Deep Geothermal Energy in the Shetland Isles

Shetland Heat Energy and Power (SHEAP) are exploring how to expand their district heating scheme in Lerwick. One option is to tap into the deep geothermal heat located below the islands. This report explores the feasibility of this idea and also considers heat storage in the rocks beneath Lerwick.

Granitic intrusion exposed at Burki Taing, Muckle Roe

A report by Cluff Geothermal Limited

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Executive Summary:

The economics of heat in Shetland make the business case for a deep geothermal heat scheme attractive…

Deep geothermal direct heat systems are commercially viable where a sufficient flow of hot water can be found at accessible depths, and at a reasonable distance from heat customers. This heat at depth can be exploited by drilling a pair of boreholes for 'production' and 're-injection' of the hot water, which is used for space and water heating at the surface. Such systems have a very low carbon intensity and typically function for many decades. The amount of heat from a single system is usually in the range 2-5 megawatts, with temperatures in the 65-95 °C range.

The UK Government supports deep geothermal heat through the RHI at 5.2 p/kWh, which is index-linked and payable for 20 years. Any renewable heat project in Shetland will also benefit from the high local market rate for heat: with gas central heating unavailable, the vast majority of Shetlanders use oil or electrical heating, both relatively expensive. The practical effect is to make a deep geothermal system that would be uncompetitive against gas a plausible investment option in Shetland – subject to suitable geology.

The dominant cost of a system is the up-front capital required to drill the boreholes, meaning that the long-term cost of heat produced can be known with some certainty. The cost of driving the pump is relatively small, and heat can be produced at a very high loading - more than 90% is achievable. This means that the unit cost of heat will be lowest – and profit margins highest – where systems can be run at a high load e.g. supplying a large heat network. The Shetland Heat Energy and Power (SHEAP) heat network in Lerwick is an obvious suitable heat customer. (As deep geothermal heat is non-intermittent it is more suited to meeting base load rather than peaking loads, so thought would need to needed as to how a system would fit into the future supply landscape.) Indicative analysis suggests a 3 MW borehole costing around £4.5 million and selling 60% of its heat at prices of 3.5-4p/kWh would have an IRR of around 21%. Increasing the load or achieving a higher heat price would boost this already high IRR further.

In short, the *economic* case for a deep geothermal heat plant in Shetland is very positive, assuming it was situated at a reasonable distance from heat customers and could be run at a relatively high load.

…but sadly the geology is generally unhelpful to geothermal development.

The two most common geological features associated with good geothermal potential are large 'radiothermal' granites and hot sedimentary aquifers. We judge the latter can be ruled out as an option in Shetland, but there are several granite masses distributed across the islands which justify further investigation (Page 12).

Heat flow in radiothermal granites comes from the decay of long-lasting radioactive elements in the rock. Cluff Geothermal conducted a survey of all the main granite outcrops on Shetland Mainland, Yell and Unst and Figure 7 (Page 14) shows the results. There are no outstandingly 'hot' outcrops, though some are promising. Unfortunately, the distribution of 'hotter' granites is not helpful when set against the location of Lerwick and the larger centres of population. The closest outcrop to the SHEAP, at Girlsta, showed some of the lowest readings. One possible development opportunity could be the settlement at Brae, where nearby readings were relatively good and the local fault structure could be conducive to boosting permeability.

Our judgement is that the distribution of geothermal potential in the Shetland granites is such that building a commercially viable deep geothermal heat system would be difficult (with Brae the one possible exception).

A possible inter-seasonal heat store

One method of making use of excess heat produced in the summer months is to store it below ground for use in the winter. The two most common types of underground thermal energy storage (UTES) – open and closed-loop – use multiple, relatively shallow boreholes to transfer heat directly or indirectly into the rock units below.

A future geological investigation could look into the possibility of UTES beneath Lerwick, where the geology may well be suitable. This would comprise: a hydrogeological field investigation; heat storage and retrieval modelling; and an environmental risk assessment. We estimate the budget for such an investigation as in the region of £200,000.

Part I - Deep Geothermal energy: an introduction

Deep geothermal energy exploits the vast amount of heat found in the Earth's crust. It has long been recognised as a low carbon, sustainable and renewable energy technology. Well established in areas such as Iceland and California, several projects have recently been successfully rolled out in Europe, making use of more moderate but still exploitable deep geothermal resources.

The key idea behind deep geothermal technology is transferring heat from depth to the surface – invariably using water as the transfer medium – and using it either directly for space and water heating, or to produce electricity. Producing power requires higher temperatures and much more advanced engineering, and thus presents a higher level of challenge than direct heat production.

Where does the heat come from?

Conduction of heat from the Earth's mantle provides a background flux of heat everywhere, but the more favourable locations for geothermal energy are those in which enhanced production of heat in the crust occurs by radioactive decay, and/or the transfer of heated water by thermal convection leading to accumulations of warm groundwater in particular aquifers (i.e. zones of permeable strata).

In places such as the UK (*Figure 1*), the main targets for geothermal energy exploration are accumulations of warm water in and around zones of low-level radioactive decay within 'radiothermal' granites; and water stored in hot aquifers heated by the similar processes in adjoining shales and/or convection from other hot zones.

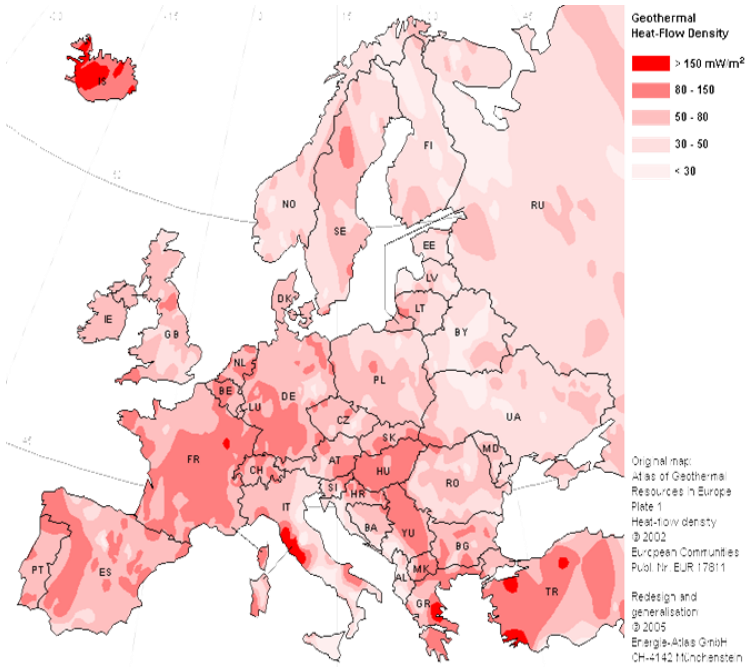


Fig. 1: Map showing areas of highest geothermal potential across Western Europe.

