dependent on having an identified end use. Moreover, additional precautions would be needed during installation on a potentially contaminated site, to include protecting personnel from exposure, preventing further dispersion by correct disposal of excavated spoil from burial of horizontal arrays, and preventing cross contamination of groundwater *via* pathways created along vertical boreholes; Previously-developed land may well retain ground obstacles derived from earlier structures, such as concrete floor slabs or foundations; Likewise, the definition of dereliction [24] implies a cost for corrective measures to rehabilitate and to address damage; Former landfilled areas will contain heterogeneous wastes with unknown properties, potential for contamination, gas or leachate generation; In more recent licensed landfills these could include a variety of engineered features, such as clay or geotextile liners, capping layers, gas or leachate collection pipework [60], although these might also offer a way to exploit the enhanced temperatures generated by decomposition of biodegradable wastes [61]; In urban areas the spacing of wells and hydrogeological conditions may further limit the performance and sustainability of ground source heating systems [62]. Other options for for reusing brownfield land are compared in Table 3. This illustrates the greater potential energy yield when used for ground source heating, with vertical systems still offering flexibility for future redevelopment.

A number of additional technical challenges might arise during the deployment of ground source heat pump systems on brownfield sites due to their history and possible ground conditions. Developers may also find other options more suitable by comparing the respective benefits or constraints (Table 3). Many of the technical challenges are directly analogous to the issues identified for the reuse of the various types of derelict, underutilised and neglected land for bioenergy [63] for which successful trials have been completed. For ground source heat pumps, future work should focus on similar demonstration projects to confirm the actual energy yields and so test the economic viability and societal benefits of using ground source heating arrays on derelict land adjacent to social housing units.

6. Conclusions

Historic, unlicensed landfill sites are shown to increase the total residual landfill area within Scotland by more than 75% to 7,281ha. Together with vacant and derelict land, a total of 18,395 ha is available which could potentially be used for the deployment of renewables. Although representing less than a quarter of one percent of the total land area of Scotland, much of this potential resource is situated close to urban centres of heat demand.

Using ground source heat pumps on all vacant and derelict land as a renewable heating technology option for 80% of a property's peak averaged heat demand for Glasgow, Scotland could serve to heat 43,754 properties or 47% of those estimated to be in fuel poverty. This is a 'worst case scenario', based on horizontal arrays where all available vacant and derelict land is used. Using higher cost vertical boreholes instead would increase this figure greatly due to the decreased technology footprint and increased energy yield. Hypothetically, the demands of all properties in heat poverty could be met, however it is necessary for a balance to be drawn between installation costs, the technology footprint, and the number of properties whose heat demand could be met, to provide the most cost effective, sustainable solution.

A correlation between urban brownfield land and social housing, suggests these are appropriate targets for deploying and utilizing ground sourced heating. Social housing provision also reflects areas of low income and associated deprivation, so can be used as a proxy for fuel poverty. Relative concentrations of social housing and brownfield land by electoral ward areas give a means of identifying zones of opportunity.

Examining a city such as Glasgow illustrates the complex legacy of former industry, such as proximity to vacant or derelict land and the prevalence of poor health in the most deprived communities, but has helped to identify solutions that could be applied across other towns and cities. It is clear that using brownfield land to provide ground source heating for social housing has the potential to contribute to alleviating fuel poverty as well as bringing significant opportunities for the restoration and reuse of vacant and derelict land.

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