Accepted Manuscript

Scottish Journal of Geology

Low-carbon GeoEnergy Resource Options in the Midland Valley of Scotland, UK

N. Heinemann, J. Alcalde, G. Johnson, J.J. Roberts, A.T. McCay & M.G. Booth

DOI: https://doi.org/10.1144/sjg2019-007

This article is part of the 'Early Career Research' available at: https://www.lyellcollection.org/cc/SJG-early-career-research

Received 7 March 2019
Revised 16 August 2019
Accepted 6 September 2019

Low-carbon GeoEnergy Resource Options in the Midland Valley of Scotland, UK

[1,2]Heinemann, N., [3]Alcalde, J., [4]Johnson, G., [4]Roberts, J.J., [5]McCay, A.T. & [6]Booth, M.G.

[1]School of Geosciences, University of Edinburgh, Grant Institute, West Main Road, Edinburgh, EH9 3JW, UK

[2]Steinmann Institute – Geology, Bonn University, Nussallee 8, 53115 Bonn, Germany

[3]Institute of Earth Sciences Jaume Almera ICTJA-CSIC, C/ Lluís Solé I Sabarís s/n, 08028, Barcelona, Spain

[4]Department of Civil and Environmental Engineering, University of Strathclyde, James Weir Building, 75 Montrose St, Glasgow, G1 1XJ, UK

[5]School of Engineering, University of Glasgow, G12 8QQ, UK

[6]Robertson (CGG), Tyn Y Coed, Llanrhos, Llandudno, LL30 1SA, UK

Abstract

Scotland is committed to be a carbon-neutral society by 2040 and has achieved the important initial step of decarbonising power production. However, more ambitious measures are required to fully decarbonise all of the electricity, transport and heating sectors.

We explore the potential to use the low-carbon GeoEnergy resources and bio-energy combined with Carbon Capture and Storage (BECCS) in the Midland Valley area to decarbonise the Scottish economy and society. The Midland Valley has a long history of geological resource extraction, and as a result, the geology of the region is well-characterised.

Geothermal energy and subsurface energy storage have the potential to be implemented. Some of them, such as gravity and heat storage, could re-use the redundant mining infrastructure to decrease investment costs. Hydrogen storage could be of particular interest as the Midland Valley offers the required caprock-reservoir assemblages. BECCS is also a promising option to reduce overall CO_2 emissions between 1.10-4.40 $MtCO_2$/yr. The Midland Valley has enough space to grow the necessary crops, but CO_2 storage will most likely be implemented in North Sea saline aquifers. The studied aspects suggest that the Midland Valley represents a viable option in Scotland for the exploitation of the majority of low-carbon GeoEnergy resources.

Introduction

The Climate Change (Scotland) Act 2009 stimulated a series of energy targets for 2050, with interim targets for 2020 including to reduce final energy consumption by 12%, install 500 MW of community and locally owned renewables, and for renewable sources to provide the equivalent of 100% of Scotland's gross annual electricity consumption and 11% of Scotland's heat demand.

While the first three of these targets were met ahead of time, progress on renewable heat has been slow (Scottish Government, 2018a). Scotland has positioned itself as a global leader in the fight against climate change. The Climate Change Bill (Scotland) was amended in May 2019, and these changes are currently (as of July 2019) awaiting final approval from Scottish Parliament. The changes to the Bill commit Scotland to delivering 'net zero' greenhouse gas emissions by 2045, and 'net zero' carbon emissions (i.e. to be carbon neutral) by 2040. The Bill cements the recommendations of the IPCC report (2018), that the world needs to be carbon neutral by the middle of this century if the worst impacts of climate change are to be avoided.

The energy transition induced by the Bills is planned to be delivered through a series of specific support mechanisms designed to develop large-scale renewable energy technologies (e.g. onshore and offshore wind, solar and marine energy) and local small-scale renewables, and to explore the role of bioenergy resources. However, the challenge of meeting such greenhouse gas reductions means that further actions will be needed in every home, every community, and across businesses and industry throughout Scotland. The nationwide energy strategy will therefore need to integrate a diverse mix of renewable energy sources, effective energy storage and the decarbonisation of fossil fuels.

This paper assesses the different options to deliver on the greenhouse gas reduction targets using and exploiting low-carbon GeoEnergy resources and applications in Scotland. "GeoEnergy" is a relatively new term that encompasses energy technologies or energy sources that derive from or interact with the geological subsurface (Table 1). GeoEnergy involves processes such as energy production (geothermal energy, conventional and unconventional hydrocarbons), energy storage (natural gas, hydrogen gas, and thermal or potential energy storage), and the disposal of energy waste in geological formations (geological CO_2 storage and radioactive waste disposal).

The Midland Valley of Scotland is the key onshore region for the energy transition in Scotland: with its two biggest cities, Glasgow and Edinburgh, it is the most populated area, it hosts the major industrial cluster in Scotland, including the Grangemouth petrochemical site, which contributed 4% of Scottish GDP, and was responsible for ~10% of Scotland's annual energy consumption in 2013 (INEOS, 2013). Additionally, the geology of the Midland Valley, mainly composed of folded sand- or clay-rich sediments, has been a target for many GeoEnergy subsurface operations, as shown by its long history of exploration and exploitation of subsurface resources. This heritage has left mining and exploration infrastructure which can be re-used to lower costs for a sustainable energy industry (e.g. Alcalde et al., 2019). Scotland's traditional, carbon-based GeoEnergy industry and history has been fundamental to the country's economic growth, and forms a part of the backbone of Scottish identity and international reputation, historically and today.

In this paper, we explore the characteristics and potential of low-carbon GeoEnergy opportunities (Table 1) in the Midland Valley of Scotland. We provide a brief summary of current and future energy perspectives to illustrate the need and potential for low-carbon GeoEnergy adoption. The geology, as well as the energy history of the Midland Valley, is subsequently introduced before we explore three approaches to using the geological assets within the region to deliver low-carbon energy or to reduce CO_2 emissions: Energy extraction, subsurface energy storage and permanent disposal of CO_2 in the context of negative emission strategies.

This study aims to scope whether and how different GeoEnergy resources could contribute towards developing a sustained societally-acceptable low-carbon energy system in this region of Scotland before 2040 - and beyond. The use of GeoEnergy resources in the Midland Valley could have an important role to play in delivering a carbon neutral Scotland, as well as help Scotland to become a leader in these technologies.

GeoEnergy for a Low-carbon Society

The urgency for a transition of Scotland's energy landscape to a low-carbon or even zero-carbon society requires substantial investment into suitable technologies. However, what is considered to be 'low-carbon' can vary depending on the viewpoint. For this study, we used the recommendations summarised in the "Scottish Energy Strategy" (Scottish Government, 2018a), which proposes measures and technologies to achieve Scotland's ambitious low-emission targets, and added other, in our view promising, low-carbon technologies (Table 1).

We define renewable heat production and geothermal energy as technically non-finite resources, if the systems are managed so that the heat is extracted at the same rate (or less) than it is replenished by natural geothermal heat flow. The carbon emissions associated with geothermal heat extraction are very low compared to conventional fossil fuel sources (McCay et al., 2019), and so the resource has the potential to significantly reduce CO_2 emissions. Energy storage of any type, which can moderate seasonal variation of heating and energy demand, also has the potential to increase energy usage efficiency and security. As an example, excess wind energy which is currently wasted and actually causes curtailment costs (Renewable Energy Foundation, 2019), can be stored and used during times of low electricity shortage. Energy storage is only discussed in this paper if the storage involves a low-carbon energy resource. Hence, the storage of natural gas is not included in our analysis because natural gas is a finite energy resource that emits CO_2 when combusted for energy. The use and storage of hydrogen is regarded as an important part for Scotland's low-carbon future outlined in the "Scottish Energy Strategy" (Scottish Government, 2018a) and will also be discussed in this paper, along with other low-carbon energy storage options.

These technology contrast with many existing GeoEnergy resources, such as shale gas or coal, that are unsustainable because they are finite and they emit greenhouse gases during their extraction or consumption. As a measure to decarbonise, we discuss the role of capture and permanent storage of carbon dioxide (CCS) in combination with bioenergy production (BECCS) as sustainable technologies to decarbonise the unsustainable portion of the energy sector and to provide potential for negative emissions.

There are two operating nuclear power stations in Scotland (Torness and Hunterston), both located in the Midland Valley, which will continue to generate energy and radioactive waste and one strategy could be to use the subsurface to store nuclear waste permanently. However, the "Scottish Energy Strategy" (Scottish Government, 2018a) points out that the "economics of these (new nuclear) stations are prohibitive, especially given the falling costs of renewable and storage technologies", and hence the disposal of nuclear waste has not been addressed in this work.

The Energy Landscape for Scotland

The final energy consumption in Scotland for 2015 shows that renewable energy sources supplied 17.8% of the total, the majority of which came from renewable electricity supply (equivalent to 59.5% of the electricity consumed in Scotland in 2015 (Scottish Government 2018a). While the oil and gas sector in Scotland is on a continuous declining trajectory, Scotland remains one of the largest oil and gas producers in the EU (Eurostat, 2018). In 2016/17, 96% of oil and 63% of gas produced in the UK was sourced from Scotland's assets (Scottish Government, 2018b). More than half of the energy consumed in homes and businesses in Scotland is used for heating (Figure 1), and an estimated 79% of homes used natural gas as their primary heating fuel (Scottish Government, 2018b).

The majority of energy storage in the UK is in the form of fossil fuel stocks such as gas storage and centralised stocks and local depots of coal and crude oil (Scottish Government, 2018). As the UK decarbonises, these stocks are being reduced and, if national carbon budgets are to be met, are likely to be replaced with renewable or low-carbon storage options. This has implications for the resilience of the energy system, since only a small proportion of energy storage systems in the UK is renewable (Scottish Government, 2018a). The total capacity of pumped hydro is ~30 GWh, little more than 1 hour of average UK electricity consumption and compared to hundreds of TWh of fossil fuel based storage in 2014 (Scottish Government, 2018a). Developing low-carbon energy storage options is therefore a priority (Scottish Government, 2018a).

The rapid pace of energy system change over the past decade makes forecasting the future energy system in Scotland difficult and uncertain. The overall final energy demand is expected to decrease (Scottish Government, 2018a). However, electrification of transport and the heating/cooling sector will likely lead to increased electricity demand. The uptake of electric heating and transport on a large scale could place extra pressure on the electricity system, unless networks become smarter, managing demand much more flexibly to reduce network constraints. Hydrogen is being investigated to support the low-carbon transition while requiring minimal upgrades to the power network infrastructure. Hydrogen could replace, or be blended with, to decarbonise industry and domestic heating and replace fossil fuels in vehicles. The generation of hydrogen requires either additional electricity, when electrolysis is used to create "green" hydrogen, or natural gas when hydrogen is made out of natural gas by steam methane reforming (SMR). SMR produces CO_2 as a by-product and will could increase greenhouse emissions up to 285 gCO_2/kWh (Committee on Climate Change, 2018), which we call "black" hydrogen, compared with the ~200 gCO_2/kWh from direct use of natural gas. If this CO_2 is captured and permanently stored, the resulting lower-carbon process is called "blue" hydrogen which has emissions intensities of between 50-180 gCO_2/kWh, with the estimation range mainly due to varying emission related to the supply of methane (Committee on Climate Change, 2018).