i) **Radiothermal granites:** Minerals containing trace radioactive elements are found in granites. The radioactive decay process (usually at a very low level) releases energy in the form of heat which is transferred steadily over many millennia into the surrounding rock. Depending on the individual circumstances of their formation, different granites will display different radioactive properties, and older rocks have predictably lower radioactivity counts. In Shetland, there are a wide range of igneous intrusions that merit investigation as suitable source rocks for a deep geothermal system.

ii) **Hot sedimentary aquifers:** The temperature of the Earth increases with depth - this is known as the 'geothermal gradient'. Some regions have steeper thermal gradients than others, making them more suitable targets for geothermal exploitation. Aquifers (underground layers of water bearing rock) at depth in these regions are obvious targets for deep geothermal energy projects. Quite simply, the hot water at depth can be pumped to the surface and used to provide space and water heating.

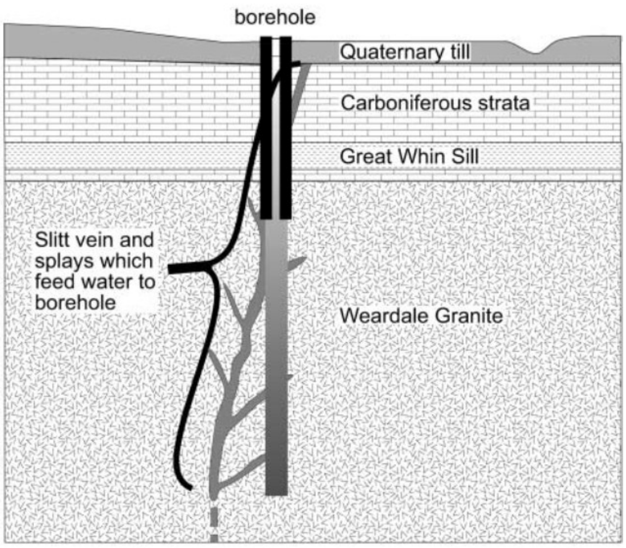
Where deep aquifers exist in proximity to hot radiothermal granites, the water in the aquifers can act as a distribution medium for the heat from the granite.

Permeability, as well as temperature, is important

An important objective for any deep geothermal project is, obviously, to find water which is hot enough to meet the demands at the surface. But equally important is finding sufficient *permeability*, or flow of water at depth. If the structure of the rocks is too tight, the flow of water will be too low to permit a commercially viable project. Ideally, therefore, any project will aim to locate a layer with high permeability – an aquifer – at a suitably high temperature.

Permeability can be caused by water moving through the small pores in the rock itself ('primary permeability') which can be very high e.g. in some sandstones; or very low, as in typical granites. 'Secondary permeability' is due to larger scale fractures and faulting in the rock.

As granites have very low primary permeability, deep geothermal systems often make use of any existing secondary permeability. In Weardale, County Durham, the 'Eastgate No. 1' borehole was drilled to a depth of 995 metres in 2004. Here, secondary permeability associated with a mineral vein (the 'Slitt Vein') was used to measure the temperature of radiothermally heated water (*Figure 2*). The level of permeability identified at Eastgate was comfortably enough to support a heat only deep geothermal energy station.



(Manning et al., 2007. *A deep geothermal exploration well at Eastgate, Weardale, UK: a novel exploration concept for low enthalpy resources*)

Fig. 2: *Schematic cross-section to illustrate the design of the Eastgate No. 1 Borehole*

What does a typical geothermal heat-only system look like?

A typical 'heat-only' project works on a very simple conceptual model. First of all, an exploratory borehole is drilled with the aim of finding a suitable source of hot water. (There will always be some uncertainty about the quality of the resource until the borehole is actually drilled and tested, and a key part of any project is identifying a drill site with the highest percentage chance of success - see Part II.)

Assuming that that a suitable source of hot water is located, this first borehole becomes the 'production' hole. Usually a second, 're-injection borehole' is drilled to return the water to a similar depth. In summary, a circuit is established: hot water is pumped from depth, the heat is used at the surface, and the now cooler water is pumped back to depth.

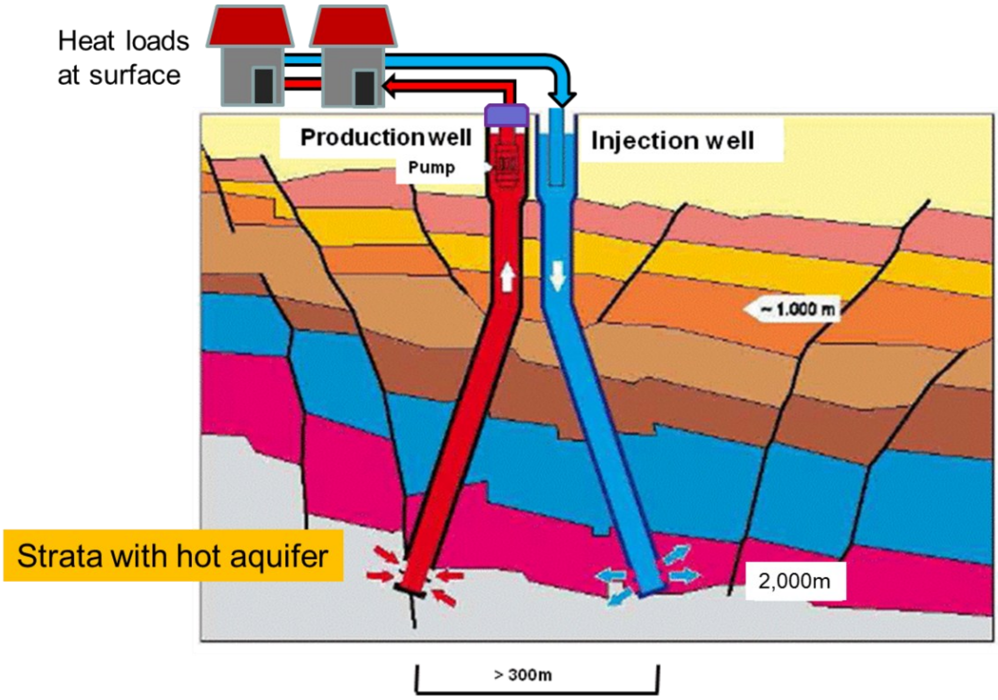


***Fig. 3:** A schematic diagram of a typical deep geothermal couplet heat system*

Often the heat is captured via a 'heat exchanger'. In other words, the heat in the water coming from depth is transferred to water that has been obtained at the surface rather than being used directly in any applications. This transfer can be done with high efficiency. The chemical composition of the water from depth is a key factor here: problematic elements present in the extracted water may make using the water directly untenable (e.g. routing it through radiators).

