Cairngorm Mountain

Geothermal feasibility report

17th January 2023

Prepared for Highlands and Islands Enterprise, and Cairngorm Mountain Scotland Ltd

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Contents

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Glossary

CE	Cairngorm Estate	kW	Kilowatt
CMSL	Cairngorm Mountain Scotland Limited	kWh	Kilowatt hour
CNPA	Cairngorm National Park Authority	kWth	Kilowatt thermal
CSR	Cairngorm Ski Resort	LAZ	Linear alterations zones
CAPEX	Capital Expenditure	l/s	Litres per second
c.	Circa	LDP	Local development plan
COP	Coefficient of performance	Ma	Mega annum (million years)
CAR	Controlled activity regulations	MW	Megawatt
oC/km	Degrees Centrigrade per Kilometer (unit for geothermal gradient)	mbgl	Meters below ground level
EGS	Enhanced geothermal systems	mOD	Meters above ordnance datum
EASR	Environmental Authorisations (Scotland) Regulations	M	Million
GBR	General building rules	NORM	Naturally occurring radioactive material
GHSP	Ground source heat pump	R&D	Research and development
HSE	Health and safety executive	SEPA	Scottish Environmental Protection Agency
ha	Hectare	delta T	Temperature change across the ground source heat pump
HDPE	High-density polyethylene	UDDGP	United Down Deep Geothermal Power
HIE	Highlands and Islands Enterprise	Wm-1	Watts per meter
HDR	Hot dry rock	$Wm^{-1} K^{-1}$	Watts per meter per kelvin

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Executive summary

Overview

Ove Arup and Partners Ltd (Arup) has been commissioned by Highlands and Islands Enterprise (HIE) and Cairngorm Mountain Scotland Limited (CMSL) to undertake a feasibility study on geothermal energy opportunities for the CMSL site (the Site) and the Cairngorm Estate (CE). If feasible, geothermal energy could help to decarbonise and support CE's journey to net zero. Net zero is a goal of CE's own 25-year master plan as well as the Scottish Government's 2045 net zero commitment for Scotland.

This feasibility study has evaluated the potential for geothermal energy to be used on-site across different scales of development, from ground source heat pumps to deep geothermal schemes for heating/cooling energy and/or electricity generation. This report also provides a roadmap for development of both GSHP and deep geothermal energy technologies.

This assessment is based on previous studies carried out by CMSL, a review of publicly available data and data from an existing British Geological Survey (BGS) 300m borehole present on Site.

The Site

HIE are custodians of the 3,500-acre CE, of which CSML has access to 1477 acres. The Site is located 15 km south-east of Aviemore in the Scottish Highlands. The developed part of the Site, which form the focus of this assessment, are the Cairngorm Mountain ski centre buildings, shown in Figure ES1 (the Site). These areas can be split into four key areas, or 'Hubs', based on transformer locations and main electrical loads: Hub 1: Overflow carpark, Hub 2: Base Station, Hub 3: White Lady, and Hub 4: Ptarmingan.

The Hubs are located at elevations between 550 and 1090 mOD and spaced apart by around a kilometre each (Figure ES1).

The weather conditions at the top of the Cairngorms are defined as sub-arctic, with snowy periods and temperatures below freezing that lasts 5 months, from early November to mid-April.

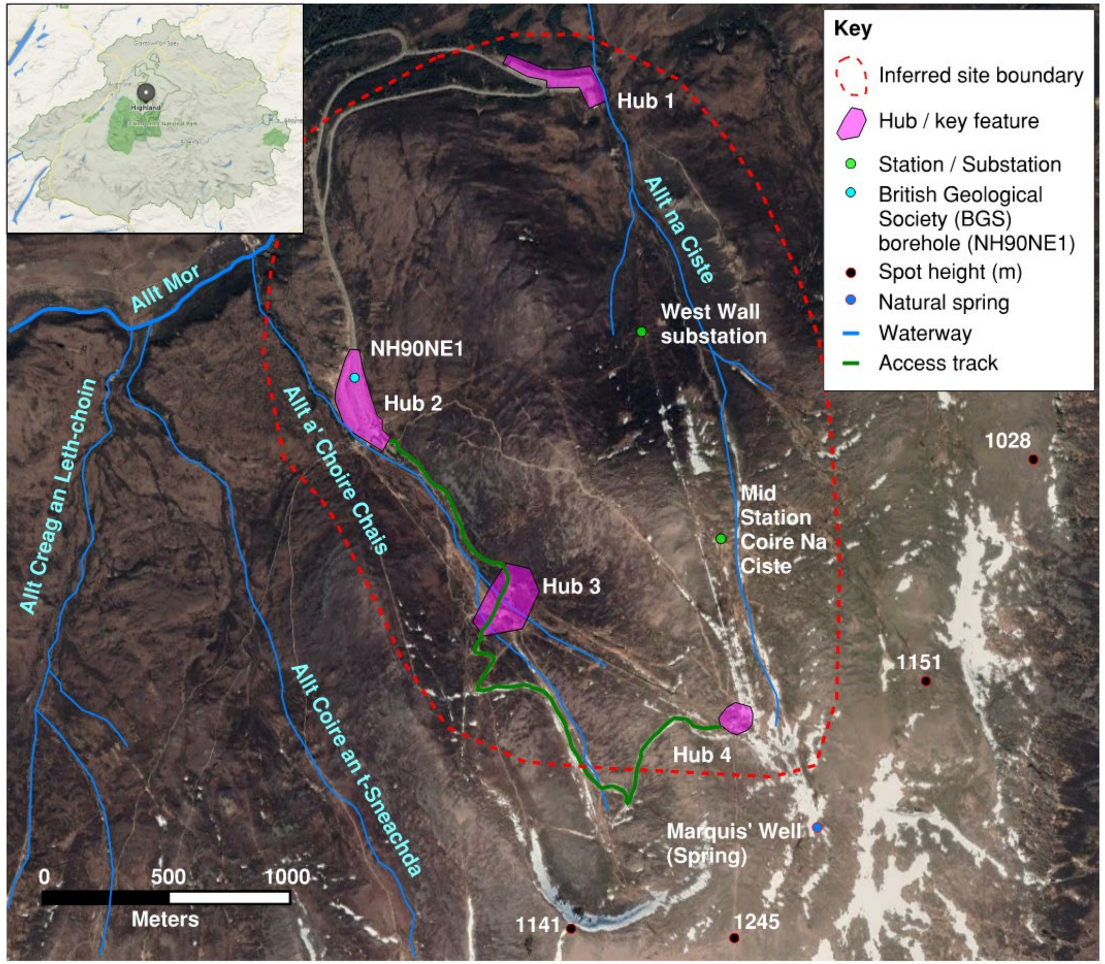

Figure ES1: Site location and features

Executive summary

Energy requirements

The energy demand from the site is currently heavily electrified, with all building heating being electric and the electric funicular line expected to become operational again in 2023. The space heating and hot water requirements are not sub-metered, and therefore it is not possible to directly estimate the heating demand from the available metered data. These demands have been inferred from electrical data.

The electrical and heat demands for each Hub were assessed based on electrical usage data. Peak electrical demands range from around 160 kWe (Ptarmigan) to 200 kWe (Day Lodge & Base Station). Peak heat demands range from around 100 kWth (Ptarmigan) to 120kWth (Day Lodge & Base Station). The snow factory, located at Hub 2, is the only non-electric asset which runs on diesel, with an annual demand of 272,304kWh and peak demand of around 185kW.

All current energy demand estimates are high-level, and would require further detailed assessment. Particularly given the potential for new buildings on the site, as raised during project discussions. All loads should be assessed to reflect the final demand for the sizing of any geothermal heat and/or electrical supply technologies.

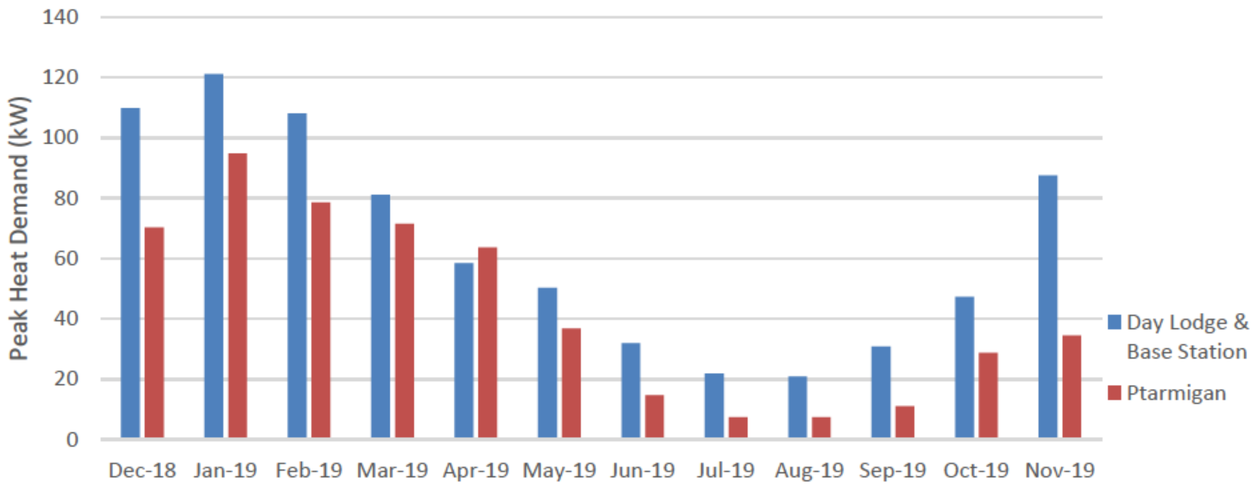

Figure ES2: Monthly peak heat demand for the Day Lodge/Base Station and Ptarmigan buildings.