The Midland Valley of Scotland

The Midland Valley of Scotland provides an extensive area for onshore and diverse regional GeoEnergy resource options. This is largely because it is the most extensive area of Scotland that is covered by relatively un-metamorphosed sedimentary rocks. Most of Scotland consists of metamorphic rocks, such as the Dalradian and Moine Supergroups to the North of the Midland Valley and the Ordovician-Silurian weakly metamorphosed sediments of the Southern Upland Accretionary Complex to the South. Although these rocks were deposited as sediments, they have been variously altered by enhanced pressure and temperature and are considered to have no matrix permeability or organic content, making them therefore uneconomic for most GeoEnergy operations. Only relatively small areas outside the Midland Valley are covered with sediments, most notably along the coast of the Moray Firth, with extensive Devonian and younger deposits. Scotland also contains a large quantity of igneous intrusions and volcanic successions. Some of the granitic intrusions have high enough heat flow to have been considered for geothermal energy (McCay & Younger, 2017) but current high risk of target temperatures being deeper than expected due to lack of deep drilling and uncertainty over hydraulic properties has resulted in no project going forward at this stage (e.g. Milligan et al., 2016)

Geological Background

The Midland Valley is an elongated WSW-ENE trending sedimentary basin bounded to the North by the Highland Boundary fault and to the South by the Southern Upland fault (Figure 2) (Dewey et al., 2015; Monaghan, 2014; Underhill et al., 2008). Activity on the major fault lineaments, formed during the lower Palaeozoic Caledonian orogeny created a mountain range comprising uplifted and deformed Pre-Cambrian and Early Palaeozoic rocks which spanned the USA, Canada, Greenland, the UK and Scandinavia (Bluck, 1985; Armstrong &

Owen, 2003). Significantly, the Carboniferous and the Devonian sedimentary rocks of the Midland Valley were mainly derived from erosion of these Caledonian mountains and deposited into a series of elongate NE-SW oriented basins across Britain (Greensmith, 1962; Lancaster et al., 2017; Leeder, 1988).

Several Palaeozoic volcanic events have occurred in the Midland Valley and attest to the tectonic history, with numerous igneous, volcanic agglomerate and volcaniclastic deposits (Upton et al., 2004; Monaghan & Parrish, 2006; Murchison & Raymond, 1989). It is suggested that the dominant sedimentary rocks of the Midland Valley, the Carboniferous and the Devonian sediments, were derived mainly from the Caledonian mountains of East Greenland, Norway and NE Scotland (Greensmith, 1962; Lancaster et al., 2017). The structure of the Midland Valley is dominated by folding and minor reverse faulting of the sedimentary rocks by compressional deformation associated with the Variscan orogeny at the end of the Carboniferous (Coward, 1993). The anticlinal structures generated formed the main traps for the existing hydrocarbon fields (e.g. Hallett et al. 1985; Underhill et al. 2008). Minor and localised tectonic events affected the Midland Valley area throughout the Mesozoic, although the most significant phase of post-Carboniferous deformation occurred during the Neogene where south-eastward tilting of the UK caused significant uplift of the Midland Valley strata (Wilkinson, 2016; Stoker et al. 2005; Thomson & Underhill 1993; Cameron & Stephenson 1985). No significant post-Carboniferous phases of deformation are recorded until the Neogene south-eastward tilting of the UK, which caused significant uplift of the Midland Valley strata (Wilkinson, 2016).

During the Devonian, the UK was landlocked within a semi-arid continental landmass that led to the deposition of aeolian desert and fluvial sandstones, collectively known as the Old Red Sandstone facies (Browne, 2002; Kendall, 2017). The Upper Devonian part of the Old Red Sandstone facies in the Midland Valley, the Stratheden Group, is dominated by conglomerates and cross-bedded sandstones that were deposited from braided fluvial river systems (Ó Dochartaigh, 2004). Aeolian influence becomes more recognisable in stratigraphically younger units, such as the upper part of the Knox Pulpit Formation (Hall & Chisholm, 1997). A change back to fluvial sedimentation is defined by the overlying Upper Devonian to Lower Carboniferous Kinnesswood Sandstone Formation of the Inverclyde Group (Paterson & Hall, 1986). The total thickness of the Upper Old Red Sandstone facies varies significantly but maximum thicknesses of more than 1000 m exist in the West of the Midland Valley near Wemyss Bay at the Firth of Clyde (Bluck, 1978). Potential reservoir formations to be used for fluid injection, storage and/or production include sandstones from the Knox Pulpit and Kinnesswood Formations which outcrop to the North and South of the Midland Valley, and are expected to extend in the subsurface across the Midland Valley based on data from the Inch of Ferryton 1 well and seismic survey analysis (Monaghan et al., 2012). These sand-rich formations are overlain by the Ballagan Formation of the Inverclyde Group, a Lower Carboniferous mudstone with traces of marine carbonates, gypsum and anhydrite (Browne et al., 1999).

Sub-tropical conditions characterise the deposition within the Midland Valley during the Carboniferous. The Lower Carboniferous Strathclyde Group deposits are dominated by thick (more than 100 m thick in the Craigleith quarry near Edinburgh) siltstone and sandstones successions, which alternate with subordinate black shale and thin limestone and coal horizons (Dean et al. 2011). The sediments were deposited in a range of environments including fluvial channels, floodplain, crevasse splay (near-coastal fluvial–deltaic) and a major lacustrine system called Lake Cadell, a 2000 to 3000 km^2 lake with minor marine incursions that originated from the east (Andrews & Nabi 1994; Loftus & Greensmith, 1988; Greensmith, 1962). During the phases of isolation, and during times of diminished clastic input into the lake, laterally extensive impermeable lacustrine mudstones and thin fossiliferous limestones beds were deposited.

The Upper Carboniferous Clackmannan Group comprises marine mudstones and limestones, which can sometimes be traced across many tens of kilometres, which are interrupted by permeable sandstones (Cameron & Stephenson, 1985). These sandstone layers are usually around 6 m thick with some up to 30 m (Cameron and Stephenson, 1985). As the UK continued to move northwards into a more tropical environment, deposition became more dominated by fluvial-deltaic and adjacent swamp environments, leading to the formation of the Scottish Coal Measures Group.

The GeoEnergy History of the Midland Valley

Carbon-based energy resources

The coal- and hydrocarbon-based GeoEnergy industry and history have been fundamental to the economic growth and the industrial development of the Midland Valley, and it forms an important part of national identity and culture.

Coal has been mined in Scotland since the 13th century and remained until recently to be an important and valuable resource in the Midland Valley, despite its decline in production since the peak in 1913 with 42 million tonnes (Cameron & Stephenson, 1985). Although large resources still exist, their mining would be uneconomical in today's globalised market, and coals use in power generation in the UK has been in constant decline (Department for Business, Energy & Industrial Strategy, 2018). There is currently no deep mining in Scotland with the last Scottish deep mine complex, Longannet, east of Kincardine, ceasing production in 2002 (Leslie et al., 2016). Nowadays, opencast coal mining still exists, but at small scale; in 2017 merely 0.8 million tonnes was produced, employing 159 people (Department for Business, Energy & Industrial Strategy, 2018). More recently, coal bed methane exploration started in 1993 from the Bannock Coal seam (Department of Energy & Climate Change, 2010b).

Although Midland Valley coal played an important role in fuelling the UK, Scotland's role for the hydrocarbon industry was much greater. Hallett et al. (1985) state that "Scotland for all practical purposes can be regarded as the birthplace of the oil industry" and gives particular praise to pioneering work of the Scotland born James “Paraffin” Young who developed the first commercial method of extracting oil from coal and oil shales. Hydrocarbon production activities started with the first extraction of oil from shales near Bathgate in 1851 (Conacher, 1927; Hallett et al., 1985). Oil-shale continued to increase to a maximum of 2 million barrels in 1912 before imports from the Middle East and America made it increasingly uneconomic and ultimately collapsed after the withdrawal of the tax concessions in 1964 (Hallett et al., 1985).

The demand for oil rose rapidly during and after the First World War and, as a consequence, the UK commissioned a drilling program to explore potential reserves in England and Scotland. Two anticlines in the Carboniferous in the eastern part of the Midland Valley were targeted as the Scottish sites, at West Calder and D'Arcy (Figure 2). The West Calder campaign began in 1919 and was mainly unsuccessful; the D'Arcy well however, commenced in 1919, encountered gas at 221 metres and at oil at 552 metres (Hallett et al., 1985).

More hydrocarbon wells were drilled in the 1930s when a discovery named the Midlothian oil field, which continued producing until 1964, was found (Hallett et al., 1985). Subsequent exploration discovered more oil and gas in the Cousland-D’Arcy anticline before a low oil price made new exploration projects uneconomically viable between 1959 and the 1980s when the oil price rose again (Monaghan, 2014). Further wells were drilled during the 1980s, and most of these wells exhibited minor oil and gas shows, for example, the Balgonie prospect in Fife, mainly in sandstones of the Strathclyde and the Clackmannan Group (Monaghan, 2014; Underhill et al., 2008).

Geothermal energy resources

In the 1980s, several areas of Scotland were part of a UK wide deep geothermal exploration effort to diversify the UK power mix. The Midland Valley was considered to have "limited geothermal potential" (Downing & Gray, 1986a). However, these studies were focussed specifically on geothermal for power production. The lower temperatures required for direct-heat use has led to positive re-evaluation of previously discounted resources in Scotland (e.g. McCay and Younger, 2017). Furthermore, later studies later studies found that resource potential was underestimated due to failure to account for palaeoclimatic effects (Westaway & Younger, 2013).

From 2010, research efforts have focussed on deep geothermal resources in the Midland Valley for direct-use heat, as the Carboniferous sedimentary aquifers may offer low-carbon heat for space heating (Younger et al., 2015). Following favourable reports over the potential resource (e.g. Gillespie et al., 2013) the Scottish Government formed the Geothermal Energy Expert Group: a panel of geothermal experts from academia and industry, tasked to advise Scottish Government on how to kickstart the geothermal industry in Scotland. The Geothermal Energy Expert Group advised the Scottish Government to support geothermal through co-funding feasibility studies in Scotland, three deep geothermal and one minewater feasibility studies were ultimately funded as part of Scotland's Low-Carbon Infrastructure Transition Programme. The studies showed that successful deep-geothermal projects in a range of geological settings in Scotland could lead significant carbon savings compared with the gas-fired business-as-usual, but resource risk prevented further private investment to the projects (Brownsort & Johnson, 2017).

GeoEnergy Applications and Resources in the Midland Valley

Geothermal Energy Production

The geothermal resources of the Midland Valley are defined here as deep resources (resources greater than 500 m depth below surface) and minewater resources which exploit flooded abandoned mines. We also consider a third geothermal resource: enhanced and ultra-deep systems (resources deeper than 5 km below surface). These resources have quite separate opportunities and risks.

The direct-heat geothermal resources of the Midland Valley would likely feed into municipal district heat networks. District heating systems are generally conceptualised as a network of users, connected via a distribution network to a heat source (Talebi et al., 2016). Analysis suggests that in Europe district heating systems may be a cost effective alternative route to electrification of heat to meet emissions targets (Connolly et al., 2014). Current district heating in the Midland Valley operating at around 90 °C have been designed for use with gas-fired "Combined Heat and Power" (CHP) and boilers. Newer designs are for district heat networks at lower temperatures (e.g. Lund et al. 2018).

Deep Geothermal Resources

The deep (>500 m) geothermal resources of the Midland Valley are contained within sedimentary aquifers of sufficient depth to host useable temperatures (50-90 °C). Studies of these aquifers at shallower depths suggest they are likely to have favourable permeability properties (e.g. MacDonald et al., 2004). Some work has been carried out on single borehole concepts in the Midland Valley which do not require permeability at depth, however the long term sustainability of these concepts is yet to be proven (Westaway 2018). The temperature and therefore depth targeted depend on the requirements of the district heat network that the resource would provide heat to. Geothermal resources within fractured igneous rocks (e.g. radiothermal granites) have not been identified in the Midland Valley (McCay & Younger, 2017).