Conversely, in some cases the water from the production borehole can be disposed of at the surface without the need for a re-injection borehole. The only working example of a deep geothermal heat plant in the UK, in Southampton (see case study below) uses precisely this arrangement. Whether this is a realistic option will again depend largely on the chemical composition of the water from depth, as approval would be required from the Environment Agency. If this was a viable model the cost of the scheme could be significantly reduced. Obviously, having relatively close access to open sea water is crucial here – entirely plausible in Shetland.

Exceptionally long project lifetimes are common

If care is taken not to over tax the production borehole's capacity, deep geothermal heat sources can be highly sustainable. Pumping too many litres per second can lead to the water level in the borehole dropping and/or a reduction in temperature. Specifically to avoid this, test pumping is carried out after a first, exploratory borehole is completed, to establish precisely how much water/ heat can be extracted from the borehole without a significant temperature drop.

In practice is it common to find that relatively large amounts of heat (of the order of 2-5 MW) can sustainably be extracted from a typical borehole. Indeed a feature of geothermal energy plants is that they are particularly long-lasting. While the pump may need to be replaced at the end of its design lifetime (typically decades) the boreholes themselves can be expected to remain useable well beyond that period without substantial further expense. It is not unknown for plants to remain productive for 100 years: the Lardarello geothermal power plant in Italy celebrated its centenary in 2013, and some heat-only schemes in the Western US date back to the 1890s.

Deep geothermal heat is ultra-low carbon in nature

Deep geothermal heat generation produces a particularly low level of greenhouse gases. The only two significant sources of these are the fuel consumed by the drilling rig (these usually run on diesel) and the input electrical power used to drive the pump. In the latter case one should note that water is not being raised from the full depth of the borehole – artesian pressure can be expected to bring it much nearer to the surface. The geothermal water itself will not give rise to any greenhouse gases as it produces heat, since no combustion is involved (volcanic geothermal sources in other countries may vent gases such as CO_2 if these are present in the water, but this is highly unlikely in Shetland).

Without knowing the amount of work the pump will need to do, it is not possible to give an exact figure for the CO_2 intensity per megawatt-hour of heat. However, a generalised example can be considered to give an indicative figure.

CO_2 footprint of a deep geothermal borehole (direct heat use)

Although drilling the borehole produces a significant amount of CO_2, these emissions should be considered against the system's full lifetime. The main source over a lifetime of (say) 30 years is the electricity-driven pump which circulates fluid out of the borehole. We assume that is the pump's lifetime, and also that: the borehole is drilled to approximately 2,000 metres; it produces 2 MW of heat; has a pumping rate of 0.02 m^3/s; and runs at 60% efficiency over its lifetime, producing a total of 315,360 megawatt-hours of direct heat. We also assume that the electricity to drive the pump is sourced from the National Grid. The calculations for total CO_2 emissions from a deep geothermal system are given below.

i) Pump power usage:

$$P = \frac{\rho g Q h}{\eta} \qquad \text{Eqn.1}$$

[where P = power (W); ρ = fluid density (kg/m³); g = gravitational acceleration (m/s²); Q = pumping rate (m³/s); h = pumping head (m) and η = efficiency of pump]

We calculate the pump power using pumping heads of 50 m (MIN) and 100 m (MAX)

MIN:

$$P = \frac{\rho g Q h}{\eta}$$

$$P = \frac{1000 \times 9.81 \times 0.02 \times 50}{0.6}$$

$$P = 16350$$

MAX:

$$P = \frac{1000 \times 9.81 \times 0.02 \times 100}{0.6}$$

$$P = 32700$$

So: pump power will range from 16.35 kW – 32.7 kW.

ii) Pump CO_2 footprint:

30 years	=	262980	hours
If pump runs 60% of the time	=	157788	hours
Grid electricity CO_2 footprint	=	0.52037	kg of CO_2 per kWh
Pump power for 50 m drawdown	=	16.35	kW
Pump power for 100 m drawdown	=	32.7	kW

iii) Drilling CO_2 footprint:

Drilling time	=	1200	hours
Fuel (diesel) use per day	=	1500	litres
Fuel use per hour	=	62.5	litres
Total fuel use	=	75000	litres
CO_2 from 1 litre of diesel	=	2.6769	kg
Total CO_2 from drilling	=	200.7675	tonnes

MIN:

CO_2 from pump over 30 years	=	1342.468	tonnes
CO_2 from drilling	=	200.7675	tonnes
Total CO_2 over 30 years	=	1543.236	tonnes
Average CO_2 produced per year	=	*51.44*	*tonnes*

MAX:

CO_2 from pump over 30 years	=	2684.936229	tonnes
CO_2 from drilling	=	200.7675	tonnes
Total CO_2 over 30 years	=	2885.703729	tonnes
Average CO_2 produced per year	=	*96.19*	*tonnes*

The carbon intensity of this typical 2 MW borehole is:

MIN: 4.89 kgCO_2/MWh

MAX: 9.15 kgCO_2/MWh

This compares to 185 kg of CO_2 per MWh of heat from natural gas central heating, and 520 kg of CO_2 per MWh of electrical heat. In other words, deep geothermal heat is exceptionally low carbon in nature and close to zero carbon in comparison with gas heat (the 'reference' heat type for the UK).

Suggested alternative sources of heat available for expanding the Lerwick district heating scheme include: electric heating sourced from wind power; wood pellet biomass burners; combined heat and power (CHP) schemes; and further waste oil incineration. These would all generate their own versions of the above carbon intensity figures, estimations of which are included below:

Wind	21.0	kgCO_2/MWh
Wood pellets	38.95	kgCO_2/MWh
Waste oil	259.14	kgCO_2/MWh

Note: Carbon intensity values for heat use from CHP systems are varied, as it is difficult to assign heat an exact proportion of emissions.