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Executive summary

Ground Source Heat Pump (GSHP) opportunity

Ground source heat pump systems, such as vertical closed loop boreholes or dual purpose deep coaxial wells, are less impacted by site constraints, have fewer regulatory requirements, and are relatively simple to install and operate compared to deep geothermal systems. These types of systems can be designed to meet peak heating demands at each of the Hubs reducing the overall carbon usage for the Site.

Deep geothermal opportunity

On-site electricity generation from a deep geothermal well and binary plant is currently considered too uncertain. Further deep geothermal data would be required to determine feasibility and if this could be considered practical for the Site. The main Site constraints include, a relatively low temperature gradient which would require very deep drilling, uncertainty that any fluid found at depth could be sustainably abstracted, and the expected difficult drilling conditions in a sub-artic environment. These constraints are likely to create significant uncertainty around project costs and viability. There is a lack of deep geological knowledge of the Cairngorm Granite, further deep data would be required to determine deep geothermal project feasibility.

	Constraint impact		
Constraint	**Vertical closed loop boreholes**	**Dual purpose deep coaxial well**	**Deep geothermal**
Access	Low	Low	Low
Typography / available space	Low	Low	Low
Weather	Moderate	Moderate	High
Water Supply	Low	Low	Moderate
Power	Low	Low	Moderate
Water disposal	Low	Low	Moderate
Drilling / capital costs	Moderate	Moderate	High
Environmental designations	Low	Low	Low
Operating Costs	Low	Low	Low
Induced seismicity	Low	Low	Moderate
Geological certainty / conditions	Low	Low	High
Overall assessment	**Low**	**Low**	**High**

Table 1: Summary of geothermal opportunity constraints and their inferred impacts. Further analysis provided in Section 6.

Executive summary

Ground conditions

The bedrock beneath the Site is the Cairngorm Granite pluton. A pluton is a type of rock formed from below ground cooling of molten rock. Plutonic rocks are often targeted as potential heat sources for geothermal reservoirs. However, the presence of a pluton on its own does not mean a geothermally productive reservoir exists.

The pluton below the Site extends to 13 km in depth and was emplaced 420 to 430 million years ago. As the granite cooled, the minerals which make up the rock stratified, based on mineral density. Less dense 'felsic' minerals dominate the top, and dense 'mafic' minerals are found at the base of the granite. Following its emplacement, subsequent erosion because of tectonic uplift and glaciation removed the upper surface of the granite. The overall rock mass has therefore become more 'mafic' in composition, as the upper 'felsic' dominated minerals were removed. This is important because felsic plutons are more commonly associated with geothermal reservoirs than mafic plutons.

Temperature gradient and electricity potential

Geothermal energy originates from the heat retained within the Earth from radioactive decay of minerals. Temperatures increase with depth, and this rate of increase is termed the geothermal gradient. Certain rocks, such as granites, generally have mineral compositions with relatively higher proportions of radiogenic elements, such as uranium. Therefore, granite plutons often have higher geothermal gradients and heat flows relative to other rocks. For example, the Cornubian pluton beneath Cornwall is characterised by a geothermal gradient greater than 34°C/km. In comparison, based on the work performed by Busby et. al, the Cairngorm Granite pluton has an estimated geothermal gradient of around 25°C/km (which is less than the global average of 30°C/km). The relatively low geothermal gradient of the Cairngorm granite is, in part, thought to be the result of its mineral composition. Felsic minerals contain higher proportions of radiogenic elements, relative to mafic minerals. As previously outlined, the Cairngorm Granite has a mafic dominated mineralogy, as a result of erosion which may explain the atypically low inferred geothermal gradient.

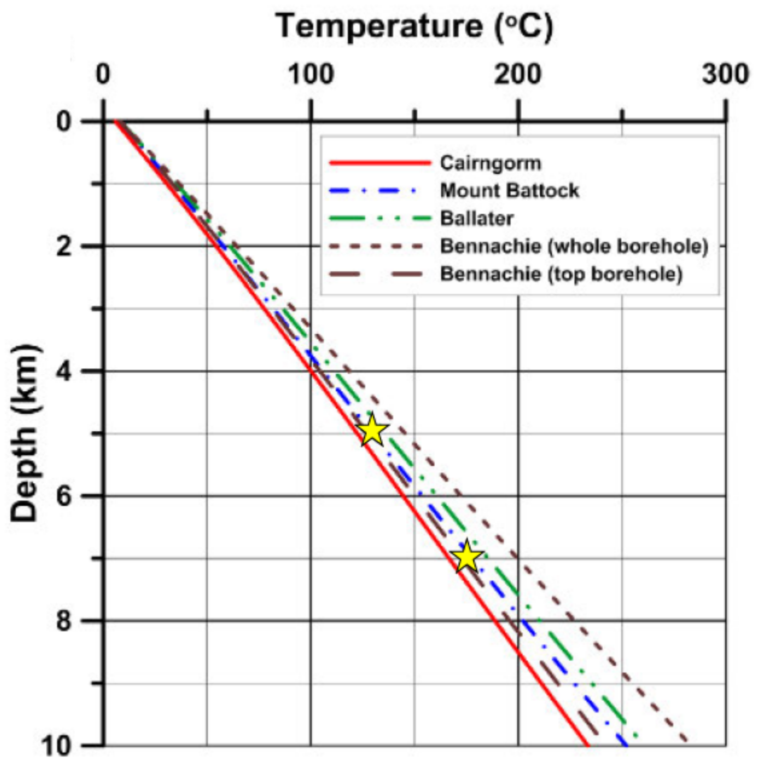

Figure ES2: Predicted subsurface temperatures of nearby granite bodies, including the Cairngorms (shown in red), based on heat flow estimates. Stars represent the estimated mean temperatures for available data for local granite bodies at 5 and 7 km [6]

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Executive summary

The geothermal gradient of the Cairngorm Granite has been estimated from a 300 m deep borehole present on the Site. Published subsurface temperature estimates across all local granites include 129°C at 5 km and 176°C at 7 km depth (shown on Figure ES2 on the preceding page). The predicted temperatures within the Cairngorm Granite is inferred to be slightly less than the average in the area. Given minimum thermodynamic requirements, a production well would need to be advanced to a depth of 7 km or more. At this depth, the likelihood of producing flow at a suitable rate decreases significantly.

Relative to the United Downs Deep Geothermal Project (UDDGP) in Cornwall, which had more favourable site conditions such as mild weather, a higher geothermal gradient, and more information on drilling conditions, the CMSL Site would required significantly greater capital investment.

Deep drilling rigs require relatively large areas during operation, however available space around Hub 1 or Hub 2 should provide sufficient area. The footprint of the power plant may be up to 0.6 to 1 ha. The drilling programme would be expected to be around a year. As an example, the UDDGP project, which comprised two wells to 5275 m and 2393 m, cost around £30M to drill and a further £15M to test and install a binary plant.

Due to the lack of deep geological information beneath the site, the assessment presented in this report is based on the limited existing data. Additional data may provide further insight into geothermal feasibility.