The primary consideration for the deployment of a geothermal project is that the necessary heat resource is present and that the rocks present permit fluid flow. Detailed constraint of aquifer hydraulic properties is needed to ensure geothermal systems are efficiently designed. If the permeability is too low then poor flow rates will lead to low heat extraction, but on the other hand unexpectedly high permeability can lead to thermal breakthrough. Comerford et al. (2018) report that flow within deep aquifers in the Midland Valley is likely to be structurally controlled, i.e. the majority of flow will be constrained through fractures or fault zones. Therefor the hydraulic behaviour of deep aquifers resembles that of shallow aquifers, in which most groundwater flow is through fractures (Ó Dochtartaigh et al., 2015). There remain significant challenges in targeting where structurally controlled high permeability zones would have the most favourable aquifer properties. Such challenges led to poor flow results for a geothermal borehole drilled in Newcastle, NE England, to target formation similar to those in the Midland Valley (Younger et al., 2016).

To date, there are no active deep geothermal projects in the Midland Valley. However, a number of feasibility studies and academic investigations have been completed (Table 2). The Guardbridge Geothermal Project (near St. Andrews) targeted sedimentary units which were known to be productive aquifers at depths of less than 300 m, for example the Scone Sandstone Formation (MacDonald et al., 2004). Robinson et al. (2016) also studied the geothermal potential of the Knox Pulpit Formation and the Kinnesswood Formation, based on information from the 567 m deep Glenrothes Borehole (Breteton et al. 1988). Younger et al. 2015 speculated, based on mapped stratigraphy and structure that the Kinnesswood Formation would be at favourable depths (2-2.5 km) in eastern Glasgow. Gravity surveys and further stratigraphical and structural analysis suggests that areas around Dalmarnock in Glasgow are the most likely location in Glasgow to target the Kinnesswood Formation at depths of 2-2.5 km, this work is as yet unpublished but mentioned in Watson et al. (in review).

Geothermal projects in deep aquifers typically access the heat through a well doublet. In this set-up, two wells are used to extract geothermal fluids from the reservoir. One well (also known as the production borehole) is for the extraction of water from the aquifer. However, significant extraction of geothermal fluids can result in undesirable drops in reservoir pressure demonstrated by Downing et al. (1984) while testing the Southampton geothermal borehole. There is the additional issue of needing to safely dispose of geothermal fluids on the surface. To combat these issues, a second well injects the water into the aquifer after heat removal.

Projects using well-doublet need to understand the permeability and porosity properties of the target aquifers to assess performance (e.g. Willems et al 2017a), as there needs to be enough permeability to allow the production borehole to produce geothermal fluids and to accommodate the injected fluid. However, there needs to be enough spacing at depth between the two wells, or else, if the injection and production rate is not reduced, the production borehole will start producing cooler, recently injected water. This effect, known as geothermal breakthrough, would significantly diminish the performance of a geothermal plant (Willems et al 2017b).

An alternative to the doublet system is using single wells. This concept involves only drilling one borehole and relying mostly on heat-conduction with the surrounding rock mass to warm fluids within the borehole (Falcone et al. 2018). A version of single well technology has been proposed and tested at the Rosemanowes Quarry in Cornwall (Law et al., 2015). The purported advantage of the method is that it requires less permeability of the rock due to its closed-loop design than a doublet would require. However, Law et al. (2015) propose some limited extraction of around 3 l/s to increase the efficiency of the system by drawing in surrounding heat to the borehole. The disadvantage of single well is an order of magnitude lower heat yields than an equivalent doublet system, e.g. Law et al. (2015) predicted a 2 km borehole could yield 400 kW of heat as an upper bound estimate. These single-well concepts remain experimental and the long-term sustainability has been questioned (Westaway, 2018).

Minewater

Abandoned coal mines can be a source of low temperature geothermal energy. When mines are abandoned, the void space created during the mining is typically flooded by groundwater once pumping of the mine system is stopped. Minewater systems are typically coupled with heat pumps to provide suitable enough temperature fluids for heating at a district scale. A number of successful minewater heating schemes exist around the world in Canada, Germany, Hungary, Norway, Poland, USA and Scotland (Hall et al., 2011). The Mijnwater Project in Heerlen, Netherlands, is widely considered an exemplar of the technology, as mines at different depths (and therefore temperatures) are used as part of a smart district heating network to respond to variations in heating and cooling demand (Verhoeven et al., 2014).

There is currently an ongoing minewater resource investigation project Dalmarnock, in the East end of Glasgow (Monaghan, 2017). The project includes one new seismic monitoring boreholes, and a number, an array of three pairs of minewater characterisation boreholes at 45-95 m depth, and an array of environmental baseline and monitoring boreholes within the superficial deposits. The boreholes are designed to collect data informing heat, chemistry, and microbiological properties of the minewater over time, to better understand the minewater heat resource in this area.

The existing schemes in Scotland are in Shettleston, Glasgow, and Lumphinnans, Fife (Banks et al., 2009). A number of feasibility studies have been conducted since 2010, for projects in the East End of Glasgow, Fortissat, Lanarkshire and Midlothian. In Shettleston water is extracted from 100 m depth and supply two heat pumps used to heat the water to 55 °C for subsequent district heating of 16 homes (Banks et al., 2009). This project is not without problems, with the Shettleston project suffering from iron precipitation in heat exchangers, maintenance difficulties, and uncertainty over depths of extraction and location of reinjection. A similar deployment is used at Lumphinnans at a slightly deeper mine (172 m) serving 18 homes, until the project was vandalised in 2005 (Banks et al., 2009; Hall et al., 2011).

Gillespie et al. (2013) estimated that a total of 4×10^{12} kWh of geothermal resource exists in the minewaters of the Midland Valley but the recoverable proportion of that will be lower and constrained by flow rate amongst other factors. Assuming a flow rate of 60 $l/s/km^2$ the potentially recoverable energy is calculated to be 12 GW compared to an estimated heat demand by 2020 of 33 GW across central Scotland. Though these values are larger in comparison to the renewable heat targets of Scotland, the actual amount exploited will undoubtedly be significantly less due to technical factors including the ability to economically retrofit for district heating, co-location of supply and demand, and trade-off between deeper mines having higher temperatures but respectively higher pumping costs (Banks et al., 2017).

Enhanced and Ultra-Deep Geothermal Systems

Enhanced and ultra-deep (>5 km) geothermal systems are widely proposed as promising geothermal development possibilities which are largely irrespective of geological properties (Olasolo et al., 2016). However, the Midland Valley has not had any projects proceed to drilling stage, such as the radiothermal granites in Cornwall (Richards et al., 1994).

Geological Energy Storage

Energy storage in the subsurface is the capture of energy at one time and its storage underground for later use, in different forms such as hydrogen, heat, compressed air storage or as potential energy in gravity storage. Energy storage at different scales is vital for energy security and will become even more important when the distribution of carbon-based energy is reduced for the benefit of increased renewable energy, such as wind and solar. For example, one of the biggest challenges for decarbonising future energy demand is the seasonal variation of heat demand. This can be illustrated by the variation in gas demand, Scotland's main heat source, from 50 GWh per day in summer to 250 GWh per day in winter (Scottish Government, 2016). Additionally, an increasing percentage of renewable energy sources will also increase the intermittency since electricity production from wind and solar is also not steady. Considering these variations, it is important to prevent imbalances in the grid that could lead to energy shortage, net instabilities and shut-downs, especially by storing energy during periods of oversupply and reproducing it when demand exceeds supply. For the Midland Valley, four types of subsurface energy storage are considered in this study: gravity storage, heat storage, compressed air energy storage (CAES) and the storage of hydrogen. Gravity storage and large pit heat storage do not need permeable reservoir formations, but the others require a certain degree of permeability depending on the technology and the energy scenario. More importantly, the extensive GeoEnergy infrastructure and geological knowledge from the mining industry, mainly wells and vertical shafts, but also the detailed understanding of the shallow subsurface, could be re-used for their implementation.

Gravity Storage

Gravity storage is a relatively new concept based on raising a large weight to store grid power, then releasing that energy by lowering the weight (Aneke & Wang, 2016; Berrada & Loudiyi, 2019). The concept would facilitate the provision of grid balancing services on a short term, as an alternative to lithium batteries or diesel generators. As an example, raising a 3000 tonne weight by 100 metres will store approximately 800 kWh of energy and longer distances or increasing the mass of the weight will allow more energy to be stored. With its intense mining history and the high density of vertical shafts compared to the rest of onshore Scotland, the Midland Valley is a promising environment for feasibility studies and test projects. As a part of the ongoing investigation into re-purposing abandoned mine shafts as vessels for gravity storage, the company Gravitricity is currently planning a 250 kW demonstration project which may lead to a 4 MW prototype (Schmidt, 2018). Future research and development will show how many, or if any, mineshafts in the Midland Valley are in suitable condition to be re-purposed for the provision of gravity storage.

Heat Storage

Heat storage is achieved using two main GeoEnergy technologies: large pit storage or borehole thermal storage. Typically, these storage systems are used for the winter heat demands of modern housing or commercial buildings with lower temperature (<50 °C) heating systems. For the large pit storage concept, the suitable geology would be rocks competent enough to provide safe bearing capacity for the weight of water. Any excess settlement or collapse of unidentified mining could lead to leaks from the water mass. Large pit storage is exemplified by the Vojens Project in Denmark which is a fully insulated pit filled with 200,000 m^3 of water which is warmed up by 70,000 m^2 of solar heat panels (Lund et al., 2016). In the Vojens Project, for every 1 °C of raised temperature approximately 233,000 kWh of heat is stored.

Borehole thermal storage, where a heated working fluid is injected in the wells and the heat is then stored in the surrounding rock mass, is very dependent on the thermal properties of the rock and stable groundwater conditions. These dictate how far the storage heat would penetrate into the rock, and therefore potential limits on storage potential. Stable hydraulic properties would also be favourable, as large groundwater flows would move the heat away from the storage site. As an example, the Drake Landing Solar Community in Canada hosts 144 35 m deep boreholes which are used to store heat from a 2300 m^2 of solar thermal collectors and allows more than 90% of the community's heating demand to be met by solar heat. Building on the success of these projects, Renaldi and Friedrich (2018) investigated the potential of applying a similar concept to Scotland. They suggested that such a project could be successful in Scotland if a mixture of free heat sources, for example, solar energy and waste industrial heat source with integrated heat pumps could be linked. There are several projects in Scotland already in operation which use geo-heat-exchange to balance summer cooling demand with winter heating demand of commercial buildings, e.g. Robert Gordon University in Aberdeen which uses 66 boreholes of 200 m depth to balance such inter-seasonal cooling and heating demand (Singh et al., 2019). Future research has to reveal if the Midland Valley geology is suitable for heat storage, but the use of redundant onshore hydrocarbon wells for heat storage could reduce construction costs significantly (Westaway, 2016).

Energy Storage using Gases

The remaining two energy storage options, CAES and hydrogen storage rely on large storage volumes, which are typically provided by engineered caverns in thick salt formations or in aquifers and depleted hydrocarbon fields. The technology for gas injection and storage in porous media is well established. Gas is injected into a porous and permeable reservoir formation, such as an aquifer or a depleted hydrocarbon field, via injection wells, and displaces the in-situ pore fluid, usually brine, and spreads out underneath an impermeable caprock (Mouli-Castillo et al., 2019; Heinemann et al., 2018; Edlmann et al., 2019). Since thick salt formations are absent in the Midland Valley, storage in porous media has to be investigated. A proven petroleum system, including hydrocarbon reservoir and seal assemblages, exists in the West Lothian Oil Shale Formation of Carboniferous age, and its eastern equivalents (Dean, 2018; Department of Energy & Climate Change, 2013). Deeper aquifer units of the Upper Devonian and Lower Carboniferous Old Red Sandstone are investigated regionally and show promising reservoir qualities for gas injection, although studies show that reservoir quality decreases with depth (Ó Dochartaigh, 2004). These formations are, among others, promising examples for future gas storage research projects in the Midland Valley ambitions.