Geothermal energy in the UK – the Southampton experience:
There is one example of a working deep geothermal energy station in the UK, in Southampton. Despite a relatively low profile it has been a great success, running continuously from the mid-80s until the pump failed around 2010. A new pump is being installed and the system is expected to be working again in 2014.

The genesis of the scheme was an 1,800 metre deep borehole drilled in the course of a 1980s Department of Energy geothermal research project. Rather than see it abandoned Southampton City Council bought it for £1. With a pump installed the well became a 1.5 MW heat source and was used to kick start a heat network with the Council HQ (*Figure 4*) as the anchor heat load. The outflow water is disposed of into the sea, which has not caused any environmental issues.

***Fig 4:** Southampton Council HQ – geothermally heated since the 80s*

The surface footprint of the geothermal well is very small – a few parking spaces in a car park – and it enjoys high levels of public acceptance. In fact, a substantial percentage of the local population probably do not realise it is there and the project may be less celebrated than one might expect due to being developed before climate change and decarbonisation became high profile issues.

The Southampton heat network shows what can be achieved with a good geothermal resource and supportive heat customers.

Government policy and regulatory background

Recent UK Governments (both the Coalition and Labour) have been strong supporters of deep geothermal energy, despite the sector being at a very early stage of development in the UK. Some £5 million of grant funding was allocated to deep geothermal projects in 2009-2011, while deep geothermal was given its own dedicated tariff under the Renewable Heat Incentive (RHI), a subsidy regime for renewable heat generators that was introduced in 2011.

The RHI gives deep geothermal heat generators 5.2p (which is index linked) for every kilowatt hour they generate for a 20 year period. This is a highly attractive incentive which is payable only on 'useful heat' (i.e. it is designed to avoid incentivising generators to produce heat in a wasteful way). One condition of a project being eligible for the RHI is that it has not received government grants – though note that grant funding for an associated heat network would <u>not</u> make deep geothermal heat produced ineligible for a RHI funding.

The regulatory environment for deep geothermal is relatively light, due mainly to the absence of any explicit legislation covering it. Boreholes need to go through the normal planning procedures (though as temporary structures this is not always necessary) and – in England – a water abstraction licence is required from the Environment Agency. As there are no deep geothermal boreholes in Scotland, there are no precedents for SEPA to follow, and their approach would need to be explored.

How could deep geothermal heat contribute to the Lerwick heat network?

Shetland is not connected to the UK gas or electricity grid, and most heating is done using fuel oil. Typical costs to the consumer are 8.5 p/kWh, which is high by UK standards. This creates a positive environment for a heat network.

The base load heat input to the network is provided by the 'unwanted' heat from a 6.8 MW waste incinerator (Martin and Spence, 2010). This generates heat continuously, an inflexibility which leads to the venting of 2-3 MW of unneeded heat in the summer when demand is low. In winter there is a peak demand of 11.5 MW, necessitating using fuel oil as a back-up heat source. The cost of heat to domestic consumers connected to the heat network is 6.3p/kWh.

The attraction of a potential deep geothermal scheme is that it could provide heat to cover the extra peak load in winter in a way that is more cost-effective than fuel oil. The flow of income from the Renewable Heat Incentive provides crucial support in this regard. Sourcing heat from a deep geothermal network would also be a much lower carbon option than using fuel oil: a typical deep geothermal well might produce 5-9 $kgCO_2/MWh$, compared to around 250 $kgCO_2/MWh$ for fuel oils.

Notwithstanding the previous paragraph, the non-intermittent nature of deep geothermal heat is perhaps a drawback here. Given the fixed cost of the heat produced (which will be dominated by the up-front capital cost of the boreholes), deep geothermal schemes will be most commercial where they can be run as close to a full loading as possible i.e. they are naturally most suited to meeting steady base load demand. Pairing the technology with another that is suited to providing base load (such as the SHEAP waste incinerator) could be argued to be an inefficient arrangement, unless both were able to provide near-continuous heat to an expanded heat network.

(A further possibility of interest to SHEAP is using the geology around Lerwick to construct a large scale inter-seasonal heat storage facility. This option is considered in Part III.)

The costs and carbon intensity of deep geothermal and the likely alternatives

In weighing the benefits of a deep geothermal heat source (set out above) for Lerwick, we should bear in mind the other alternatives. These are as follows:

- Using wind turbines to provide power directly to immersion heaters and a large thermal storage tank. This would certainly work on a practical level (loading on wind turbines can be up to 50% in Shetland, which has an exceptional wind resource). Some might argue that using expensive (and highly subsidised) renewable electricity to provide heat rather than obtaining it from a cheaper – and perhaps also renewable – source is economically unbalanced.

- Using biomass. This would, obviously, be dependent on imported fuel. Other such schemes on the British Mainland have worked well, though typical problems developers face are: identifying a suitable long-term source of *sustainable* biomass fuel (some uncertainty continues to surround what constitutes 'sustainable'); the need for relatively large fuel storage facilities; and limited public acceptance.

- Using the waste heat from a new power station. SSE have proposed a new 120 MW oil or gas (not yet decided) power station at Lerwick to replace the current oil-powered 67 MW power station at Gremista. The heat network would utilise the heat from this power station, which is scheduled to be completed in 2016 or 2017. A possible connection to the Mainland electricity grid is a factor in how this power station would be run.

- Burning the 2000 tonnes of waste oils currently exported from Shetland.

- An arrangement involving large scale heat pumps, possibly sea-based.

Exploiting a deep geothermal option would clearly be a much lower carbon option than burning waste heavy oils, and would also be lower carbon than a heat pump solution (although note that if the heat pumps were being run on renewable energy – the power drawn by the pump is the largest source of carbon emissions – this would also be a very low carbon option). Deep geothermal heat would almost certainly be less carbon intensive than biomass heat, although giving an exact figure for the latter will be dependent on specific arrangements for fuel sourcing and transport arrangements.

It is much harder to quantify the relative carbon intensity of deep geothermal heat and a CHP scheme. If heat at a suitable temperature was available from the proposed SSE power plant, the effective carbon intensity of that heat would be low; but any reduction in efficiency that the power plant experiences in order to provide a suitable heat supply gives rise to carbon emissions that are attributable to the heat.