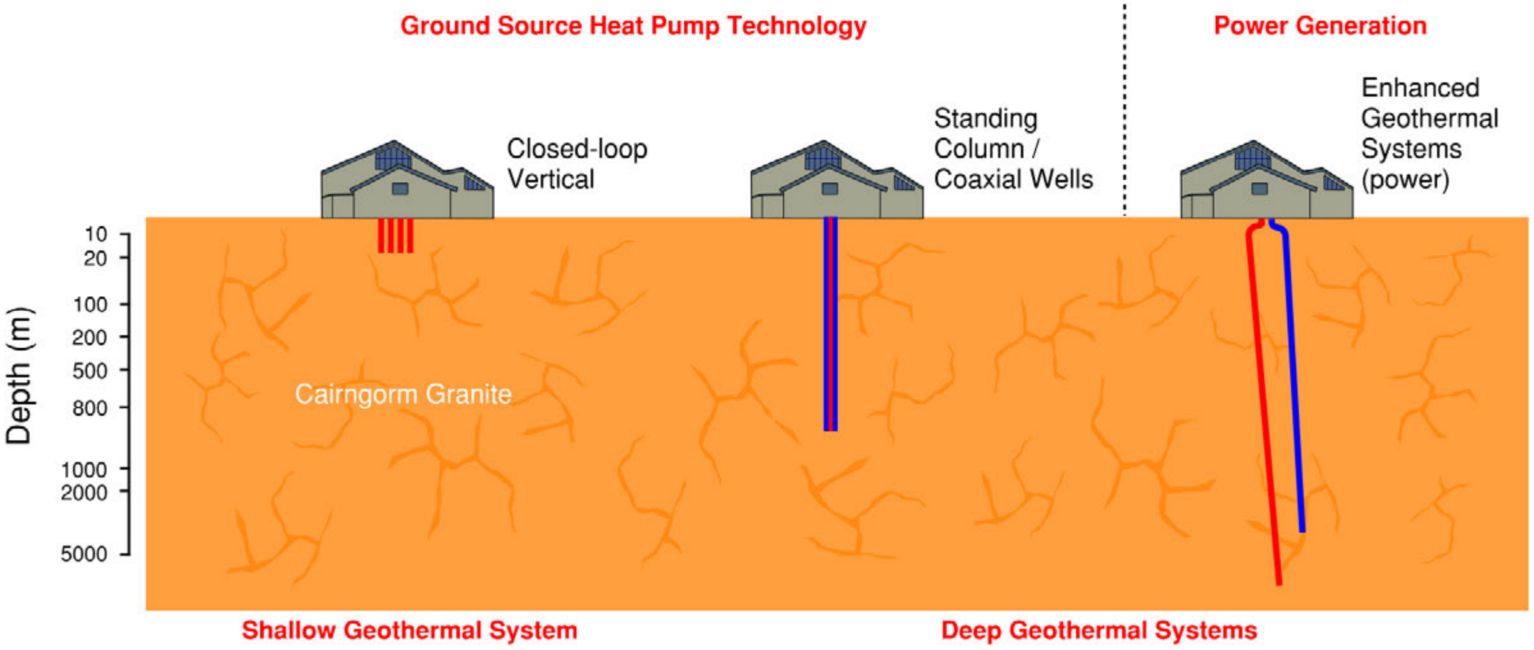


Figure ES3: Summary of geothermal systems

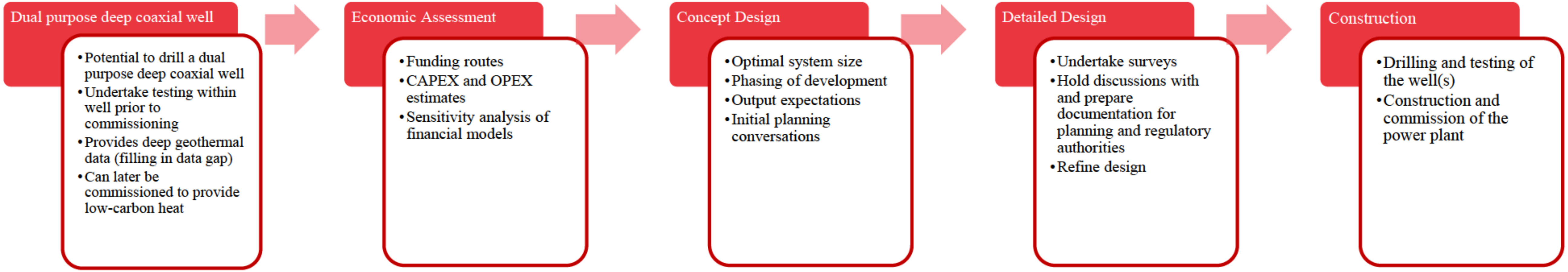
Executive summary

Deep geothermal roadmap

A typical roadmap to progress a deep geothermal project has been prepared for information and funding options outlined, in line with the scope requirements.

To progress a deep geothermal project a detailed economic assessment should be undertaken to identify how best to fund the project. Following this, a concept design can be developed, setting out geological requirements for a successful system and outlining well design configurations. A comprehensive electrical demand and heat load survey should also be undertaken to evaluate total demand before considering planning constraints.

A phased approach could also be considered. For example, initially a dual purpose deep coaxial well could be installed which would be sufficient to meet some of the heat demand and decarbonise a portion of the heat supply. Downhole surveys could also be undertaken within a dual purpose deep coaxial well, prior to its commissioning, providing better information on the geothermal conditions beneath the site.



Typical deep geothermal roadmap (with preliminary dual purpose deep coaxial well)

Executive summary

Deep geothermal summary

A culmination of an atypically low geothermal gradient, a lack of deep geological information, and high-impact site constraints mean that development of a deep geothermal project on the Site is likely to require deep, 7km, wells with little certainty on potential productivity. The project requirements would lead to an inflated CAPEX, in excess of the £45M cost for the UDDGP. As a result, this assessment concludes a need for more data to inform decision making for a deep geothermal at the Site. Alternative locations in the Cairngorms may be more suitable, from a drilling perspective. However, the same prognosis on temperature gradient and geologic uncertainty would remain.

GSHP summary

Peak heat demands per Hub are inferred to be less than 120 kW. Based on the high-level closed loop and dual purpose deep coaxial well assessments, a borefield comprising ten 200 m deep boreholes, or one 1000 m deep dual purpose deep coaxial well, may be able to meet the peak heat demands per Hub. Noting that these systems need to be designed to provide sustainable heat for the life of the project, a follow-up study is recommended to further evaluate these options. Any new buildings proposed at the Base Station, could consider opportunities for including a wet-heating system and utilising geothermal heat and heat pumps to meet the required heat demands. As such, estimates provided in this report are indicative until further building specific evaluations are performed.

Phased approach

It could be considered appropriate to initially install a dual purpose deep coaxial well (up to 1km depth). This well could provide information on two fronts: a downhole surveys could be undertaken within the well, prior to its commission, providing further insight of the geothermal conditions beneath the Site, and filling in the current data gap; and following commission, the well would provide low-carbon heat to the Site using GSHP technology.

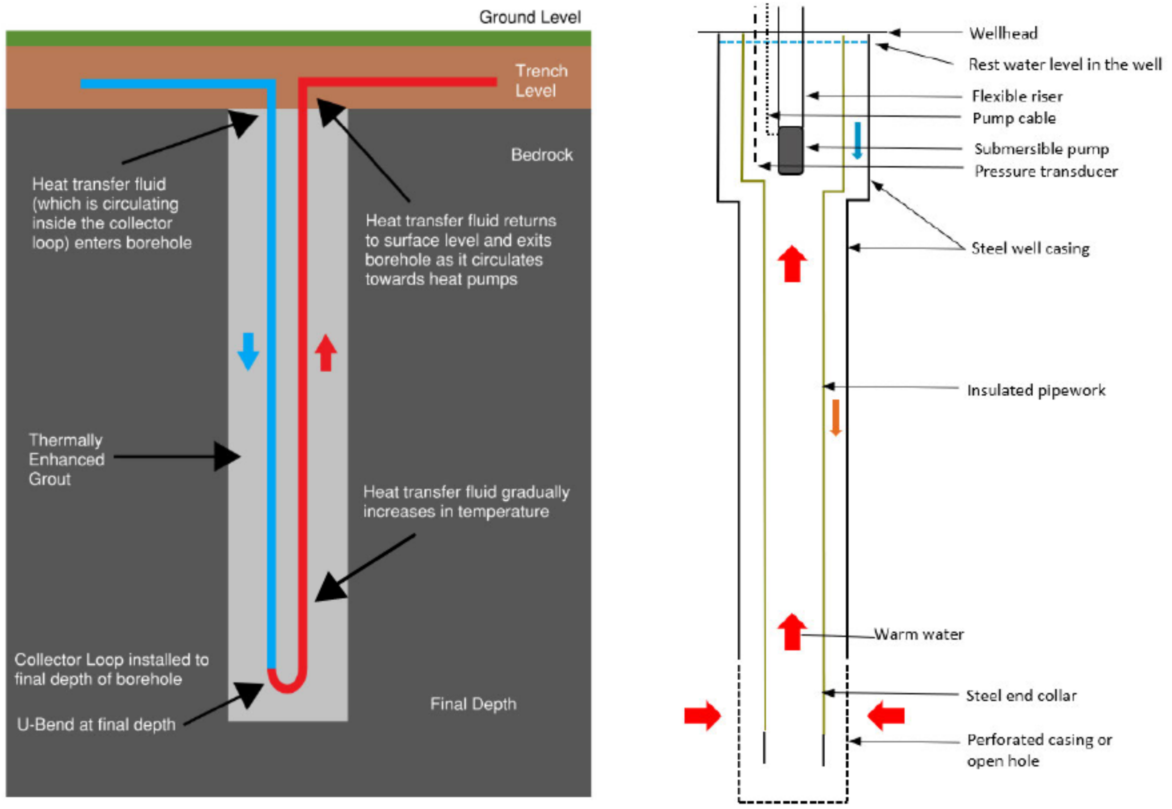


Figure ES5: (left) typical design of a closed loop borehole, (right) schematic of a dual purpose deep coaxial well

1. Introduction

Project background and scope

Background

Ove Arup and Partners Ltd (Arup) has been commissioned by Highlands and Islands Enterprise (HIE) and Cairngorm Mountain Scotland Limited (CMSL) to undertake a feasibility study assessing the potential for utilising geothermal energy on the CMSL site and the Cairngorm Estate (CE). Geothermal energy has the possibility to enable wide decarbonisation across the Site in line with Scottish Government 2045 targets and CMSL's 25-year master plan.

Scope of work

This report sets out to identify how geothermal energy could support in decarbonising CMSL operations across the CE. Part of this will include investigation into the potential opportunities, and challenges around deep geothermal including electricity generation and grid export.

It is understood that CMSL is particularly interested in the feasibility of deep geothermal for the site and the potential for electricity generation on site. While our study will include the feasibility of such a plant, it will also consider smaller geothermal schemes which could provide low carbon heat to CMSL's buildings on Site.

Methodology

The following methodology was used to undertake this assessment:

- Initial review of literature, including previous work undertaken by the client, and publicly available data. Spatial data was incorporated and assessed within an ArcGIS Pro workspace.
- Discussion with academics from University of Edinburgh with past research or pertinent knowledge of the geology of the Site.
- Weekly team meetings to share ideas and align direction of project.
- Site walkover on 31st August 2022. Included a walkover of pertinent areas of the Site, including the lower carpark Coire na Ceste, office, café buildings and the waste treatment plant.

Data available

The following data sources were reviewed as part of this assessment:

- Online spatial data from Scottish Environment Protection Agency (SEPA) [1], and British Geological Survey (BGS) [2];
- BGS technical report WJ/GE/84/23 [3];
- SEPA regulatory guidance documents [25];
- CSML Cairngorm Estate UAV data;
- Cairngorm Mountain Electricity Infrastructure and Energy Demands; and
- CCBM UK Ltd, Cairngorm Mountain - Electrical Infrastructure Review Report [4].