CAES is a technology which allows bulk energy storage reaching MW of power and GWh energy. The conventional system is composed of a compressor, an underground store and a gas turbine. During charging mode air is compressed into the store. The plants currently in operation, one in Germany and one in the US, and a planned site in Larne (Northern Ireland), utilise underground salt caverns as the air store, where the electricity is generated by expanding the air through a gas turbine fired with natural gas, also called "conventional" CAES (Succar & Williams, 2008). The Larne project will be the most powerful one with the potential to generate 330 MW for up to 6 hours. Recent research has been investigating subsurface porous media targets such as aquifers for CAES (Mouli-Castillo et al., 2019). The use of these aquifers could reduce upfront costs because no caverns have to be engineered. Aquifers are present in the Midland Valley, for example, the extensive Old Red Sandstone of Upper Devonian age, and hence the technology should be geologically applicable. More detailed work is required to investigate if Carboniferous formations, which are less extensive and consist of alternating shale and sand systems, would also be suitable targets.

The concept of hydrogen usage and storage was already discussed at the 1st World Hydrogen Energy Conference in 1976, which closed with, among others, the conclusion that there are "no insurmountable or environmental problems" in using underground hydrogen storage (Walters, 1976). Onshore hydrogen storage in subsurface porous media in the Midland Valley could provide an opportunity to store significant amounts energy in the subsurface (Figure 3). The usage of hydrogen as a fuel substitute for heating and transport has received growing attention (Committee on Climate Change, 2018; H21 Leeds City Gate Core Team, 2016; Staffell et al., 2019; Alcalde et al., 2019) and several ambitious hydrogen pilot projects, such as H21 Leeds City Gate (England), BIG HIT (Scotland) and others would be backed by additional subsurface hydrogen storage capacity. Hydrogen has high potential value to re-purpose gas grids, as long as the infrastructure has been upgraded to be able to transport hydrogen. If large volumes of hydrogen are being produced, especially as “green” hydrogen using excess renewable electricity, large storage space close to consumers is required. However, although both research and industry have become increasingly intrigued by the obvious advantages of the use of hydrogen, large scale storage at low cost and high tonnage remains unproven.

To date, there are no commercial pure hydrogen storage in porous media projects in operation (Kruck, 2014). However, there is significant experience of subsurface natural gas storage in the UK (e.g. Wilson et al., 2010). Since natural gas storage in the Rough Field (southern North Sea) has come to an end, there are only two gas storage facilities left in porous media (Hatfield Moor and Humbly Grove with a working gas capacity equivalent of 1.25 and 3.12 TWh, respectively) and a few more in salt caverns, all located in England (Le Fevre, 2013).

The storage of hydrogen follows roughly the same principle as the natural gas storage. An anticline or any other trap structure prevents the injected hydrogen from escaping. Depleted hydrocarbon fields are often considered as a preferred potential target because a) their geology is well understood, b) the existing hydrocarbon infrastructure can be re-used, hence lowering the investment costs, and c) they have proven their ability to retain buoyant fluid over geological timescales. However, hydrogen is a much smaller molecule with a higher buoyancy compared to natural gas and hence a seal that retains natural gas may not be sufficient for hydrogen storage.

In times of energy need, the stored hydrogen can be reproduced directly from the reservoir via production wells. A small share of the gas, often referred to as cushion gas, will remain in the reservoir as a precaution to maintain operational pressure and to minimise the possibility of water breakthrough during gas withdrawal. There is still very little known about a multi-phase flow system including hydrogen and more research on unwanted chemical and biological reactions with the injected hydrogen and about the behaviour of hydrogen in a water-wet porous media is needed.

CO_2 Storage and Negative Emission Technology

The scale and severity of the accumulated anthropogenic climate change makes CO_2 emission reduction or even cessation alone insufficient to keep its consequences under control (Gillett et al., 2011). A potential solution to this issue is the active removal of atmospheric CO_2 in combination with emission reduction efforts. Negative Emission Technologies (NETs), together with deep CO_2 emissions reductions, are likely to be required at a large-scale to achieve the atmospheric CO_2 concentrations targeted in most climate change mitigation scenarios (e.g. Smith et al., 2015; Rogelj et al., 2016; IPCC, 2018). There are multiple NETs options that can be combined in different ways to achieve these targets. Smith et al. (2015) and Smith (2016) propose a methodology for obtaining the characteristics and potential impacts of different land-based NETs, based on the costs and requirements of the following technologies: Bioenergy with carbon capture and storage (BECCS); direct air capture (DAC); enhanced weathering (EW) of basic and ultrabasic minerals; enhancing the sink capacity of forests by means of afforestation and reforestation (AR); soil carbon sequestration (SCS) through change of agricultural practices; and biomass conversion to biochar (descriptions of and references to these different NETs approaches can be found in Smith et al. (2015), Smith (2016) and references therein. Based on this methodology, Alcalde et al. (2018) calculated the potential for implementation of these land-based NETs in Scotland.

Land-based NETs in the Midland Valley

We apply the methodology of Alcalde et al. (2018) to the land-based NETs resources available in the Midland Valley, in terms of negative emission potential and economic and energy cost (Figure 4). This method combines the economic cost, energy requirement and negative emission potential with the available land areas for each technology. From the land areas provided in Alcalde et al. (2018), we employed GIS techniques to calculate the proportion of available land areas in the Midland Valley in terms of negative emission potential and economic and energy cost. We digitised the short rotation coppice suitability map by Andersen et al (2005) to produce an approximation to the agricultural area in Scotland suitable for NETs, and calculated the land proportion of each land subdivision (i.e. suited, highly suited and marginally suited land). Of the 1.96 Mha of available agricultural area in Scotland (Andersen et al., 2005), 41% (0.81 Mha) is located in the Midland Valley. This divides into approximately 0.52 Mha of suited land (semi-natural communities, rough grass), 0.19 Mha of highly suited land (arable or improved pasture) and approximately 0.1 Mha of marginally suited land (scrub or maritime pasture). We assume that this marginally suited land will be the only one available for BECCS and biochar feedstock production, to avoid competition with food production. We only consider dedicated crops for BECCS, but BECCS feedstock from agricultural residues can help to reduce the competition for land with feedstock crops. EW or SCS do not change the land use, so we assume that they could be applied to the entire available land. DAC technology is both at an early stage of development and is not constrained by land availability (rather energy provision and storage availability), and so we have excluded it from our modelling.

The results of this negative emission potential analysis are presented in Figure 5 and show similar characteristics as those observed for the whole of Scotland (Alcalde et al., 2018). EW shows the greatest CO_2 abatement potential, with 2.43 - 7.60 Mt CO_2/yr, and its implementation does not involve a change in land use, so it is combinable with other NETs. However, the economic cost (19 - 1215 £/t CO_2)*[1] and, above all, the energy involved in its application (0.8 - 12.6 Gj/t CO_2) can penalise this technology. BECCS presents smaller, yet

[1] the costs of capturing and storing a t CO_2 are from studies using approximate 2005 to 2015 US$ values; here we have converted the cost values to 2019 £.

significant negative emission potential (1.10 - 4.40 Mt CO_2/yr), with moderate cost (27 £/t CO_2) and potential for negative energy cost implementation (-10.5 - 2.4 Gj/t CO_2). Biochar competes for land with BECCS, so they are mutually exclusive. The negative emission potential for biochar is smaller than BECCS (0.42 - 2.75 Mt CO_2/yr) and the economic cost is highly variable (-171 - 248 £/t CO_2), depending on the market and the technique used. However, the pyrolysis used in its making can be used to produce energy, making this technology energy negative (-13.6 to -5.5 Gj/t CO_2).

As reported by the Forestry Commission Scotland, the target for forest expansion is 0.1 Mha in the period 2012-2022, under the Scottish Government's Land Use Strategy (Scottish Government, 2011). According to this target, set for the whole of Scotland, Alcalde et al. (2018) calculated an AR negative emission potential of 0.34 Mt C-eq./yr - or 1.25 Mt CO_2/yr. The Scottish Government did not set regional targets for forest expansion, but most woodland areas are located in regions other than the Midland Valley, to the South-Southwest (Dumfries & Galloway and South Ayrshire regions), to the Northwest (Argyll & Bute) and in the Highlands (WEAG, 2012). The geo-demographical characteristics of the Midland Valley, compared to the rest of the country (i.e. densely populated, significantly build-up and substantial cropland vs woodland areas), suggest that AR initiatives will be carried out primarily in other regions.

In terms of greatest negative emissions potential for the Midland Valley, our analysis shows that the best combination would be BECCS + EW + SCS giving the maximum potential of ~15 Mt CO_2/yr removal. This compares to a CO_2 emissions footprint in the Central Belt of 20.1-22.8 Mt CO_2/yr (Department for Business, Energy & Industrial Strategy, 2018) in 2018 (depending on the local authority data included) and hence equates to 65-75% of emissions in the Central Belt, or 60% of Scotland's total annual emissions. Crucially BECCS (as would DAC, but not assessed here) also relies heavily on the deployment of geological storage of CO_2 (Herzog, 2011).

The Geological Resource

As discussed for gas energy storage, suitable caprock and reservoir assemblages for permanent subsurface storage of CO_2 are available in the Midland Valley. However, CO_2 storage of any BECCS project in Scotland, and indeed in much of Europe, will likely take place offshore in the North Sea, which offers great storage capacity and well-proven injection and containment properties (Bentham et al., 2014). There are also abundant hydrocarbon fields with existing redundant infrastructure (e.g. wells, platforms or pipelines) that can be re-used for CO_2 storage purposes, greatly reducing the implementation costs (e.g. Alcalde et al., 2019). Much work has been done on assessing the potential CO_2 storage capacity of the UK North Sea sector (e.g. Heinemann et al., 2012; Bentham et al., 2014; Akhurst et al., 2015). Additionally, a number of engineering studies have explored the potential for CO_2 storage offshore in Scottish waters including the Goldeneye project (Tucker & Tinios, 2017) and the Acorn project (Alcalde et al., 2019), and the CASSEM project in the Firth of Forth, as an example for onshore waters (Smith et al., 2011 and references therein). Although public acceptance for offshore CO_2 storage is not guaranteed, it removes some public perception concerns such as immediate risk exposure and property pricing (Roberts et al., 2017; Gough et al., 2018).

Closing Remarks

We have presented a preliminary assessment of potential low-carbon GeoEnergy resources available within the Midland Valley of Scotland, which is summarised in Table 3. Resource development in the Midland Valley is already adapting to fit the low-carbon energy landscape; the coal-mining and oil shale industries that were of immense historical importance in this region are now demised and in recent years there has been a number of advances in low-carbon GeoEnergy resource assessment and/or developments, such as minewater geothermal district heating. Our scoping work suggests that the diverse array of low-carbon GeoEnergy resources within the Midland Valley will be valuable for assisting the delivery and maintenance of a zero-carbon future in Scotland.

In particular, geothermal energy and energy storage are likely to be vitally important for the success of Scotland's energy transition, including the replacement of carbon-based energy with renewables. Geothermal energy is a promising option for the Midland Valley but needs de-risking through research to constrain the resource potential for deep and ultra-deep geothermal exploration. The existing minewater geothermal schemes in Scotland show that decentralised small-scale low-carbon energy generation is a promising and applicable option for the Midland Valley.