The business case for geothermal heat in Shetland

We have used our standard financial model to give indicative IRRs for a successful 3 MW deep geothermal borehole. We used the following assumptions:

- The production hole is capable of supplying 3 MW of heat
- The capital costs are £3.8 million in Year 1, covering all pre-drilling costs and three boreholes (an allowance for one ‘dry’ hole)
- Further capital costs of £1 million in Year 2 to connect the borehole to the network
- Heat sales begin in Year 3, and are eligible for support under the RHI
- One third of the sales are to commercial customers and two thirds are to domestic customers.

We have also assumed that a relatively high percentage of the heat can be sold as useful heat i.e. that the network has been expanded at some future point and offers a steady heat load for much of the year. We initially considered two cases: approximately a 60% load (6,000 MWh commercial sales, 10,000 MWh domestic sales) and approximately an 85% load (7,500 MWh commercial sales, 15,000 MWh domestic sales).

We assumed that the heat prices to commercial and residential prices would be significantly higher than on the Mainland at 5.5p/kWh and 6p/kWh respectively. We also considered an intermediate case with values of 4p and 3.5p/kWh.

The outturn IRRs for a system with these parameters were high, driven mainly by the high local prices for heat sales. For the high sales price + 60% load case we find an IRR of 25.6%, and even the intermediate sales price + 60% load case gives an IRR of 20.7%. In the case of a very high load (85%) the IRRs were higher still at 28.9% (low sales price) and 34.4% (high sales price).

It might be supposed that a production borehole that was operating at a rather low loading (say 30%) would be a non-starter, but even this looks a commercially viable proposal – if a lot more marginal – with IRRs of 9.7% and 12.8% for the low and high price cases respectively. (Throughout all this modelling the level of RHI is of course constant.)

In summary, the business case for a deep geothermal heat system in Shetland – if the geological resource permitted it – would be very positive, helped particularly by the market value of heat being higher than it is on the Mainland.

Part II - Deep geothermal energy resources: a reconnaissance appraisal of potential in Shetland

Hot sedimentary aquifers

Of the two deep geothermal reservoir resources described in Part I, it seems unlikely there will be any substantial hot aquifers beneath Shetland. This is mainly due to the overall rock structure of the islands, and lack of any notable deep sedimentary basins (see *Figure 5* below).

We judge that making use of a deep sedimentary aquifer for a geothermal project on Shetland can be discounted.

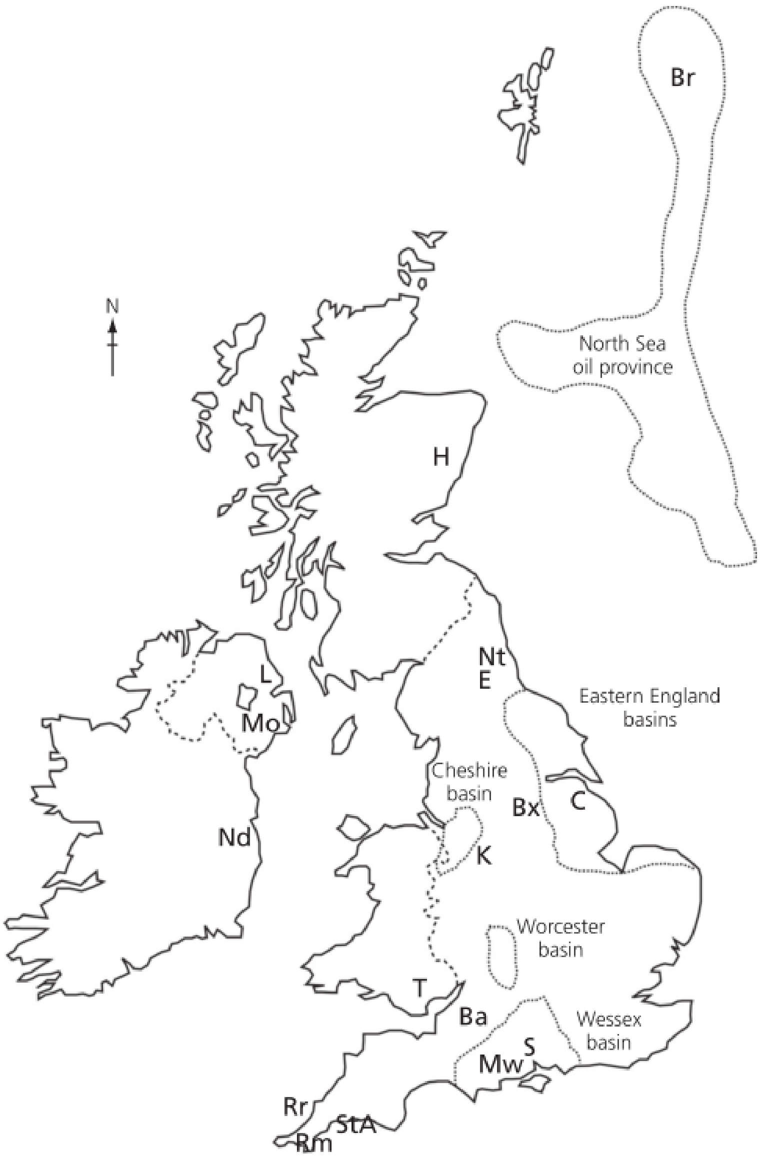


Fig. 5: *Deep sedimentary basins in and around the British Isles (Younger et al. 2012)*

Radiothermal granites – geological suitability

Outcrops of various igneous intrusions are present throughout the region, with a wide range of ages and composition. These are scattered across the islands from a large outcrop of granodiorite near St. Ninian's Isle in the south to the most northerly Skaw Granite on Unst. Their locations are shown on the geological map in *Figure 6*.

These rocks' radiothermal properties result from the low-level radioactive decay of Potassium, Uranium-series and Thorium-series decay elements, which generates heat energy. The differing compositions of igneous rocks lead to some accumulating more heat energy than others, and we can measure this in microwatts per square metre (µW/ m^2).