Site background

HIE are custodians of the 3500 acre CE, an accessible area of stunning natural beauty that lies within a wild sub-arctic landscape. It offers opportunities for locals and visitors to take part in a range of outdoor activities throughout the year.

HIE are striving to deliver environment and habitat restoration and conservation, promote outdoor activities and educational opportunities, while ensuring sustainable tourism to support local businesses and communities.

CSML who lease 1477 acres of the estate, are aiming to decarbonise their operations in alignment with HIE's ambition to deliver sustainable tourism in the CE.

Further details on the site can be found in **Section 2**.

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1. Introduction
Report structure and limitations

Structure of this report

This report has the following structure:

- Section 2: Site information: Site details, Environmental designations, Existing borehole assets, Topography, Hydrology, Weather conditions, Daylight, Temperature, Precipitation and Wind;
- Section 3: Geology:
  - Section 3.1: Regional geology: Geological setting and history, Rock composition, Hydrogeology
  - Section 3.2: Hydrogeology: Superficial deposits, Granite bedrock, Permeability and flowrates
  - Section 3.3: Structural geology: Structural features, Stress regime
  - Section 3.4: Geothermal properties: Geothermal gradient and Thermal conductivity;
- Section 4: Energy demands:
  - Section 4.1: Electrical demands: Electricity supply arrangements, Current electrical loads, Future electrical loads
  - Section 4.2: Heat demands;
  - Section 4.3: Future energy work
- Section 5: Geothermal opportunity assessment
  - Section 5.1: Geothermal systems: Closed loop system, Dual purpose deep coaxial wells, Open loop system
  - Section 5.2: Vertical closed loop boreholes
  - Section 5.3: Dual purpose deep coaxial wells
  - Section 5.4: Enhanced geothermal systems and Binary power plant;
- Section 6: Site constraints and opportunities:
  - Section 6.1: Confidence profile;
- Section 7: Investigation options and confidence analysis: Overview of potential investigation and impact on project confidence;
- Section 8: Deep geothermal roadmap: Concept design, Detailed design, Construction;
- Section 9: Regulator, planning, and funding considerations:
  - Section 9.1 Environmental regulation: General, Borehole, Groundwater abstraction and Naturally occurring radioactive materials
  - Section 9.2 Planning application: Definition of development – Town and Country Planning (Scotland) Act 1997, Planning application, Major vs local application, Environmental impact assessment - The Town and Country Planning (Environmental Impact Assessment) (Scotland) Regulations 2017, Community engagement, Planning policy
  - Section 9.3 Funding options: Funding round 1 - site investigation and permitting, Funding round 1 - drilling campaign, Funding round 3 – powerplant; and
- Section 10: Next steps and recommendations: Overview, Deep geothermal next steps.

Report use and limitations

This document was prepared by Arup on behalf of HIE and CMSL to provide an assessment of geothermal feasibility at their Cairngorm Estate site. It takes into account the Client's particular instruction and requirements and addresses their priorities at the time of report generation. This report was not intended for, and should not be relied on by, any third party and nor responsibility are undertaken to any third party in relation to it.

All reasonable skill, care and diligence have been exercised within the timescale available and in accordance with the technical requirements of the brief.

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2. Site information

Site details

CSML has access to 1,477 acres of the Cairngorm Estate in the Cairngorm National Park, 15km south-east of Aviemore in the Scottish Highlands. The developed part of the site, which forms the focus of this assessment, is the Cairngorm Mountain ski centre buildings, shown in **Figure 1** (the Site).

The Site is split into four key areas, denoted as 'Hubs':

- Hub 1 (Carpark Hub): comprising the Coire Na Ciste carpark and building, centred at grid ref: 7423,8205.
- Hub 2 (Base Station Hub): comprising the Base Station, upper carpark, Rangers Office, Day Lodge and snow machine, centred at grid ref: 7431, 8190.
- Hub 3 (White Lady Hub): comprising the White Lady Shieling, Cairngorm Café and out-buildings, centred at grid ref: 7428, 8183.
- Hub 4 (Ptarmingan Hub): comprising the Ptarmingan and The Shop At The Top, centred at grid ref: 7419, 8178.

Access to the Site is provided via a single carriageway, Cairngorm Road from Glenmore. The road passes the Coire Na Ciste carpark and terminates at the Base Station carpark.

Electricity is distributed around the Site via the Scottish and Southern Electricity Network (SSEN) 11kV ring circuit originating from Aviemore Substation. Six SSEN substations distribute Low Voltage (LV) power to various location across the site. These include, Day Lodge, White Lady Shieling (Mid Station), Ptarmingan, Mid Station Coire na Ciste, West Wall and Coire na Ciste Carpark.

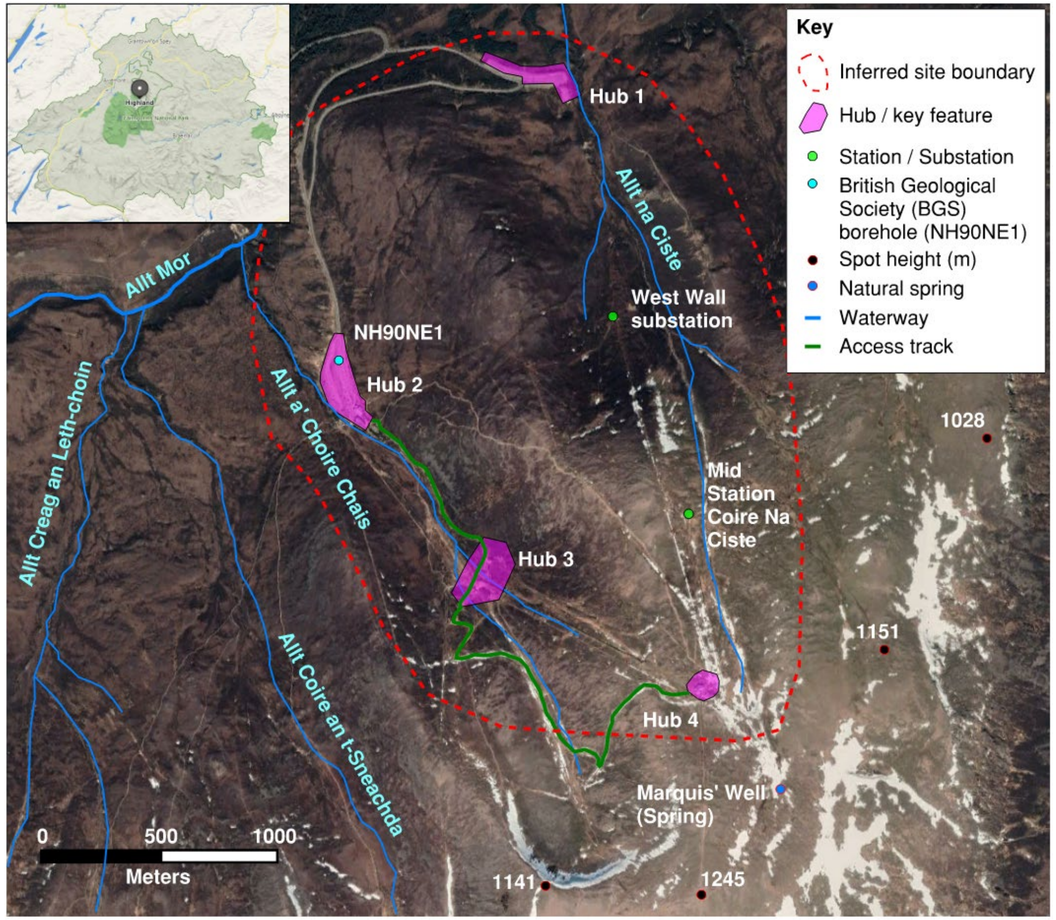

Figure 1: Inferred site boundary, hub locations and key station and substations

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2. Site information

Environmental designations

Online spatial data from Scottish Environment Protection Agency (SEPA) [1] was used to assess the location of the Site relative to environmental designations.

The Site is bordered by sites officially designated for environmental protection and scientific interest. However, the Site itself does not lie within any environmental designations, shown in **Figure 2**.

Existing borehole assets

An existing British Geological Survey (BGS) borehole, reference NH90NE1 [3], which extends to 300m depth is present on Site. This borehole has been reviewed and used to inform on geological conditions of the Cairngorm granite. Several shallower BGS boreholes near to the site were also reviewed [2].