There are numerous abandoned mine shafts and onshore wells in the Midland Valley. The presence of these legacy infrastructures could significantly reduce the investment costs to deliver heat and gravity storage. Energy storage in porous media using hydrogen or compressed air could be geologically feasible because the regional geology of the Midland Valley provides potential reservoir and caprock assemblages. Small research projects in suitable potential storage sites of Carboniferous age could be investigated to test the feasibility of the technologies in the Midland Valley. Bigger projects could be implemented in Devonian sandstones, such as the Knox Pulpit Formation, once confidence in the technology has increased (Heinemann et al., 2018). Hydrogen storage is a particularly attractive GeoEnergy resource because it offers potential to reduce emissions across three energy sectors: replacing fossil fuels in vehicles, replacing natural gas for industry and domestic heating, and provide seasonal storage to replace existing fossil fuel-based energy storage. In terms of NETs, the combination of BECCS + EW + SCS could abate up to 75% of yearly CO_2 emissions in Scotland, and so offers a huge asset to the decarbonisation of the energy system. Although the geological storage of CO_2 is unlikely to be undertaken in the reservoir-caprock systems present within the Midland Valley, the existing clusters of industry infrastructure (e.g. Grangemouth) and their proximity to the offshore reservoirs in the North Sea makes the Midland Valley region an excellent candidate for the development of CCS projects.

As such, we find that there is a promising future for GeoEnergy resources in the Midland Valley of Scotland. However, while a diverse array of GeoEnergy resources are available, the scope and scale of their development depends on a range of technical, economic and social factors, including local and national political decisions and public acceptability of different GeoEnergy resources.

Acknowledgements

The authors thank their GeoEnergy research groups at the Universities of Edinburgh, Glasgow, Strathclyde and Aberdeen. Thanks to Prof Pete Smith for providing the spreadsheet of NETs impacts which was adapted for use in this study. We thank Dr Edlmann and Ms Corey for their support for this paper.

Niklas Heinemann is funded by EPSRC Grant EP/P026214/1 and the European Union's H2020 Accelerating CCS technologies. Juan Alcalde is funded by EIT Raw Materials – SIT4ME project (17024). Gareth Johnson is funded by EPSRC Grant EP/P026214/1 and the University of Strathclyde Faculty of Engineering. Jennifer Roberts is funded the University of Strathclyde Faculty of Engineering. Alistair McCay has received financial support for Scottish geothermal exploration from the Energy Technology Partnership and the Scottish Government through the Low-Carbon Infrastructure Transition Fund.

References

Aneke, M., & Wang, M., 2016. Energy storage technologies and real life applications–A state of the art review. *Applied Energy*, *179*, 350-377. https://doi.org/10.1016/j.apenergy.2016.06.097

Akhurst, M., Callaghan, E., Hannis, S., Kirk, .K, Monaghan, A.A., Pearce, J., Williams, J., Jin, M., Mackay, E., Pickup, G., Goldthorpe, W., Mallows, T., Haszeldine, R.S. & McDermott, C., 2015. Optimising CO_2 storage in geological formations; a case study offshore Scotland CO_2 MultiStore project, SCCS. http://www.sccs.org.uk/expertise/reports/co2multistore-joint-industry-project

Alcalde, J., Smith, P., Haszeldine, R.S. & Bond, C.E., 2018. The potential for implementation of Negative Emission Technologies in Scotland. International Journal of Greenhouse Gas Control, **76**, 85-91. https://doi.org/10.1016/j.ijggc.2018.06.021

Alcalde, J., Heinemann, N., Mabon, L., Worden, R.H., de Coninck, H., Robertson, H., Maver, M., Ghanbari, S., Swennenhuis, F., Mann, I., Walker, T., Gomersal, S., Bond, C.E., Allen, M.J., Haszeldine, R.S., James, A., Mackay, E.J., Brownsort, P.A., Faulkner, D.R. & Murphy, S., 2019. Acorn: Developing full-chain industrial CCS in a resource- and infrastructure-rich hydrocarbon province. Journal of Cleaner Production, 233, 963-971.

Andersen, R.S., Towers, W. & Smith, P., 2005. Assessing the potential for biomass energy to contribute to Scotland's renewable energy needs. Biomass and Bioenergy 29, 73–82. https://doi.org/10.1016/j.biombioe.2005.04.004

Armstrong, A.A. & Owen, A.W., 2003. The Caledonian Orogeny in northern Britain – a state of the arc. The Open University Geological Society Journal, 24, 11–18.

Banks, D., Fraga Pumar, A. & Watson, I., 2009. The operational performance of Scottish minewater-based ground source heat pump systems. Quarterly Journal of Engineering Geology and Hydrogeology, 42, 347-357. DOI 10.1144/1470-9236/08-081

Banks, D., Athresh, A., Al-Habaibeh, A. & Burnside, N., 2017. Water from abandoned mines as a heat source: practical experiences of open-and closed-loop strategies, United Kingdom. Sustainable Water Resources Management, 1-22. https://doi.org/10.1007/s40899-017-0094-7

Bentham, M., Mallows, T., Lowndes, J. & Green, A., 2014. CO_2 Storage Evaluation Database (CO_2 Stored): the UK's online storage atlas. Energy Procedia, 63, 5103-5113. https://doi.org/10.1016/j.egypro.2014.11.540

Berrada, A., & Loudiyi, K., 2019. Gravity Energy Storage. Elsevier. ISBN: 978-0-12-816717-5

Bluck, B. J., 1978. Sedimentation in a late orogenic basin: the Old Red Sandstone of the Midland Valley of Scotland. In: Bowes, D.R. Leake, B.E. (eds), Crustal Evolution in northwestern Britain and Adjacent Regions. Geological Journal Special Issue 10, 249–278.

Bluck, B. J., 1985. The Scottish paratectonic Caledonides. Scottish Journal of Geology, 21, 437–464. https://doi.org/10.1144/sjg21040437

Brereton, R., Browne, M.A.E., Cripps, A.C., Gebski, J.S., Bird, M., Halley, D.N., Mcmillan, A.A. & Gebski, J.S., 1988. Glenrothes Borehole: Geological Well Completion Report. Investigation of the Geothermal Potential of the UK. British Geological Survey.

Browne, M. A. E., Dean, M. T., Hall, I. H. S., McAdam, A. D., Monro, S. K. & Chisholm, J. I., 1999. A lithostratigraphical framework for the Carboniferous rocks of the Midland Valley of Scotland. British Geological Survey, Keyworth.

Browne, M.A.E., Smith, R.A., Aitken, A.M., 2002. Stratigraphic Framework for the Devonian (Old Red Sandstone) Rocks of Scotland South of a Line from Fort William to Aberdeen. British Geological Survey Research Report, RR/01/04. British Geological Survey, 67 pp.

Brownsort, P. & Johnson, G., 2017. Geothermal Energy in Scotland: A synthesis report covering four feasibility studies. Scottish Carbon Capture and Storage. Retrieved from http://www.sccs.org.uk/expertise/reports

Cameron, I.B. & Stephenson, D., 1985. The Midland Valley. British Geological Survey.

Committee on Climate Change, 2018. Hydrogen in a low-carbon economy. Retrieved from https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/

Conacher, H.R.J., 1927. History of the Scottish Oil-Shale Industry. Reprinted from "The Oil Shale of the Lothians". Memoirs of the Geological Survey, Scotland. 3rd Edition.

Connolly, D., Lund, H., Mathiesen, B. V., Werner, S., Möller, B., Persson, U., Boermans, T., Trier, D., Oestergaard, P.A. & Nielsen, S., 2014. Heat Roadmap Europe: combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 65, 475–489. https://doi.org/10.1016/j.enpol.2013.10.035

Coward, M. P., 1993. The effect of Late Caledonian and Variscan continental escape tectonics on basement structure, Palaeozoic basin kinematics and subsequent Mesozoic basin development in NW Europe. In: Parker, J.R. (ed), Geological Society, London, Petroleum Geology Conference series, 4, 1095-1108. https://doi.org/10.1144/0041095

Comerford, A., Fraser-Harris, A., Johnson, G. & McDermott, C.I., 2018. Controls on geothermal heat recovery from a hot sedimentary aquifer in Guardbridge, Scotland: Field measurements, modelling and long term sustainability. Geothermics, 76, 125-140. https://doi.org/10.1016/j.geothermics.2018.07.004

Dean, G., 2018. The Scottish oil-shale industry from the viewpoint of the modern-day shale-gas industry. Geological Society, London, Special Publications, 465, 53-69. SP465.13. https://doi.org/10.1144/SP465.13

Department for Business, Energy & Industrial Strategy, 2018. UK local authority and regional carbon dioxide emissions national statistics. UK local authority and regional estimates of carbon dioxide emissions from 2005. Retrieved from: https://www.gov.uk/government/collections/uk-local-authority-and-regional-carbon-dioxide-emissions-national-statistics

Department of Energy & Climate Change, 2010b. The hydrocarbon prospectivity of Britain's onshore basins – Coalbed Methane (CBM). https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/66172/uk-onshoreshalegas.pdf

Department of Energy & Climate Change, 2013. The hydrocarbon prospectivity of Britain's onshore basins. https://www.ogauthority.co.uk/media/1695/uk_onshore_2013.pdf

Dewey, J.F., Dalziel, I.W.D., Reavy, R.J., & Strachan, R.A., 2015. The Neoproterozoic to Mid-Devonian evolution of Scotland: a review and unresolved issues. Scottish Journal of Geology, 52(2). 112–112. https://doi.org/10.1144/sjg2016-015

Downing, R.A., Allen, D.J., Barker, J.A., Burgess, W.G., Gray, D.A., Price, M. & Smith, I.F., 1984. Geothermal exploration at Southampton in the UK: a case study of a low enthalpy resource. *Energy exploration & exploitation*, *2*(4), 327-342.

Downing, R.A. & Gray, D.A., (eds.) 1986a. Geothermal Energy - The potential in the United Kingdom. HMSO, London.

Edlmann, K., Hinchcliffe, S., Heinemann, N., Johnson, G., McDermott, C. & Ennis-King, J., 2019. Cyclic CO_2 – H_2O injection efficiency and storage security. International Journal of Greenhous Gas Control, 80, 1-9. https://doi.org/10.1016/j.ijggc.2018.11.009

Eurostat, 2018. Energy, transport and environment indicators, 2018 Edition. Luxembourg: Publications Office of the European Union, 2018. doi:10.2785/94549

Falcone, G., Liu, X., Okech, R.R., Seyidov, F. & Teodoriu, C., 2018. Assessment of deep geothermal energy exploitation methods: The need for novel single-well solutions. Energy, 160, 54-63.

Gillespie, M.R., Crane, E.J. & Barron, H.F., 2013. Deep geothermal energy potential in Scotland. British Geological Survey Commissioned Report, CR/12/131.

Gillett, N.P., Arora, V.K., Zickfeld, K., Marshall, S.J. & Merryfield, W.J., 2011. Ongoing climate change following a complete cessation of carbon dioxide emissions. Nature Geoscience, 4, 83-87. https://doi.org/10.1038/ngeo1047

Gough, C., Cunningham, R. & Mander, S., 2018. Understanding key elements in establishing a social licence for CCS: An empirical approach. International Journal of Greenhouse Gas Control, 68, 16-25.

https://doi.org/10.1016/j.ijggc.2017.11.003

Greensmith, J.T., 1962. Rhythmic deposition in the Carboniferous Oil-Shale group of Scotland. Journal of Geology, 70, 355–364. https://doi.org/10.1086/626825

Hall, A., Scott, J.A. & Shanga, H., 2011. Geothermal energy recovery from underground mines. Renewable and Sustainable Energy Reviews, 15, 916–924. https://doi.org/10.1016/j.rser.2010.11.007

Hall, I.H.S. & Chisholm, J.I., 1997. Aeolian sediments in the Late Devonian of Scottish Midland Valley. Scottish Journal of Geology, 25, 203–208. https://doi.org/10.1144/sjg23020203

Hallett, D., Durant, G.P. & Farrow, G.E., 1985. Oil exploration and production in Scotland. Scottish Journal of Geology, 21, 547-570. https://doi.org/10.1144/sjg21040547

Heinemann, N., Wilkinson, M., Pickup, G.E., Haszeldine, R.S. & Cutler, N.A., 2012. CO_2 storage in the offshore UK Bunter Sandstone Formation. International Journal of Greenhouse Gas Control, 6, 210-219. https://doi.org/10.1016/j.ijggc.2011.11.002

Heinemann, N., Booth, M.G., Haszeldine, R.S., Wilkinson, M., Scafidi, J., Edlmann, K., 2018. Hydrogen storage in porous geological formations e onshore play opportunities in the midland valley (Scotland, UK). International Journal of Hydrogen Energy, 43, 20861-20874. https://doi.org/10.1016/j.ijhydene.2018.09.149

Herzog, H.J., 2011. Scaling up carbon dioxide capture and storage: From megatons to gigatons. Energy Economics, 33, 597-604. https://doi.org/10.1016/j.eneco.2010.11.004

H21 Leeds City Gate Core Team, 2016. H21 Leeds city gate. https://www.northerngasnetworks.co.uk/wp-content/ uploads/2017/04/H21-Report-Interactive-PDF-July-2016. compressed.pdf.