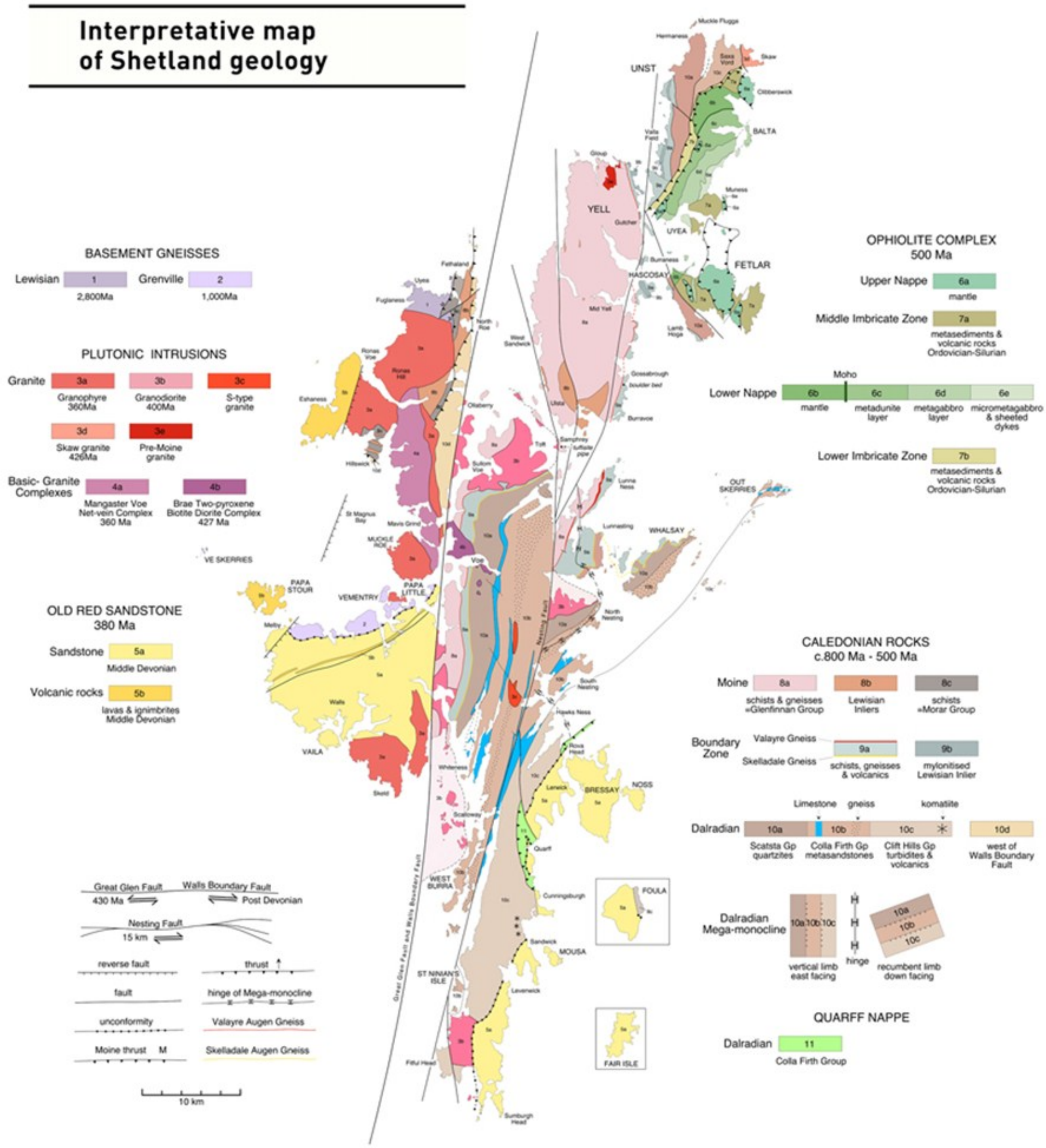


Fig. 6: *The hugely varied geology of Shetland*

During Cluff Geothermal's field visit to Shetland, surveys were carried out on outcrops of each of the granitic intrusions present on the islands. These resulted in measurements of radioactivity (in parts per million for equivalent Uranium and Thorium, and percentage for Potassium) and also overall heat production at each site. The results from these measurements are shown in *Table 1*.

For comparison, *Table 2* shows the results from a similar survey of Scottish eastern Highland granites. This survey used the same handheld gamma ray spectrometer technique so the results can be used as a good benchmark against the Shetland readings.

Figure 7 shows the average heat production values from each of the twelve locations. These show that the Shetland granites exhibit a wide range of values, some reasonably promising. *Figure 7* also includes heat production values from two comparable granites – Cairngorm and Weardale. These represent the upper range of heat production values from UK granites, so some of the Shetland sites fit into the 'mid-range' bracket when considering their suitability as heat producers. However, as discussed in Part I, permeability is equally as important when considering a geothermal resource. Further investigation could determine the suitability of individual granites.

Radiothermal granites – suitability for exploitation

The distribution of the 'hotter' granites is not, unfortunately, helpful given the location of the islands' main population centre and heat load at Lerwick. The closest granite outcrop to SHEAP, at Girlsta, had the second lowest heat production of the twelve, above only that recorded at Breckon in Yell (which is in fact far older than the other granites in Shetland, and almost 'burnt out'). The highest readings were in the far south of Mainland, not far north of Sumburgh airport; near Skeld; on Muckle Roe; and at Heylor on Ronas Voe.

These latter locations are at some distance from any population concentrations, with the exception of Muckle Roe and the small town of Brae. Readings from the granite on Muckle Roe (which is largely constituted of a granite mass) are relatively high, and the area is also very close – indeed bisected by – the Walls fault. We would therefore expect that secondary permeability would be good. A directionally drilled borehole relatively close to Brae would thus appear to have the best chance of uncovering a commercially viable deep geothermal resource on Shetland.

In summary, in our judgement a commercially viable deep geothermal borehole exploiting radiothermal granites to create a direct heat source is unlikely to be achievable near Lerwick or Scalloway. The prospects for this are more positive in the area of the township of Brae, to the north.