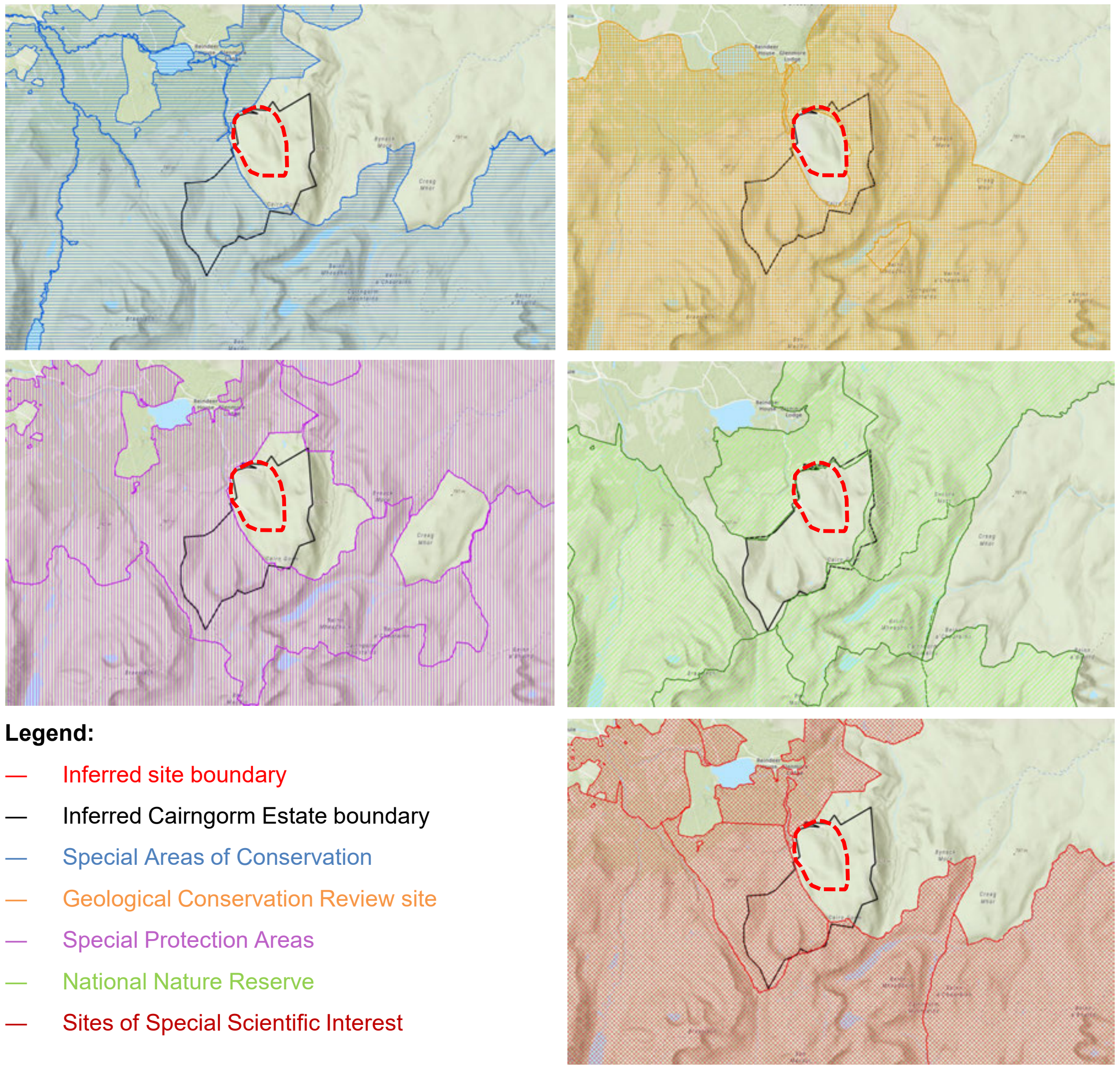

Figure 2: SEPA environmental designations [1]

2. Site information

Topography

The Cairngorm Granite forms an upland massif with a distinctive and relatively uniform landscape. It outcrops over an area of 365 km^2 in the central Scottish Highlands.

Topography across the Site is highly variable due to the mountainous terrain with steep hill slopes and limited flat lying areas. Hub 1 is situated on relatively flat lying ground at the base of the Coire na Ciste valley. Hub 2 is situated on a relatively flat area at the foot of a narrow valley. Hub 3 is situated halfway up the valley, from which the terrain rises sharply up to a rounded ridge where Hub 4 is located. The summit access track from Hub 2, to Hub 4 via Hub 3, has an average gradient of 5.5%.

Topographic elevations across the Site are as follows: Hub 1 at 549 to 555 mOD , Hub 2 at 622 to 630 mOD, Hub 3 at 748 to 764 mOD and the Hub 4 at 1089 mOD [2].

Hydrology

River and surface water flood risk is of low likelihood, 0.1% chance of flooding each year. Flood risk increases during seasonal snowmelt as groundwater flow rate and ground saturation increase [1].

The Allt a' Choire Chais stream runs directly through the Site past Hubs 2 and 3, shown in **Figure 1**. Flow rate of streams is unknown.

The Marquis' Well (Spring) is present near the summit of Cairngorm.

Weather conditions

The weather conditions at the top of the Cairngorms are defined as sub-arctic. The Cairngorm summit weather station is both the coldest and windiest station in the UK [9]. Weather conditions were assessed from online data [9][10].

In the Cairngorms National Park, the summers are cool; the winters are long, very cold, snowy, and windy; and it is mostly cloudy year round. Over the course of the year, the temperature typically varies from -2°C to 17°C and is rarely below -8°C or above 21°C. Over winter there are typically greater than three windy days, >30km/h, per week. While over summer it ranges between one and two windy days per week [11].

Daylight

The shortest day is 21st December, with 6 hours, 42 minutes of daylight; the longest day is 21st June, with 17 hours, 54 minutes of daylight.

2. Site information

Temperature

The cold season lasts 4 months, between mid-November to mid-March, with an average daily high temperature of 6ºC. The warm season lasts 3 months, from mid-June to mid-September, with an average daily high temperature above 14°C, shown in **Figure 3**.

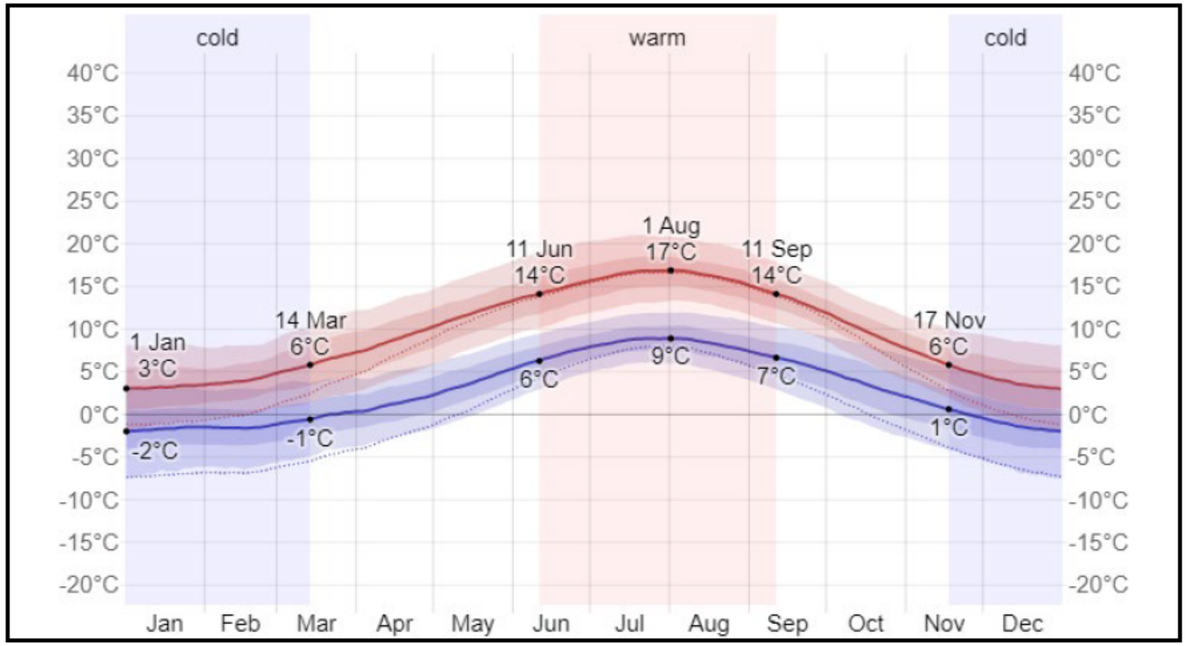

Figure 3: Annual average temperature profile for the Cairngorms National Park [10]

Precipitation

The wetter season lasts 7½ months from early June, to late January, with >34% chance of a given day being a wet day, defined as a day with at least 1mm of precipitation, shown in **Figure 4** – top image.

The snowy period lasts for 5 months, from early November to mid-April, with sliding monthly snowfall of at least 25mm. Snow is typically absent outside of this period, shown in **Figure 4** – bottom image.

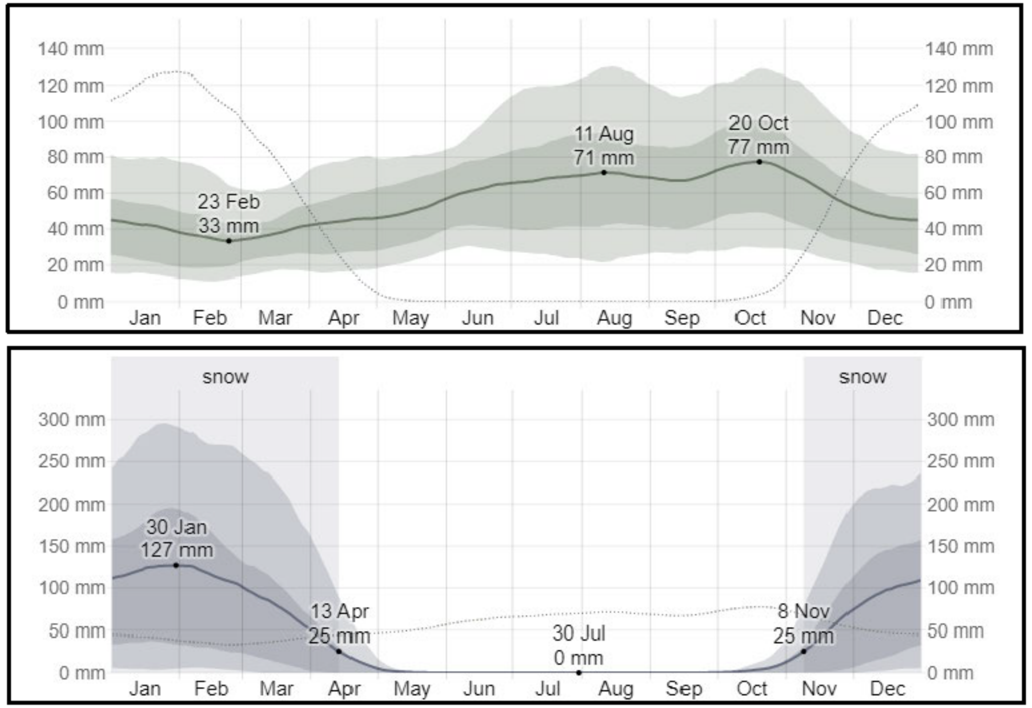

Figure 4: Annual average precipitation (top) and snowfall profile (bottom) for the Cairngorms National Park [10]

2. Site information

Wind

The Cairngorms National Park is characterised by windy conditions. The windier period lasts for 6 months, from early October to early April, with average wind speeds of more than 20 kph, shown in **Figure 5**. Outside of this period, wind speeds are still high, with an average of 16 kph. Strong gusts are also prevalent. Wind speeds of 185 kph were experienced during a winter storm in December 2011; and the UK's strongest gust speed record of 278 kph was recorded on the Cairngorms in 1986.

