Renewable Energy 116 (2018) 344–355

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

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

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A R T I C L E I N F O

Article history:
Received 4 August 2015
Received in revised form
26 February 2017
Accepted 10 September 2017
Available online 15 September 2017

Keywords:
Brownfield land
Fuel poverty
Social housing
Geothermal
Ground source heat pumps

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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https://doi.org/10.1016/j.renene.2017.09.037

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,

$$\begin{aligned}\text{Electrical Power Input to GSHP} &= \text{Useful Heat Output/COP}\\ &= 8\ \text{kWt}/3.3 = 2.4\ \text{kWe}\end{aligned} \tag{1}$$

and

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

$$\begin{aligned}\text{Collector size per unit} &= \text{Ground Source Energy/energy yield}\\ &= 5600/15 = 373\ \text{m}^2\end{aligned} \tag{3}$$

And

$$\begin{aligned}&\text{Collector size per unit including 20\% buffer} = 373 \times 1.2\\ &\quad= 448\text{m}^2\end{aligned} \tag{4}$$

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

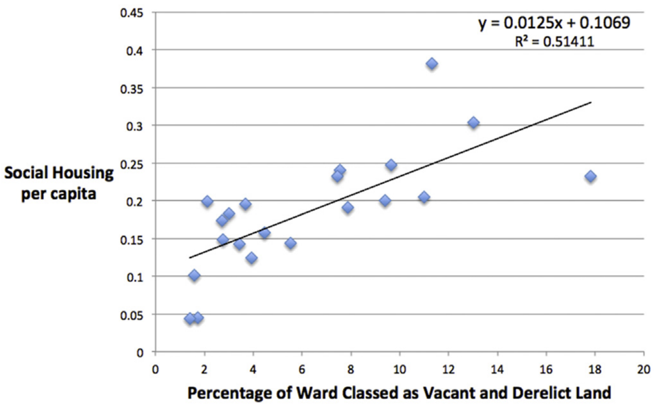

Fig. 2. Social Housing and the relationship to Brownfield Land.

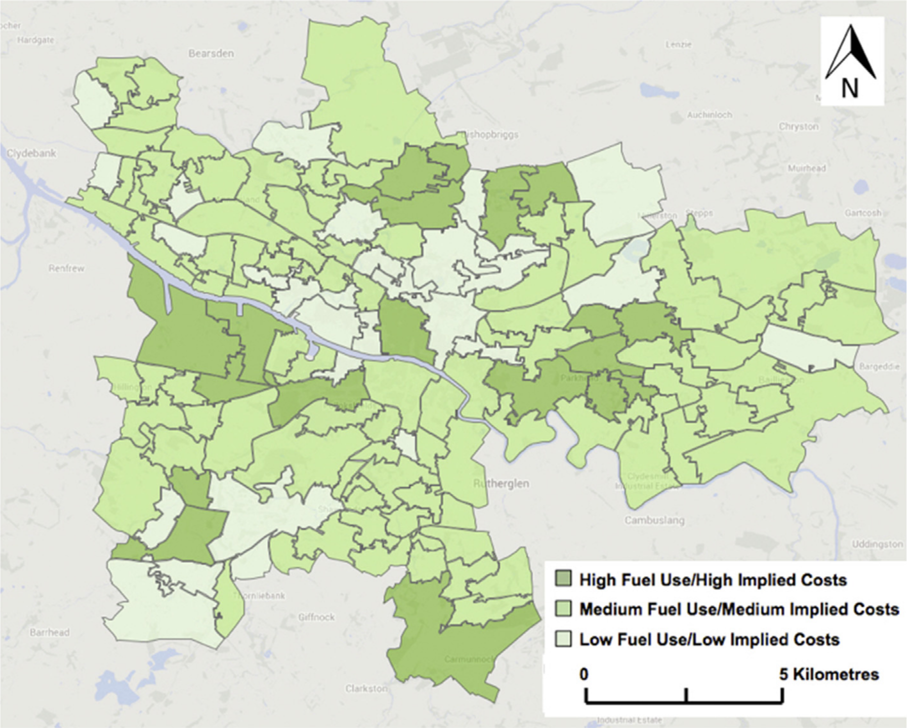

Fig. 3. Fuel use Map for Glasgow, Scotland.
Source: http://www.glasgow.gov.uk

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.