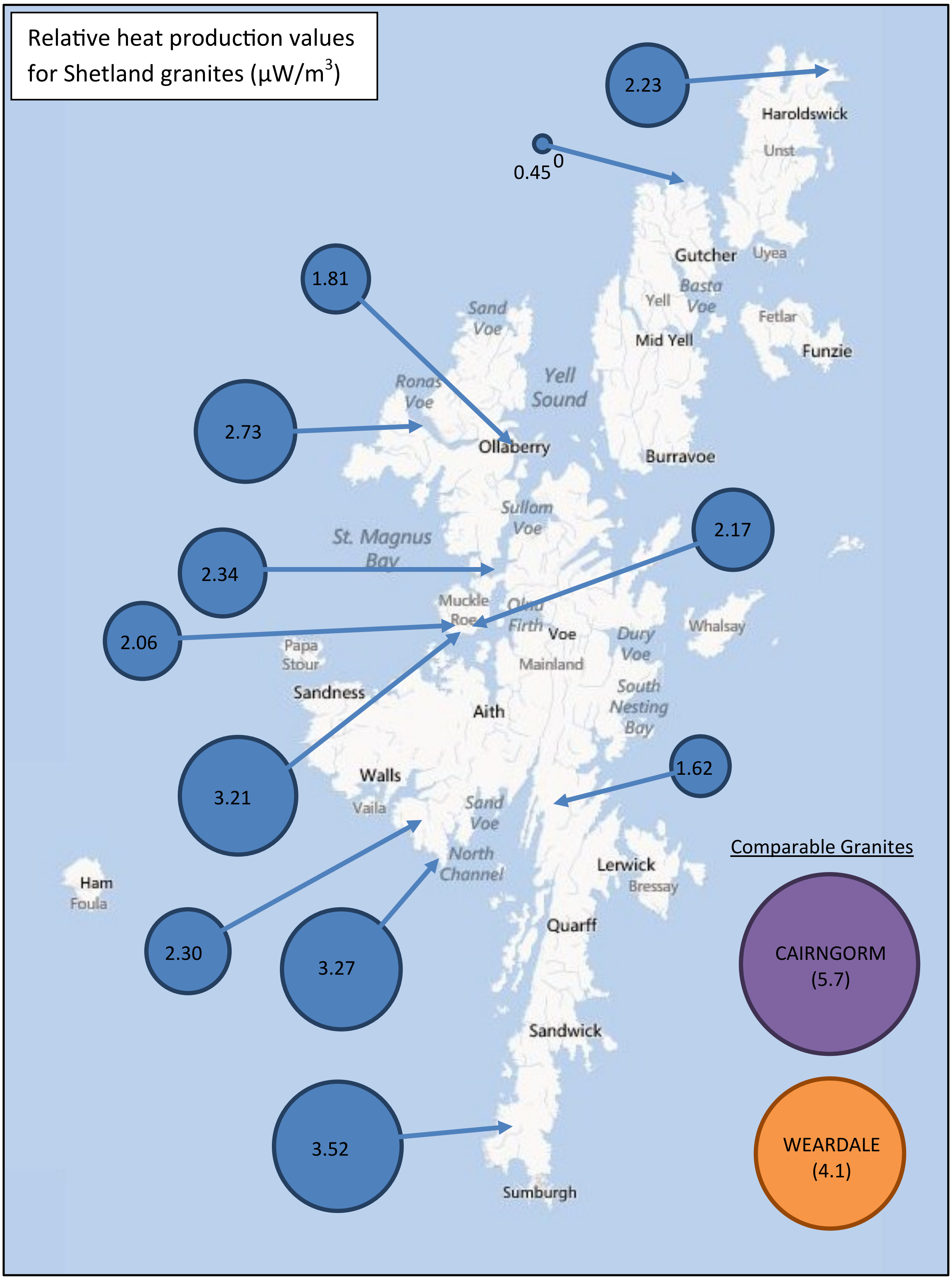


***Fig. 7:** Location of Shetland granitic intrusions with relative heat production*

Date	Site	Sample	Grid Reference (GPS)	K (%)	U (ppm)	Th (ppm)	Heat production (µW/m^3)	Notes
21/08/2013	Spiggie	A	HU 36659 17963	3.91	7.18	22.45	3.825927	
		B	HU 36659 17963	4.50	5.41	21.01	3.317031	
		C	HU 36659 17963	4.05	6.39	19.37	3.416040	
21/08/2013	Silwick	A	HU 29334 48489	5.44	4.14	26.43	3.453732	
		B	HU 29334 48489	5.75	4.96	25.44	3.628287	
		C	HU 29327 42425	5.17	3.90	17.18	2.716011	
21/08/2013	Hestinsetter	A	HU 28998 45665	4.31	1.69	15.00	1.902906	
		B	HU 28998 45665	4.44	2.78	15.43	2.230848	
		C	HU 28998 45665	4.39	5.32	13.69	2.769201	
21/08/2013	Ell Wick (Brae)	A	HU 34549 67967	4.23	1.72	15.37	1.929177	
		B	HU 34549 67967	4.22	4.93	15.47	2.775951	
		C	HU 34549 67967	4.01	3.50	14.59	2.319813	
22/08/2013	Muckle Roe: Cumle	A	HU 32304 62925	3.24	3.07	16.07	2.238327	
		B	HU 32304 62925	3.80	2.41	16.00	2.113479	
		C	HU 32296 62954	2.31	1.85	18.07	1.971324	
		D	HU 32296 62954	2.20	3.24	18.70	2.369196	Best exposure at this locality
22/08/2013	Muckle Roe: Burki Taing (west cliff)	A	HU 31679 62764	2.72	5.14	19.10	2.944026	
		B	HU 31679 62764	4.34	4.86	23.12	3.305988	
		C	HU 31679 62764	0.30	3.10	28.17	2.817774	Found to be thin granite layer on front of dark intrusion
		D	HU 31679 62764	3.69	4.79	25.26	3.376458	
22/08/2013	Muckle Roe: Mill Lochs	A	HU 32248 63319	4.58	3.96	12.38	2.339010	
		B	HU 32257 63325	3.96	1.89	11.89	1.703889	
		C	HU 32261 63304	4.67	2.20	15.93	2.135781	
22/08/2013	Heylor	A	HU 29833 80542	4.09	2.81	21.78	2.651400	
		B	HU 29833 80542	4.85	3.06	25.23	3.030885	
		C	HU 29833 80542	5.36	2.79	18.11	2.508543	
22/08/2013	Back of Ollaberry	A	HU 37134 80930	2.57	3.12	13.81	2.029455	Walls Boundary Fault location on cliffs
		B	HU 37134 80930	3.47	2.62	8.83	1.633959	
		C	HU 37134 80930	3.89	2.11	12.17	1.774548	
22/08/2013	Skaw (Unst)	A	HP 66033 16359	4.02	2.00	15.55	1.995300	
		B	HP 66033 16359	4.07	2.45	13.04	1.941678	
		C	HP 66033 16359	4.68	3.46	20.02	2.753838	
22/08/2013	Mid Ness (Breckon)	A	HP 52669 05424	3.09	0.00	0.92	0.356589	
		B	HP 52669 05424	4.01	0.00	1.46	0.481437	
		C	HP 52669 05424	2.85	0.24	2.52	0.509085	
23/08/2013	Girlsta	A	HU 41931 50589	4.38	1.78	9.47	1.544886	
		B	HU 41931 50589	4.50	4.01	7.99	2.036367	
		C	HU 41931 50589	4.23	0.79	10.64	1.353564	
		D	HU 41931 50589	4.56	2.36	7.09	1.546722	