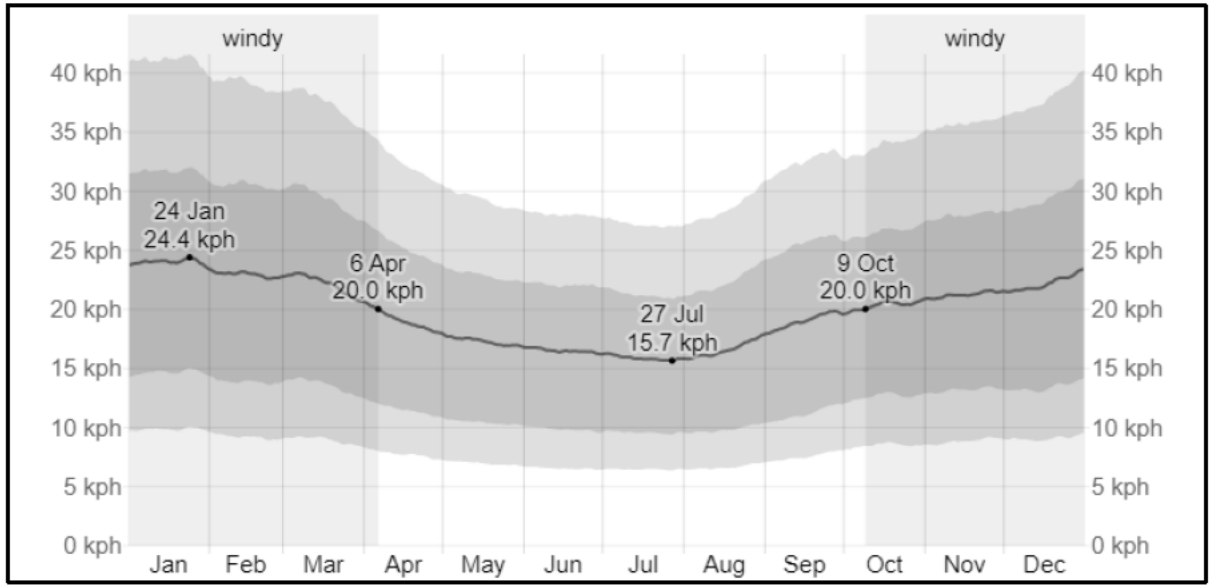

Figure 5: Annual average wind profile for the Cairngorms National Park [10]

3. Geology

3.1 Regional geology

Geological setting and history

Emplacement of the Cairngorm granite pluton (a type of rock formed from below ground cooling of molten rock), via partial melting of crustal material, occurred during the Caledonian Orogeny, around 430 to 420 Ma. The Caledonian Orogeny was a mountain forming event driven by the closure of the Iapetus Ocean.

Following emplacement, the pluton was subject to extensive Quaternary glaciation, between 2.4 to 3.6 Ma. The glaciation event eroded and weathered the outcropping rock mass. Vertical variation in the degree of weathering and erosion is observed on the mountain. Summits of the Cairngorms express relatively minor glacial features, while the base of the Cairngorms express greater degrees of glacial modification, where distinct glacial troughs have formed along zones of structural weakness [13].

As the glaciers retreated, the mass overlying the pluton was unloaded, resulting in the formation of sub-vertical and sub-horizontal joints (fractures). Horizontal joint spacing is thought to be expressed within the upper 1 to 2 km, with joint spacing increasing with depth; and vertical joints persisting at greater depths [12].

Superficial deposits, formed as a result of weathering and erosion of the granite bedrock, are present across the Cairngorms. These comprise talus, as well as head, glacial, glaciofluvial and alluvial deposits. These typically accumulate at the base of steep slopes, mountain tops or in valleys, streams and depressions and comprise clays, sands, and gravels [2].

Rock composition

The composition of the Cairngorm granite is well constrained in the top 300 m due to existing BGS borehole data [3]. This borehole represents the deepest borehole in the region. To depths of 180 m, the granite is heavily altered with numerous joints infilled with secondary mineral. The granite below 180 m is typically fresh and unaltered, with occasional 2-8 m zones of slightly altered and jointed granite.

Rock porosities ranges between 0.4 and 2.3% in the top 300 m [3].

Ground conditions at greater depths have been based on available literature. The granite is inferred to comprised a relatively homogenous mass with medium grain size, average crystal sizes of 5 to 6 mm [14].

The Cairngorm Granite was identified as a 'high geothermal potential granite' with high silica content, SiO_2 percentage of 70 -78%, and evolved geochemical characteristics [7]. This is discussed further in **Section 3.3**.

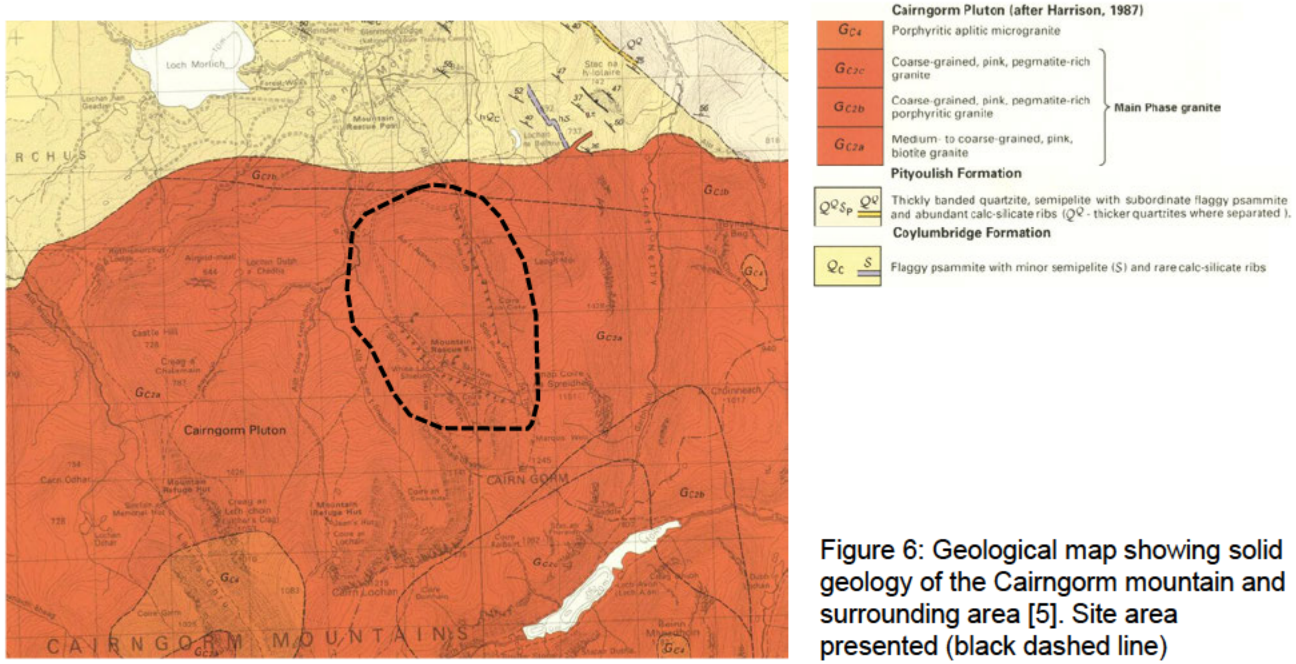

Figure 6: Geological map showing solid geology of the Cairngorm mountain and surrounding area [5]. Site area presented (black dashed line)

3. Geology
3.2 Hydrogeology

Hydrogeology

There is limited data available on hydraulic properties of the various geological units. Shallow and deep water-bearing rocks have principally been inferred from historic trial pit and borehole data, respectively [2].

Mountain springs form groundwater discharge points, that are supplied by groundwater flow through shallow superficial deposits and the upper regions of fractured granite bedrock [8].

Superficial deposits

A number of shallow superficial aquifers are present across the site. These include relatively shallow coarse drift deposits composed of block fields, talus and head boulders, at elevations of greater than 800 mOD [8]. At lower elevations, till and patches of sand and gravel make up thicker superficial deposits that accumulate towards the base of the mountain.

There are no designated source protection zones on or around the Site [2]. However, the shallow permeable nature of superficial deposits at higher altitudes, means groundwater availability may be vulnerable to environmental changes [8].