INEOS, 2013. An Industry Perspective: Significant Challenges and Potential Costs of CCS. Presented at "Tackling industry's carbon emissions: drivers and barriers to CO_2 capture in Scotland", Grangemouth, Scotland, 10 October. Retrieved from: https://www.sccs.org.uk/events/past-events/11-workshops-for-industrial-emitters-2013

Kendall, R.S., 2017. The Old Red Sandstone of Britain and Ireland — a review. Proceedings of the Geologists' Association, 128. 409-421. https://doi.org/10.1016/j.pgeola.2017.05.002

Kruck, O., 2014. Assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe. http://www.fch.europa.eu/sites/default/files/project_results_and_deliverables/D3.3_Benchmarking%20of%20selected%20storage%20options%20%28ID%202849644%29.pdf

Lancaster, P.J., Daly, J.S., Storey, C.D. & Morton, A.C., 2017. Interrogating the provenance of large river systems: Multi-proxy in situ analyses in the Millstone Grit, Yorkshire. Journal of the Geological Society of London, 174, 75–87. https://doi.org/10.1144/jgs2016-069

Law, R, Bridgland, D., Nicholson, D. & Chendorain, M. 2015. Heat extraction from deep single wells. In: Proceedings World Geothermal Congress 2015, 19–25 April 2015, Melbourne, Australia. https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/28002.pdf

Leeder, M.R., 1988. Devono-Carboniferous river systems and sediment dispersal from the orogenic belts and cratons of NW Europe. In: Harris, A.L. & Fettes, D.J. (eds.), The Caledonian-Appalachian Orogen. Geological Society, London, Special Publications, 38, 549-558. https://doi.org/10.1144/GSL.SP.1988.038.01.37

Le Fevre, C., 2013. Gas storage in Great Britain. 2013. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2013/01/NG72.pdf

Leslie, A.G., Browne, M.A., Cain, T. & Ellen, R., 2016. From threat to future asset—The legacy of opencast surface-mined coal in Scotland. International Journal of Coal Geology, 164, 123-133. https://doi.org/10.1016/j.coal.2016.06.017

Loftus, G.W.F. & Greensmith, J.T., 1988. The lacustrine Burdiehouse limestone formation - a key to the deposition of the Dinantian oil shales of Scotland. In: Fleet, A.J. Talbot, M.R. (eds), Lacustrine Petroleum Source Rocks. Geological Society of London, Special Publication 40, 219-234. https://doi.org/10.1144/GSL.SP.1988.040.01.19

Lund, H., Østergaard, P.A., Connolly, D., Ridjan, I., Mathiesen, B.V., Hvelplund, F., Thellufsen, J.Z. & Sorknæs, P., 2016. Energy storage and smart energy systems. International Journal of Sustainable Energy Planning and Management, 11, 3-14. https://doi.org/10.5278/ijsepm.2016.11.2

Lund, H., Østergaard, P.A., Chang, M., Werner, S., Svendsen, S., Sorknæs, P., Thorsen, J.E., Hvelplund, F., Mortensen, B.O.G., Mathiesen, B.V. and Bojesen, C., 2018. The status of 4th generation district heating: Research and results. Energy, 164, 147-159. https://doi.org/10.1016/j.energy.2018.08.206

Macdonald, A.M., Ball, D.F. & Ó Dochartaigh, B.É., 2004. A GIS of aquifer productivity in Scotland: explanatory notes. BGS Commissioned Report CR/04/047N.

Mabon, L., Shackley, S. & Bower-Bir, N., 2014. Perceptions of sub-seabed carbon dioxide storage in Scotland and implications for policy: a qualitative study. Marine Policy, 45, 9-15. https://doi.org/10.1016/j.marpol.2013.11.011

Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, Maycock, M. Tignor & T. Waterfield (eds.), 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland, 32 pp.

McCay, A.T. & Younger, P.L., 2017. Ranking the geothermal potential of radiothermal granites in Scotland: are any others as hot as the Cairngorms? Scottish Journal of Geology, 53, 1-11. https://doi.org/10.1144/sjg2016-008

McCay, A.T., Feliks, M.E.J. & Roberts, J.J., 2019. Life cycle assessment of the carbon intensity of deep geothermal heat systems: A case study from Scotland. Science of the Total Environment, 685, 208-219. https://doi.org/10.1016/j.scitotenv.2019.05.311

Milligan, G., Wood, G., Younger, P. L., Feliks, M., McCay, A., Gillespie, M., Steen, P., McBeth, N., Townsend, D., Townsend, P., Stephenson, R. & Gomez-Riva E., 2016. Hill of Banchory Geothermal Energy Project Feasibility Study. Retrieved from http://www.gov.scot/Publications/2016/03/6881

Monaghan, A.A., Ford, J., Milodowski, A., McInroy, D., Pharaoh, T., Rushton, J., Browne, M., Cooper, A., Hulbert, A., Napier, B., 2012. New insights from 3D geological models at analogue CO_2 storage sites in Lincolnshire and eastern Scotland, UK. Proceedings of the Yorkshire Geological Society, 59, 53-76. https://doi.org/10.1144/pygs.59.1.289

Monaghan, A.A. & Parrish, R.R., 2006. Geochronology of Carboniferous–Permian magmatism in the Midland Valley of Scotland: implications for regional tectonomagmatic evolution and the numerical time scale. Journal of the Geological Society, London, 163, 15-28. https://doi.org/10.1144/0016-764904-142

Monaghan, A.A., 2014. The Carboniferous shales of the Midland Valley of Scotland: geology and resource estimation. British Geological Survey for Department of Energy and Climate Change, London, UK.

Monaghan, A.A., 2017. Unconventional energy resources in a crowded subsurface: Reducing uncertainty and developing a separation zone concept for resource estimation and deep 3D subsurface planning using legacy mining data. Science of the Total Environment, 601-602, 45-56. https://doi.org/10.1016/j.scitotenv.2017.05.125

Mouli-Castillo, J., Wilkinson, M., Mignard, D., McDermott, C., Haszeldine, R.S., Shipton, Z.K., 2019. Inter-seasonal compressed air energy storage using saline aquifers. Nature Energy, 4, 131-139. https://doi.org/10.1038/s41560-018-0311-0

Murchison, D.G. & Raymond, A.C., 1989. Igneous activity and organic maturation in the Midland Valley of Scotland. International Journal of Coal Geology, 14, 47-82. https://doi.org/10.1016/0166-5162(89)90078-5

Ó Dochartaigh, B.E., 2004. The Physical properties of the Upper Devonian/Lower Carboniferous aquifer in Fife. British Geological Survey Internal Report, IR/04/003. 27 pp.

Ó Dochartaigh, B.E., Macdonald, A.M., Fitzsimons, V. & Ward, R., 2015. Scotland's aquifers and groundwater bodies. Nottingham, UK, British Geological Survey, 63pp. British Geological Survey open Report OR/15/028. http://nora.nerc.ac.uk/id/eprint/511413/

Olasolo, P., Juárez, M.C., Morales, M.P. & Liarte, I.A., 2016. Enhanced geothermal systems (EGS): A review. Renewable and Sustainable Energy Reviews, 56, 133-144. https://doi.org/10.1016/j.rser.2015.11.031

Paterson, I.B. & Hall, I.H.S., 1986. Lithostratigraphy of the latedevonian and early carboniferous rocks in the Midland valley of Scotland. British Geological Survey Report, Vol. 18, No. 3.

Renaldi, R. & Friedrich, D., 2019. Techno-economic analysis of a solar district heating 9system with seasonal thermal storage in the UK. Applied Energy, 236, 388-400. https://doi.org/10.1016/j.apenergy.2018.11.030

Renewable Energy Foundation. Balancing Mechanism Wind Farm Constraint Payments. Available at: http://www.ref.org.uk/constraints/indextotals.php. (Accessed: 18th July 2019)

Richards, H.G., Parker, R.H., Green, A.S.P., Jones, R.H., Nicholls, J.D.M., Nicol, D.A.C., Randall, M.M., Richards, S., Stewart, R.C. & Willis-Richards, J., 1994. The performance and characteristics of the experimental hot dry rock geothermal reservoir at Rosemanowes, Cornwall (1985–1988). Geothermics, 23, 73-109. https://doi.org/10.1016/0375-6505(94)90032-9

Roberts, J.J., Gilfillan, S.M.V., Stalker, L., Naylor, M., 2017. Geochemical tracers for monitoring offshore CO_2 stores. International Journal of Greenhouse Gas Control, 65, 218-234. https://doi.org/10.1016/j.ijggc.2017.07.021

Robinson, R.A.J., Townsend, P., Steen, P., Barron, H., Abesser, C.A., Muschamp, H., McGrath, I. & Todd, I., 2016. Geothermal Energy Challenge Fund: the Guardbridge Geothermal Technology Project. Scottish Government. Retrieved from: https://www.gov.scot/publications/guardbridge-geothermal-technology-demonstrator-project-feasibility-report/

Rogelj, J., Elzen, M. Den, Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K. & Meinshausen, M., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature, 534, 631–639. https://doi.org/10.1038/nature18307

Schmidt, O., 2018. Levelised Cost of Storage for Gravitricity storage systems. Imperial College London (Consultants). Available upon request from Gravitricity. https://www.gravitricity.com/

Scottish Parliament, 2009. Climate Change (Scotland) Act 2009. Edinburgh, UK.

Scottish Government, 2011. Scottish Government's Land Use Strategy. Getting the Best from Our Land. Retrieved from: https://www.gov.scot/publications/getting-best-land-land-use-strategy-scotland/

Scottish Government, 2016. Energy in Scotland 2016. Retrieved from: http://www.gov.scot/Topics/Statistics/Browse/Business/Energy/EIS2016

Scottish Government, 2018a. Scottish Energy Strategy: The Future of Energy in Scotland. Available at: https://www.gov.scot/publications/scottish-energy-strategy-future-energy-scotland-9781788515276/

Scottish Government, 2018b. Oil and Gas Production Statistics 2017-18. https://www2.gov.scot/Resource/0054/00540203.pdf

Singh, R.M., Sani, K.A. & Amis, T., 2019. An overview of ground-source heat pump technology. In: Letcher, T. (ed) Managing Global Warming: An Interface of Technology and Human Issues. Elsevier. p. 455-485.