Table 1: *Shetland survey results*

Pluton	K (wt%)	U (ppm)	Th (ppm)	Th/U	Heat Production (mWm-3)	Dosage Rate (nGy/h)
Monadhliath granite (n=22)						
average and stdev[1]	4.6 ± 0.8	6.1 ± 3.2	32.4 ± 9.8	5.4 ± 3.1	4.3 ± 1.5	175 ± 47
Cairngorm granite (n=37)						
average and stdev	4.2 ± 0.6	11.8 ± 8.1	31.2 ± 11.6	3.4 ± 1.9	5.7 ± 2.6	200 ± 70
Lochnagar granite (n=35)						
average and stdev	4.6 ± 0.6	8.3 ± 3.1	24.7 ± 4.9	3.0 ± 1.6	4.4 ± 1.0	169 ± 30
Ballater granite (n=19)						
average and stdev	4.9 ± 0.8	18.0 ± 4.8	42.7 ± 8.3	2.4 ± 1.7	8.2 ± 1.5	272 ± 37
Grantown granite (n=6)						
average and stdev	3.6 ± 0.8	2.5 ± 1.9	10.9 ± 9.9	4.4 ± 5.2	1.7 ± 1.2	86 ± 37
Strathspey granite (n=4)						
average and stdev	3.6 ± 0.7	2.1 ± 1.5	5.7 ± 0.7	2.7 ± 0.5	1.2 ± 0.4	70 ± 13
All Data Combined (n=123)						
global average	4.4 ± 0.8	9.6 ± 6.8	28.2 ± 12.8	3.9 ± 2.4	5.1 ± 2.4	182 ± 69

note 1: averages and standard deviations are derived from the point-by-point measurements of K, U and Th without incorporating associated measurement uncertainties.

Table 2: *Comparison survey results from Scottish eastern Highland granites (Harley, 2013)*

Part III – Geological heat storage potential in Shetland

Expansion of the Lerwick district heating network would require a larger heat load during the peak winter months. One method of increasing this is to make use of the excess heat generated in the summer by storing it for winter. SHEAP already makes use of a hot water storage tank, but as the scheme expands the need for further storage increases. A geological equivalent of the storage tank may be a realistic solution.

There are two ways of creating an underground thermal energy store (UTES), depending on the nature of the strata:

i) Closed-loop UTES, using downhole heat exchangers in an array of boreholes. Essentially, these are engineered just as in closed-loop ground-source heat systems (e.g. Banks 2012), and are reasonably inexpensive per unit. Closed-loop UTES are applicable in strata of both low and high permeability, but are generally most effective in rocks of reasonably high thermal conductivities (which typically means quartz-rich rocks, such as sandstones, conglomerates and other siliciclastic rocks). Generally speaking, a significant number of reasonably well-spaced boreholes are needed to dump, store and retrieve heat in this manner over an annual cycle. As a rough guide, one would anticipate requiring 10 to 15 m of downhole heat-exchanger (and thus length of borehole) for each kW of heat stored[1].

ii) Open-loop UTES: whereas the closed-loop boreholes do not directly access groundwater, in open-loop systems native groundwater is directly accessed. An open-loop UTES system would consist of at least two boreholes (one injection, one extraction) forming a 'couplet' (a shallow version of *Figure 3*). This would target a shallow aquifer rock unit, which would ideally be a confined aquifer (or a deep unconfined aquifer with no local hydraulic connection to surface water), so there would be no water flow out of the storage area. Open-loop UTES requires far fewer boreholes per kW stored than in the case of closed-loop, although the boreholes in open-loop need to be engineered to a higher standard. All other things being equal, open-loop applications generally begin to out-compete closed-loop on cost for applications in excess of 250 kW.

   Strata suitable for open-loop UTES include sedimentary bedrock aquifers (limestones, sandstones etc.) and sand-and-gravel aquifers (see Birks *et al.* 2013). The geological formation beneath Lerwick is the Old Red Sandstone (ORS), a suite of Devonian sedimentary rocks which cover Orkney, southern Shetland and much of the north-east coast of Scotland. Being siliciclastic, these would certainly lend themselves to a closed-loop UTES, albeit for high capacities (> 1 MW) this would begin to become a very expensive option. Open-loop UTES can be very effective at high capacities, but their viability critically depends on local aquifer properties. Elsewhere in Scotland – notably in Fife – the ORS includes the most prolific aquifer in the country, the Knox Pulpit Formation (Robins 1990). However, there appears to be no information in the public domain characterising the hydrogeological properties of the sandstone units within the Shetland ORS. It is evident from outcrop patterns and dips that the ORS on Shetland is up to four kilometres thick in places, and that substantial intervals comprise sandstones (which are far more promising for open-loop UTES than conglomerates). There are therefore good grounds for optimism over the likelihood of finding a suitable zone for open-loop UTES.

[1] Incidentally, the figure quoted for borehole length for ground-source heat pump systems in correspondence from David Pearson dated 20th August 2013 is wrong by an order of magnitude: a 10 kW system would typically only need a single borehole of 100 to 150 m depth (Banks 2012), *not* 1000 m as claimed.

A future geological investigation could investigate this possibility beneath Lerwick, quantifying the amounts of energy it would be possible to store, the inter-seasonal 'decay' in stored energy due to advection and dispersion, as well as covering key environmental risk assessment tasks, such as minimising any possibility of heat 'escape' during the storage process. Such a study would require:

i) A hydrogeological field investigation, comprising of two or more boreholes being drilled and test pumped. It would be sensible to monitor these boreholes over a period of at least one year to determine the location's natural recharge and storage coefficient before fully committing to a heat storage project.
ii) Analytical and numerical modelling of heat storage and retrieval.
iii) Outline environmental risk assessment, including preliminary liaison with SEPA.

The budget for such an investigation is estimated to be in the region of £200,000.

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