Granite bedrock

Infiltration rates into deeper groundwater bodies are likely to be limited due to the impermeable nature of the granite body and infiltration is likely localised around joints and fracture zones.

Groundwater chemistry across the Cairngorms has been monitored from various springs across the region.. Groundwater is moderately acidic (mean pH 5.9), with very low alkalinity (mean 18meqL^{-1}) [8].

The Marquis' Well (spring) exists near the Cairngorm summit, and provides an important groundwater discharge point on the high altitude plateau. Hydrogeochemical influence of springs on surface water is localised [8].

Porosity ranges between 0 – 17% down to 300 mbgl, with higher porosities located in altered zones [3].

Permeability and flowrates

Permeability, and consequently flowrates, in granite rock types are primarily controlled by the distribution of fractures and fracture networks, as natural permeability is typically low. Permeability reduces with depth and structural features, such as fractures, become increasingly tight with depth.

Within the Cairngorm Granite, the upper core between 94-100 mbgl is mildly to severely altered and jointed, middle core is mildly altered and jointed between 214-221 mbgl and predominantly fresh granite with few joints in the lower core between 294-296 mbgl [3].

High flow rates are feasible in fractured granites, case studies include [15]:

- Cooper Basin in Australia flow rates 10 - 40 l/s (targets natural occurring fractures, which are then hydraulically stimulated);
- Soultz-sous-Foret, France flow rates of 5 – 40 l/s (during hydraulic stimulation);
- Rosemanowes, UK average flow rates of 8.5 l/s - 20-35 l/s; and
- Fjallbacka, Sweden flow rates of between 20 - 30 l/s.

Deep permeability and flow rates of the Cairngorm Granite are unknown.

3. Geology

3.3 Structural geology

Structural features

The Cairngorm Granite has two distinct sets of structural features that run parallel to the walls of glaciated valleys, these include:

- near-horizontal sheets (continuous fractures) which formed parallel to topographic surfaces; and
- near-vertical joints (fractures) [12].

Horizontal spacing between near-vertical joints was measured across the Cairngorm mountain. On the lower south-west side of the mountain, joint spacing ranges from 0.5 to 8 m, while near the summit, it is much shorter ranging between 1 and 2.5 m. This could indicate that joint spacing increases with depth in the Cairngorm Granite pluton [14].

Linear alterations zones (LAZ) exist within the Cairngorm Granite pluton, see **Figure 7**. LAZs form when hot fluids alter the rock mass, leading to the formation of fractures, veins, and secondary minerals. These features can mechanically weaken the rock causing low thermal conductivity but higher permeability and flow rates. LAZs can extend up to several kilometres in length and greater than 700 m deep [13]. The orientation of these features is presented in **Figure 8**.

Stress regime

Maximum compressive stress, a horizontal force responsible for the orientation of structural features, is orientated E-W in the Cairngorms; aligning with the regional stress fields [14].

The orientation of structural features in the region suggest a local, rather than regional, tectonic control on the formation of dominant joint sets [14].

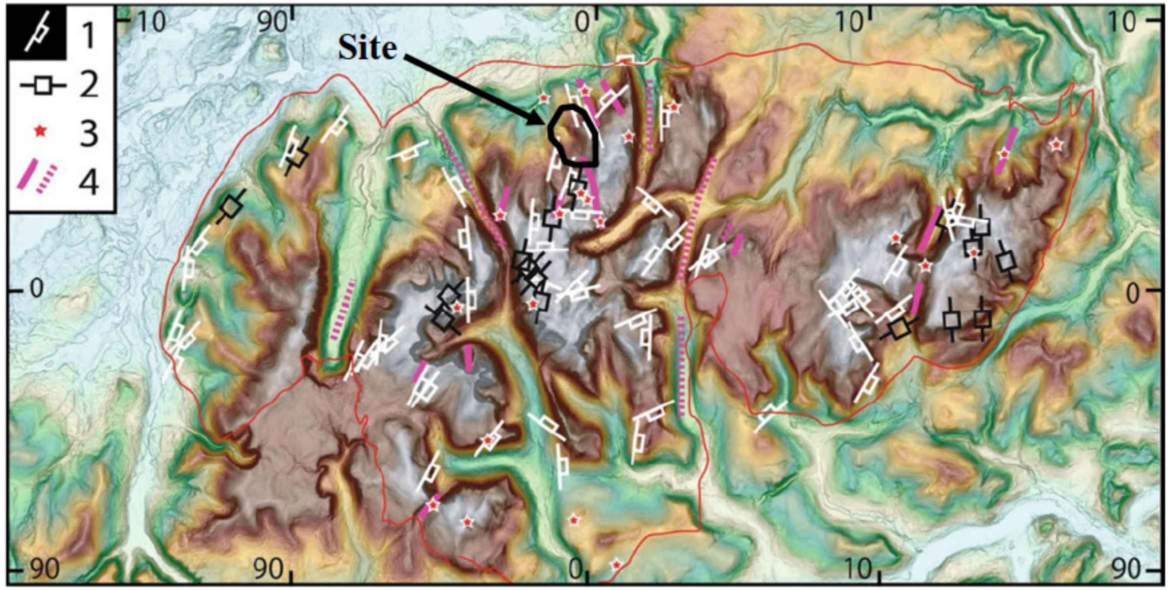

Figure 7: Cairngorms: Quartz veins and linear alteration zones, (1) Quartz veins, (2) LAZs, (3) Saprolite [13]. Inferred site location shown in Black

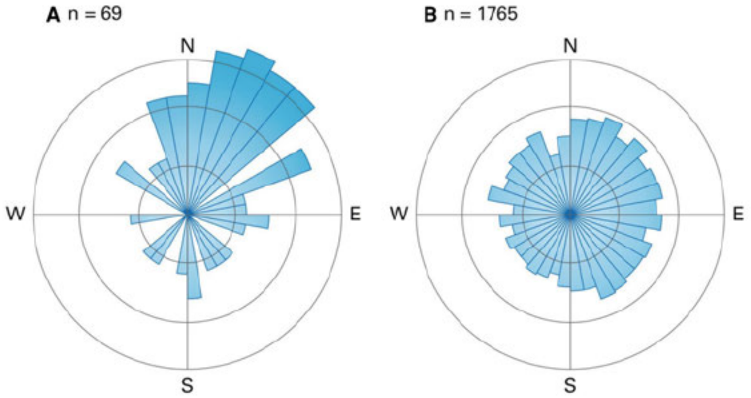

Figure 8: Cairngorms: orientation of different structural features: (A) quarts veins (proxy for LAZs), (B) joint sets (data showing feature strike; the dip direction of these features is 90 clockwise from strike) [13]

3. Geology

3.4 Geothermal properties

Geothermal gradient

Granitic bodies are often characterised by high geothermal gradients as a result of extensive radioactive decay. However, the Cairngorm granite is characterised by an atypically low geothermal gradient, of 25 ºC/km, see **Figure 9**.

The low geothermal gradient is thought to be a result of the pluton unroofing, erosion of its upper surface, following its emplacement. As the granitic body cooled the mineral composition stratified, with denser 'mafic' minerals at its base and less dense 'felsic' minerals at the top. Radiogenic decay, which provides granites with their elevated geothermal gradient, is more extensive within felsic minerals relative to mafic minerals [23]. Following emplacement, pluton unroofing exposed and eroded away much of the felsic dominated upper surface and left behind the mafic-rich base. This has resulted in the lower than anticipated geothermal gradient. In addition, it is inferred the granite becomes more mafic with depth and therefore, the influence of radiogenic decay on heat production may decrease with depth.

Based on the work done by Busby et al. [6] and their heat flow estimates, the Cairngorm Granite pluton has an estimated geothermal gradient of around 25 ºC/km, which is less than the global average of 30 ºC/km. Given the geology, it is expected that the gradient is higher than 25 ºC/km; however, uncertainties exist as the geothermal gradient was extrapolated from shallow 300 m borehole measurements.

Published subsurface temperature estimates across all local granite bodies include 129 °C at 5 km depth and 176 °C at 7 km depth [6]. The predicted temperature in the Cairngorm Granite is inferred to be less than this, see **Figure 9**.

Modelling using the Bouguer gravity anomaly estimates that granite intrusions extend down to 13 km with a volume of 25,000 km³ [6].

Thermal conductivity

Heat production values estimated by gamma-ray spectrometric surveys, indicate the Cairngorm granite has a surface heat production value of 5.88 μWm^{-3} [7]. Subsurface temperatures were reconstructed from a single borehole, estimating temperature values ranging between 5.7 °C at 21 m to 10.9 °C at 283 m [16].

The Cairngorm Granite is classified as a high heat production granite with paleoclimate corrected heat flows of 86 ± 7 mW/m^{-2} [6].