Smith, M., Campbell, D., Mackay, E. & Polson, D., 2011. CO_2 Aquifer Storage Site Evaluation

and Monitoring. Heriot-Watt University, Edinburgh.
http://nora.nerc.ac.uk/id/eprint/17527/1/CASSEM_Comp_12_12_11.pdf

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R.J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A.A., Yamagata, Y., Edmonds, J., Yongsung, C., Grubler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R.J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A.A., Yamagata, Y., Edmonds, J. & Yongsung, C., 2015. Biophysical and economic limits to negative CO_2 emissions. Nature Climate Change, 6, 42–50. https://doi.org/10.1038/nclimate2870

Smith, P., 2016. Soil carbon sequestration and biochar as negative emission technologies. Glob. Chang. Biol. 22, 1315–1324. https://doi.org/10.1111/gcb.13178

Staffell, I., Scamman, D., Velazquez Abad, A., Balcombe, P., Dodds, P.E., Ekins, P., Shah, N. & Ward, K.R., 2019. The role of hydrogen and fuel cells in the global energy system. Energy & Environmental Science, 12, 463-491. DOI: 10.1039/C8EE01157E

Stoker, M.S., Praeg, D., Shannon, P.M., Hjelstuen, B.O., Laberg, J.S., Nielsen, T., Van Weering, T.C.E., Sejrup, H.P. & Evans, D. 2005. Neogeneevolution of the Atlantic continental margin of NW Europe (Lofoten Islands to SW Ireland): anything but passive. In: DORE´, A.G. &VINING, B.A. (eds) Petroleum Geology: North-West Europe and Global Perspectives - Proceedings of the 6th Petroleum Geology Conference, 1057–1076. Geological Society, London.

Succar, S. & Williams, R., 2008. Compressed Air Energy Storage: Theory, Resources, and Applications for Wind Power. https://acee.princeton.edu/wp-content/uploads/2016/10/SuccarWilliams_PEI_CAES_2008April8.pdf

Talebi, B., Mirzaei, P.A., Bastani, A., & Haghighat, F., 2016. A review of district heating systems: Modeling and Optimization. Frontiers in Built Environment, 04 October 2016. https://doi.org/10.3389/fbuil.2016.00022

Taylor, L.L., Quirk, J., Thorley, R.M.S., Kharecha, P.A., Hansen, J., Ridgwell, A., Lomas, M.R., Banwart, S.A. & Beerling, D.J., 2015. Enhanced weathering strategies for stabilizing climate and averting ocean acidification. Nature Climate Change, 6, 402–406. https://doi.org/10.1038/nclimate2882

The Scottish Parliament (2018). Climate Change (Emissions Reduction Targets) (Scotland) Bill. Retrieved from: https://www.parliament.scot/parliamentarybusiness/Bills/108483.aspx

Thomson, K. & Underhill, J.R. 1993. Controls on the development and evolution of structural styles in the Inner Moray Firth Basin. In: Parker, J.R. (ed) Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference, 1167-1178. Geological Society, London.

Trewin, N.H., 2003. The Geology of Scotland. 4th revised edition. The Geological Society.

Tucker, O. & Tinios, L., 2017. Experience in developing the Goldeneye Storage Permit Application. Energy Procedia, 114, 7466-7479. https://doi.org/10.1016/j.egypro.2017.03.1880

Underhill, J.R., Monaghan, A.A. & Browne, M.A.E., 2008. Controls on structural styles, basin development and petroleum prospectively in the Midland Valley of Scotland. Marine and Petroleum Geology, 25, 1000–1022. https://doi.org/10.1016/j.marpetgeo.2007.12.002

Upton, B.G.J., Stephenson, D., Smedley, P.M., Wallis, S.M., & Fitton, J.G., 2004. Carboniferous and Permian magmatism in Scotland. Geological Society, London, Special Publications, 223(1), 195–218. https://doi.org/10.1144/gsl.sp.2004.223.01.09

Verhoeven, R., Willems, E., Harcouët-Menou, V., De Boever, E., Hiddes, L., Op't Veld, P. & Demollin, E., 2014. Minewater 2.0 project in Heerlen the Netherlands: transformation of a geothermal mine water pilot project into a full scale hybrid sustainable energy infrastructure for heating and cooling. Energy Procedia, 46, 58-67. https://doi.org/10.1016/j.egypro.2014.01.158

Walters, A.B., 1976. Technical and environmental aspects of underground hydrogen storage. 1st World Hydrogen Energy Conference 65–79, Miami Beach, Florida, US.

Watson, S., Westaway, R., Burnside, N. & Bradley, F. Influence of historic mining on Glasgow's subsurface thermal state to inform geothermal research: a review and synthesis. In review in the Scottish Journal of Geology.

Woodland Expansion Advisory Group (WEAG), 2012. Report of the Woodland Expansion Advisory Group to the cabinet secretary for rural affairs and environment, Richard Lochhead MSP 92. https://scotland.forestry.gov.uk/images/corporate/pdf/WEAGFinalReport.pdf

Westaway, R., 2016. Repurposing of disused shale gas wells for subsurface heat storage: preliminary analysis concerning UK issues. Quarterly Journal of Engineering Geology and Hydrogeology, 49, 213-227. https://doi.org/10.1144/qjegh2016-016

Westaway, R. & Younger, P.L., 2013. Accounting for palaeoclimate and topography: a rigorous approach to correction of the British geothermal dataset. Geothermics, 48, 31-51. https://doi.org/10.1016/j.geothermics.2013.03.009

Westaway, R., 2018. Deep Geothermal Single Well heat production: critical appraisal under UK conditions. Quarterly Journal of Engineering Geology and Hydrogeology, 51, 424-449. https://doi.org/10.1144/qjegh2017-029

Wilkinson, M., 2016. Cenozoic erosion of the Scottish Highlands–Orkney–Shetland area: implications for uplift and previous sediment cover. Journal of the Geological Society of London. https://doi.org/10.1144/jgs2016-064

Willems, C.J.L., Nick, H.M., Donselaar, M.E., Weltje, G.J. & Bruhn, D.F., 2017a. On the connectivity anisotropy in fluvial Hot Sedimentary Aquifers and its influence on geothermal doublet performance. Geothermics, 65, 222-233.

Willems, C.J.L., Nick, H.M., Goense, T. & Bruhn, D.F., 2017b. The impact of reduction of doublet well spacing on the Net Present Value and the lifetime of fluvial Hot Sedimentary Aquifer doublets. Geothermics, 68, 54-66.

Wilson, I.A.G., McGregor, P.G. & Hall, P.J., 2010. Energy storage in the UK electrical network: Estimation of the scale and review of technology options. Energy Policy, 38, 4099-4106. https://doi.org/10.1016/j.enpol.2010.03.036

Younger, P.L., Feliks, M.E., Westaway, R., McCay, A.T., Harley, T.L., Elliott, T., Stove, G.D., Ellis, J., Watson, S. & Waring, A.J., 2015. Renewing the exploration approach for mid-enthalpy systems: Examples from northern England and Scotland. In: World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015. Retrieved from: http://eprints.gla.ac.uk/107240/

Younger, P.L., Manning, D.A., Millward, D., Busby, J.P., Jones, C.R. & Gluyas, J.G., 2016. Geothermal exploration in the Fell Sandstone Formation (Mississippian) beneath the city centre of Newcastle upon Tyne, UK: the Newcastle Science Central deep geothermal borehole. Quarterly Journal of Engineering Geology and Hydrogeology, 49, 350-363. https://doi.org/10.1144/qjegh2016-053

Tables, figure captions and figures

Tables

Table 1: Summary of different GeoEnergy resources. In this work, we only consider resources that fit with Scotland's ambitions for a low-carbon country.

	Type	Technology	Description	Discussed in this study
Energy production	Geothermal energy	Deep geothermal energy	Extraction of heat from aquifers deeper than 500 m below surface.	**Yes**
		Enhanced geothermal systems	Extraction of high grade (high enthalpy) heat (>100 °C) from deep formations that require stimulation to create permeability.	**Yes**
		Mine water geothermal	Extraction of heat from groundwater-filled abandoned mines.	**Yes**
	Conventional hydrocarbons	Coal	Conventional coal extraction by open cast or underground mining.	No
		Oil & Gas	Oil and natural gas extraction from conventional reservoir-seal systems.	No
		Oil shale	Oil released by heating shale containing high organic content.	No
		Enhanced Oil Recovery (EOR)	Extraction of additional oil by secondary and tertiary methods.	No
	Unconventional hydrocarbons	Coal bed methane	Methane absorbed onto coal seams, released by dewatering the coal seams.	No
		Coal mine methane	Extraction of methane that naturally accumulates in coal mines.	No
		Tight gas	Natural gas produced from low-permeability reservoirs which need stimulating to enhance permeability to enable extraction.	No
		Shale gas	Natural gas trapped in low permeability shales which need hydaulic fracturing to enable extraction	No
		Underground Coal Gasification (UCG)	Process by which coal in un-mined seams is converted via oxidation into gas and extracted.	No
Energy storage	Thermal storage	Seasonal heat storage	Storage of excess or waste heat.	**Yes**
	Gas storage	Natural gas storage	Storage of natural gas in geological formations.	**Yes**
		Compressed Air Energy Storage (CAES)	Excess energy is used to compress air in geological formations, which can be decompressed to release energy.	**Yes**
		Hydrogen storage	Storage of hydrogen as substitute of natural gas.	**Yes**
	Gravimetry		Storage of energy by raising a weight, release energy by lowering the weight.	**Yes**
Storage of energy by-products	Geological CO_2 disposal	Carbon, Capture, and Storage (CCS)	Capture and permanent storage of CO_2	**Yes**
		Bio Energy with CCS (BECCS)	Capture and permanent storage of CO_2 from the combustion of biomass specifically grown for this process.	**Yes**
	Radioactive waste disposal		Permanent storage of high level radioactive waste in geological formations.	**Yes**

Table 2: Overview and state of all active geothermal projects in the Midland Valley from the last five years. DOR – Dormant, FEA – Feasibility study, OPE – Operational, DEV – Development phase. (Banks et al., 2009; Robinson et al., 2016; Brownsort & Johnson, 2017; Monahgan, 2017)

Type	Project	Location	Target depth	Purpose	Capacity	Status
Deep geothermal	HALO	Kilmarnock	2 km	Heat recovery via hybrid closed loop borehole	400 kW	DOR
	Collegelands	Glasgow City Centre	6 km	Power production and heat recovery	10+ MW	FEA
	Guardbridge Geothermal	Near St Andrews	1.1 km	Heat recovery via single well	139-418 kW	FEA
Minewater	Shettleston Minewater	Shettleston (Glasgow)	0.2 km	Minewater heat recovery	16 dwellings	OPE
	Lumphinnanas	Near Cowdenbeath (Fife)	0.2 km	Minewater heat recovery	18 dwellings	OPE
	UKGEOS	Dalmarnock/ Rutherglen (Glasgow)	0.2 km	Minewater energy research	n/a	DEV
	Fortissat Community Minewater	Fortissat (North Lanarkshire)	~0.3 km	Minewater heat recovery	0.7 - 2 MW (300 - 600 dwellings)	FEA

Table 3: Low-carbon GeoEnergy sources and applications proposed in this study, their readiness for implementation and their current status in the Midland Valley.

<table>
<tr><th colspan="2" rowspan="2">Type</th><th rowspan="2">Technology</th><th colspan="2">Development status</th></tr>
<tr><th>International</th><th>Midland Valley</th></tr>
<tr><td rowspan="2">Energy production</td><td rowspan="2">Geothermal Energy</td><td>Deep geothermal heat</td><td>System in operation</td><td>Feasibility stage</td></tr>
<tr><td>Mine water geothermal</td><td>Technology demonstration</td><td>Demonstration stage</td></tr>
<tr><td rowspan="5">Energy storage</td><td>Thermal storage</td><td></td><td>System in operation</td><td>Feasibility stage</td></tr>
<tr><td rowspan="3">Gas storage</td><td>Natural gas storage</td><td>System in operation</td><td>No current interest</td></tr>
<tr><td>Compressed air energy storage</td><td>Prototype in operation</td><td>No current interest</td></tr>
<tr><td>Hydrogen storage</td><td>Research to prove feasibility</td><td>Research stage</td></tr>
<tr><td>Gravity storage</td><td></td><td>Technology demonstration</td><td>Prototype development</td></tr>
<tr><td rowspan="2">Storage of energy bi-products</td><td rowspan="2">Geological CO_2 disposal</td><td>Carbon Capture and Storage (CCS)</td><td>System in operation</td><td>No current interest</td></tr>
<tr><td>Bio Energy with CCS (BECCS)</td><td>Research to prove feasibility</td><td>Research stage</td></tr>
</table>

Figure Captions

Figure 1: Final energy consumption in Scotland in 2015, split into broad end use sectors, including heat, transport, and electricity. From Scottish Government (2018).