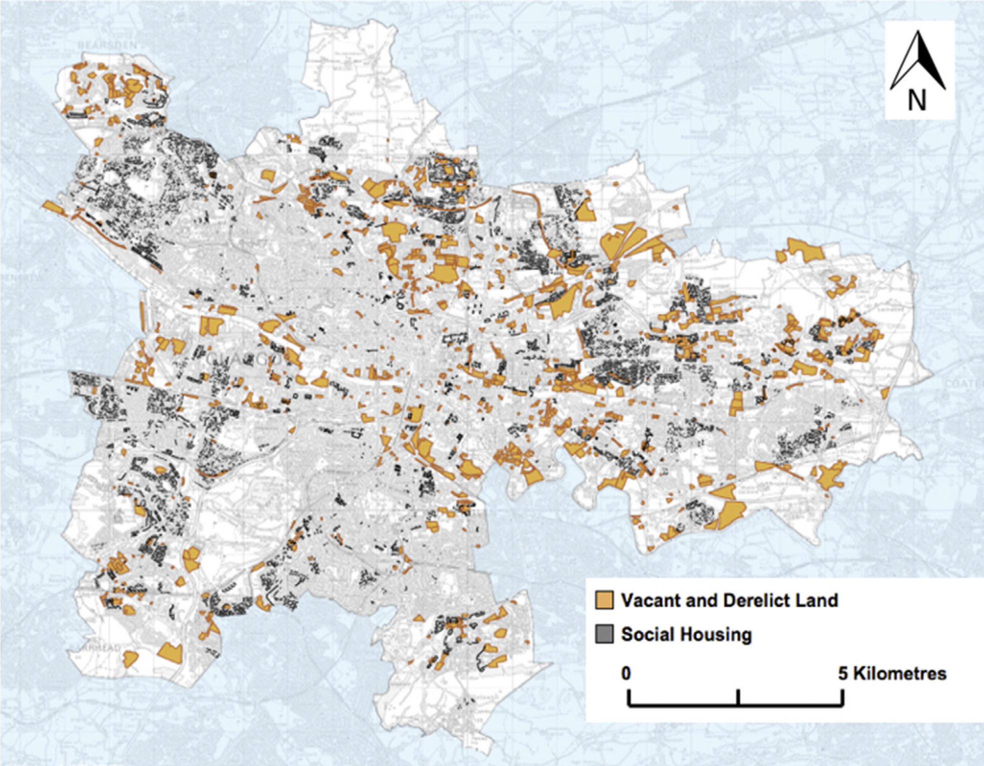

Fig. 4. Vacant & Derelict Land and Social Housing distribution in Glasgow, Scotland.
Sources: http://www.glasgow.gov.uk (V&D Land Layer) & http://www.gha.org.uk (housing layer)

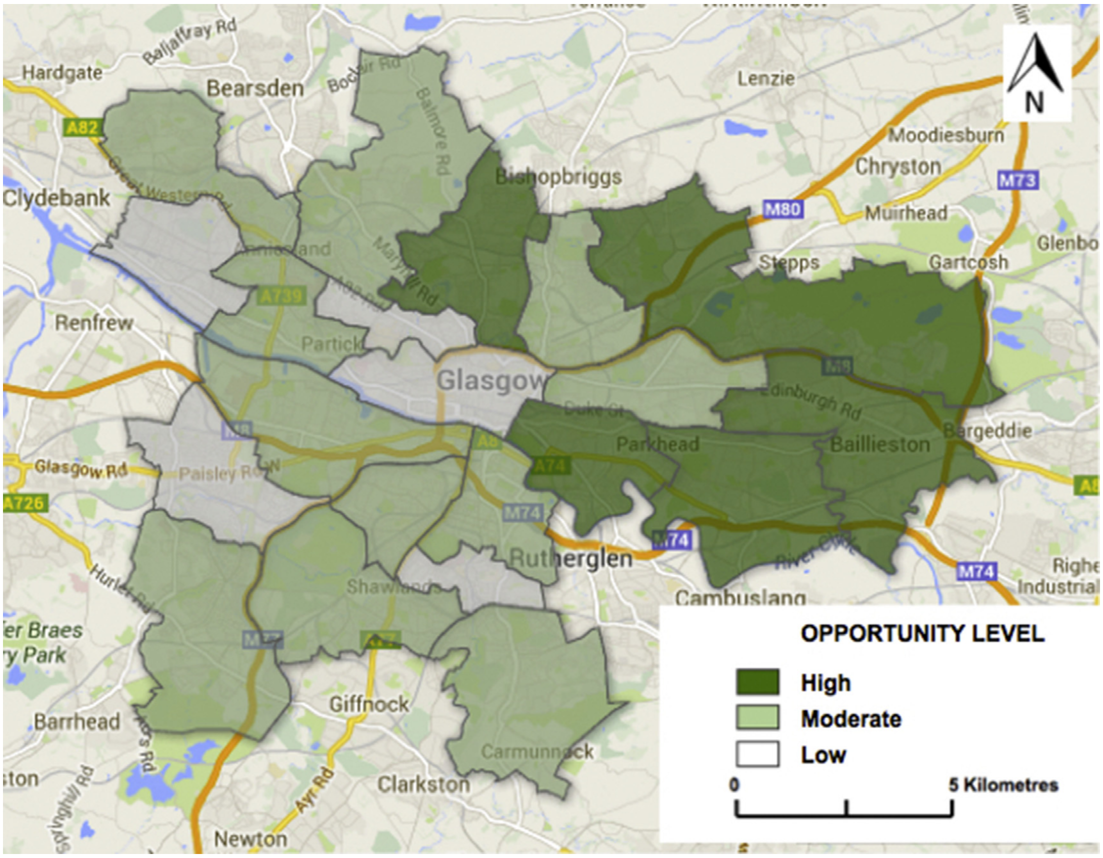

Fig. 5. Social Housing and Vacant & Derelict Land Intensity by electoral ward, Glasgow, Scotland.

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.

Acknowledgements

The Building Research Establishment Trust, the Energy Technology Partnership, the University of Strathclyde and the Natural Environment Research Council (NE/H0101432/1) are thanked for providing funding for the research contributing to this article. All 32 local councils within Scotland are thanked for their help in providing and or collating data on vacant and derelict land, together with the Scottish Environment Protection Agency, Glasgow City Council, Glasgow Housing Association (GHA) and North Glasgow Housing Association (nghomes).

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