Figure 2: Geological map of the Midland Valley. Other major and minor faults together with major anticlines and synclines are indicated (including: CF, Campsie Fault; NTF, North Tay Fault; STF, South Tay Fault; LF, Lammermuir Fault; CS, Clackmannan Syncline; LS, Lochore Syncline; BA, Burntisland Anticline; MLS, Midlothian-Leven Syncline; DA, D'Arcy-Cousland Anticline). The locations of the West Calder and the D'Arcy well, the first two oil exploration wells in Scotland, are highlighted. Compiled from BGS data and inspired by Monaghan (2014) and Underhill et al. (2008). The map contains ©British Geological Survey Bedrock Geology 625,000 scale data.

Figure 3: Schematic figure introducing the hydrogen storage cycle in the Midland Valley. For "blue" hydrogen, natural gas would be transported from North Sea hydrocarbon fields to the mainland and separated into hydrogen and CO_2 by steam methane reforming (SMR). The CO_2 would be captured and transported to depleted offshore fields for permanent storage. Alternatively, the sustainable "green" hydrogen, produced by electrolyses with renewable electricity will be produced using excess energy. The hydrogen would then be stored in subsurface reservoirs and reproduced when energy demand is high, and to be transported via pipelines to consumers.

Figure 4: Agricultural land suitability map of the Midland Valley. Modified from Andersen et al. (2005).

Figure 5: Negative emission potentials and energy and economic cost of abatement for the four NETs modelled in the Midland Valley.

Figures

Figure 1

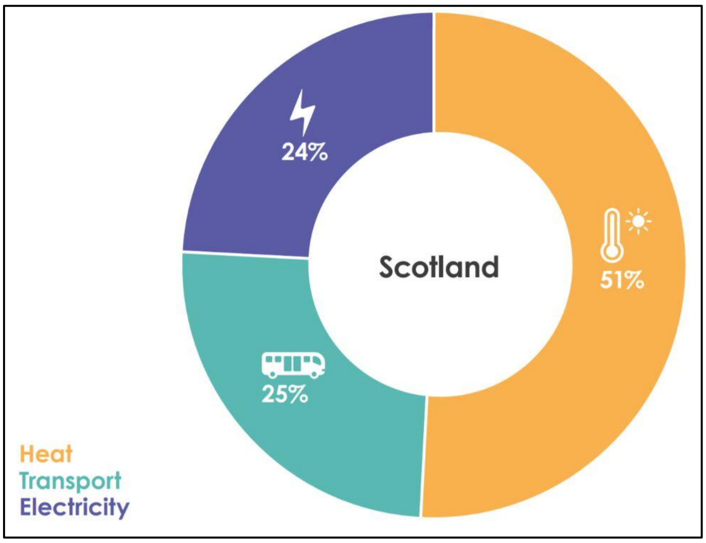
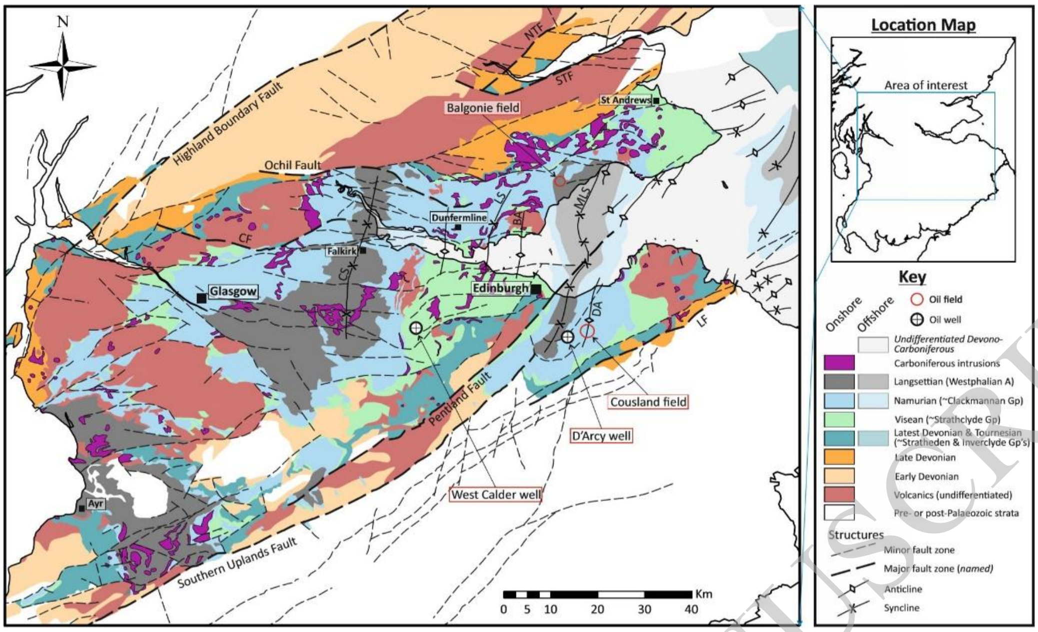
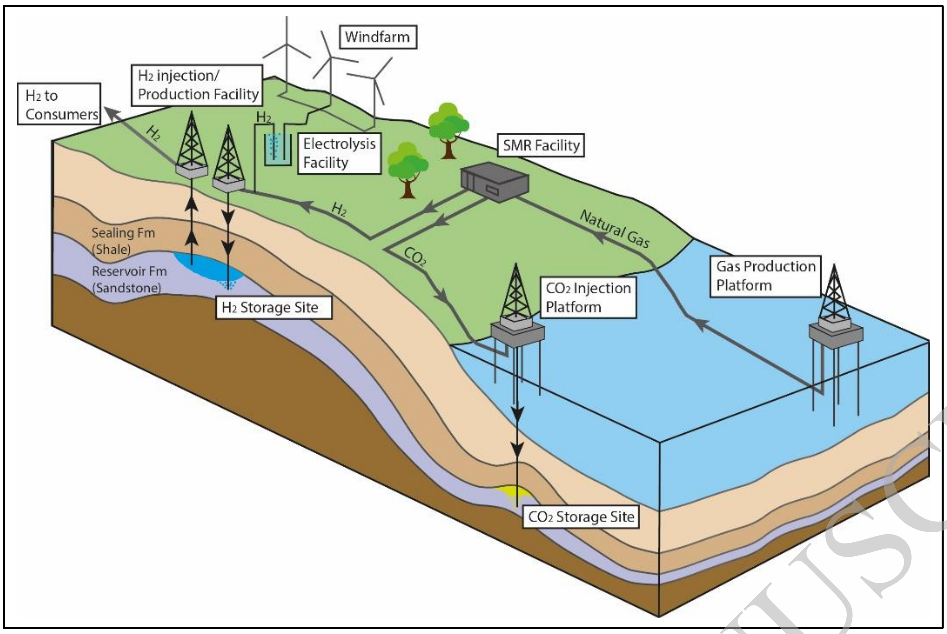


Figure 2



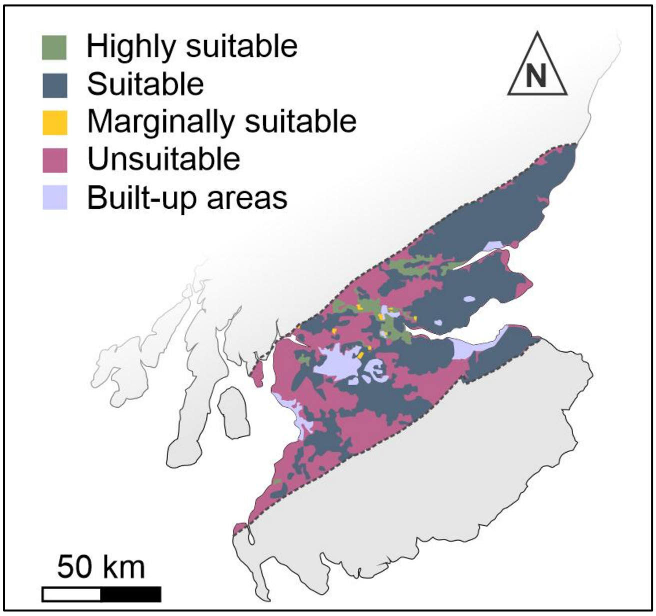
N
Highland Boundary Fault
Ochil Fault
NTF
STF
Balgonie field
St Andrews
CF
Dunfermline
LS
BA
MLS
Falkirk
CS
Glasgow
Edinburgh
DA
LF
Pentland Fault
Cousland field
D'Arcy well
West Calder well
Ayr
Southern Uplands Fault
Km
0 5 10 20 30 40
Location Map
Area of interest
Key
Onshore
Offshore
Oil field
Oil well
Undifferentiated Devono-Carboniferous
Carboniferous intrusions
Langsettian (Westphalian A)
Namurian (~Clackmannan Gp)
Visean (~Strathclyde Gp)
Latest Devonian & Tournesian (~Stratheden & Inverclyde Gp's)
Late Devonian
Early Devonian
Volcanics (undifferentiated)
Pre- or post-Palaeozoic strata
Structures
Minor fault zone
Major fault zone (named)
Anticline
Syncline

Figure 3



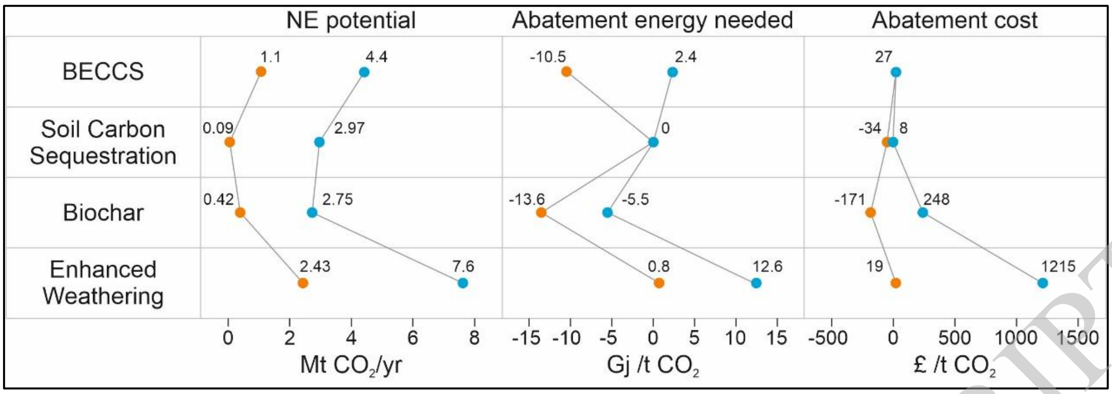
Windfarm
H2 injection/
Production Facility
H2 to
Consumers
H2
H2
Electrolysis
Facility
SMR Facility
H2
Natural Gas
CO2
Sealing Fm
(Shale)
Reservoir Fm
(Sandstone)
H2 Storage Site
CO2 Injection
Platform
Gas Production
Platform
CO2 Storage Site

Figure 4



Highly suitable
Suitable
Marginally suitable
Unsuitable
Built-up areas
N
50 km

Figure 5



NE potential
Abatement energy needed
Abatement cost
BECCS
Soil Carbon Sequestration
Biochar
Enhanced Weathering
1.1
4.4
0.09
2.97
0.42
2.75
2.43
7.6
-10.5
2.4
0
-13.6
-5.5
0.8
12.6
27
-34
8
-171
248
19
1215
0 2 4 6 8
Mt CO_2/yr
-15 -10 -5 0 5 10 15
Gj /t CO_2
-500 0 500 1000 1500
£ /t CO_2