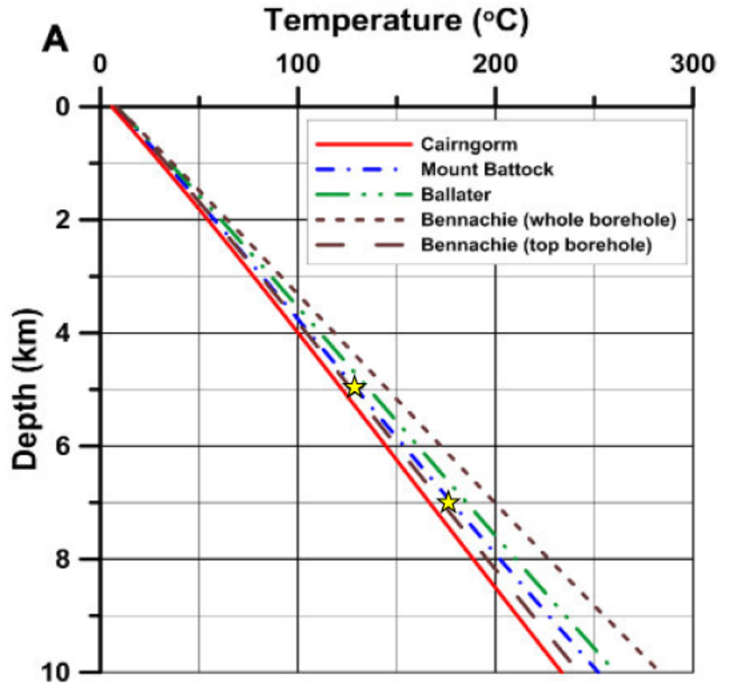

Figure 9: Predicted subsurface temperatures for multiple nearby granite bodies, based on revised heat flow estimates, assuming heat production decreases exponentially with depth. Mean temperatures across all local granitic bodies of 129ºC at 5km and 176ºC at 7km are displayed as stars. Temperatures for the Cairngorms is shown in red [6]

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4. Energy demands
4.1 Electrical demands

This section of the report provides a high level summary of the overall electrical requirements for the site. The purpose of this is to understand the potential future electrical load requirements the site might require. This requires an understanding of the current and future anticipated loads, as discussed below.

The information in this section has been informed predominantly by the initial kick-off meeting and walkover on the 31st August 2022; a meeting with CMSL to further understand the site-wide current and future demands on 12th October 2022; the CDMM UK Ltd Cairngorm Mountain – Electrical Infrastructure Review Report [4]; and supplied half-hourly metered data discussed during the 12th October meeting.

Electricity supply arrangements

Power is supplied around the CMSL Estate via an SSEN 11kV ring circuit, which includes the following sub-stations:

- Day Lodge
- Ptarmigan
- White Lady Sheiling (Mid Station)
- Mid Station Coire Na Ciste
- West Wall
- Coire Na Ciste Carpark

In addition to the 11kV ring, a separate supply was installed to provide power to the Funicular Railway, via a sub-station located within the Ptarmigan Building.

Based on discussions during the meeting on 12th October 2022, it was advised that any demands associated with the Mid Station Coire Na Ciste, West Wall and Coire Na Ciste Carpark sub-stations are very minor and should be ignored as significant further development in this area of the estate is not expected.

Current electrical loads

To develop an understanding of the current electrical demand, where possible, reference has been made to half-hourly metered data which covers various areas of the site. This has required a degree of interpretation, but in summary it is understood that:

- MPAN meter ref. 1712314574804 is associated with the Day Lodge sub-station, which serves the Day Lodge, the Base Station, and other external lifts and tows.
- MPAN meter ref. 1700051159261 is associated with the building loads within the Ptarmigan Building.

Using the above data, it has been possible to develop an understanding of the monthly electrical consumption associated with these locations, as illustrated on the following page. The graph illustrated spans an annual period from December 2018 to November 2019, representing 12-months worth of data.

Various functions or facilities exist on the site for which reliable metered data is either not available or has not been provided. Notably, this includes:

- White Lady Sheiling sub-station - metered data is not available or not been provided.
- The Funicular Railway – whilst some of the metered data provided might cover the separate supply to the Funicular Railway, the metered data available covers July 2018 – November 2019. It has been advised that the Funicular Railway ceased operation in October 2018, and was operating at reduced capacity prior to this so the metered data does not provide a good representation of the likely future Funicular Load requirements.

Where existing metered data is not available, estimates of the potential loads associated with these in the future have been made. Refer to **Section 4.1 Future electrical loads** for further information, discussed further in the report.

4. Energy demands
4.1 Electrical demands

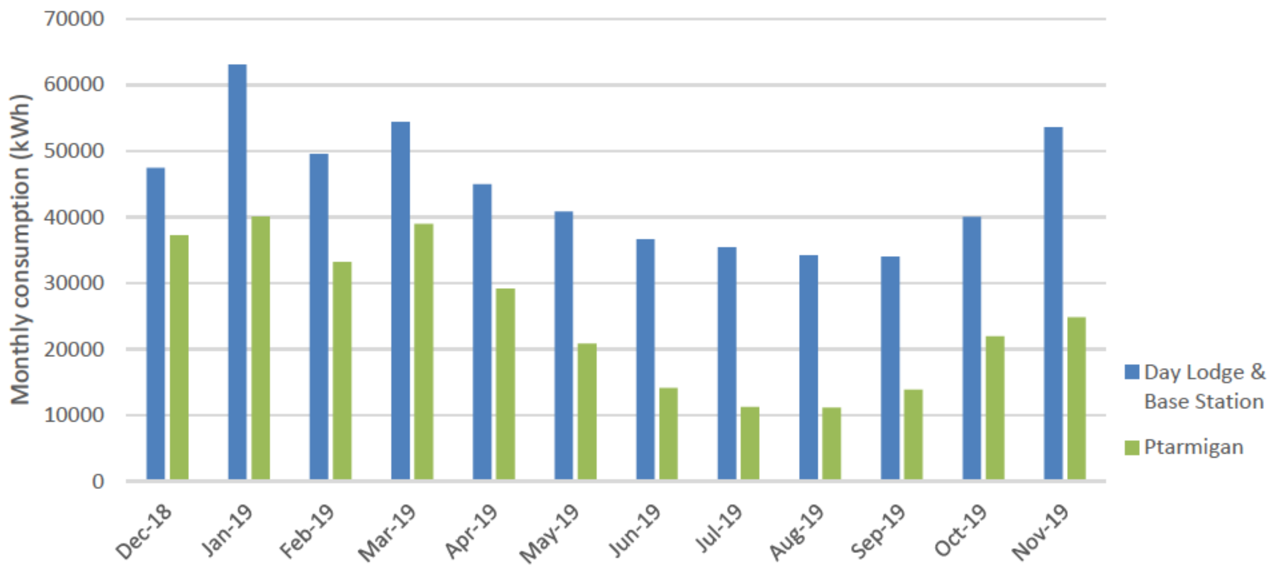

Figure 10: Monthly electrical consumption for the Day Lodge and Ptarmigan sub-stations.

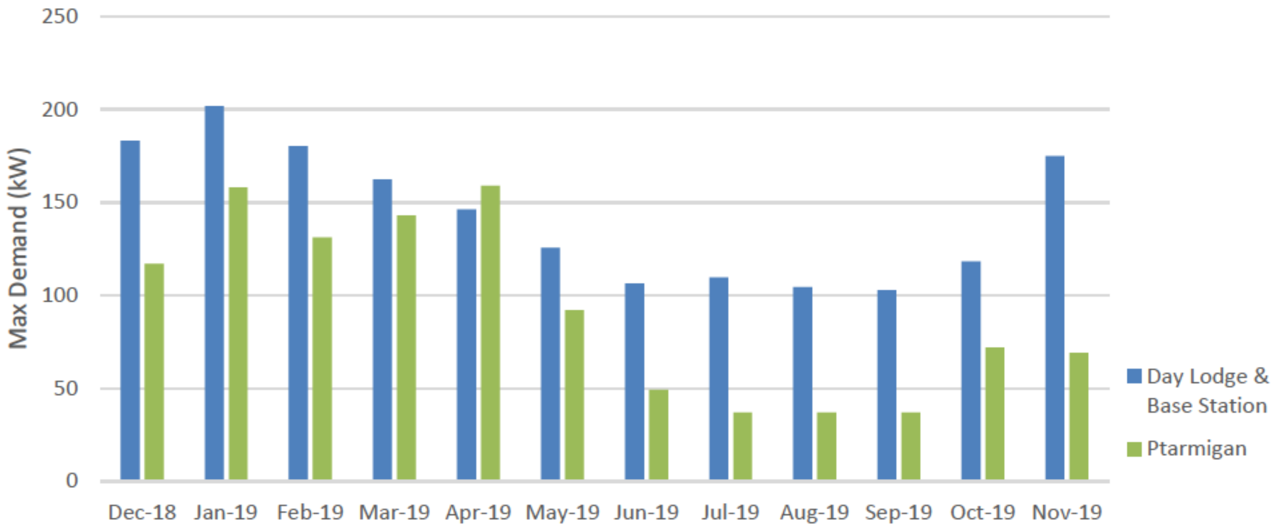

Figure 11: Max electrical demand in each month for the Day Lodge and Ptarmigan sub-stations.

The profiles presented in **Figure 10 and 11** show a clear seasonal variation, which would be expected given that all heating within the buildings is electric. Based on the above, the overall electrical consumption for this metered year period is:

- Day Lodge & Base Station: 534,036 kWh; and
- Ptarmigan: 296,480 kWh.

In addition to the above, the same metered data also enables an understanding of the peak electrical demand (maximum demand) for each day for these sub-stations. The peak demand for each month as recorded by the metered electrical supply for the above year is as presented in **Figure 11**.

Based on **Figure 11**, the maximum annual demand recorded at any point in the year for the two sub-stations is:

- Day Lodge & Base Station: 202 kW; and
- Ptarmigan: 159 kW.

For the Day Lodge sub-station, the above figure has been compared against the max demand estimate that has been made within the CDMM UK Ltd. Report [4], which estimates a maximum connected load of 196 kW, and a normal diversified load of 178 kW, which provides some confidence in the figures. The CDMM report does not provide a comparable estimate for the Ptarmigan building for comparison.

4. Energy demands

4.1 Electrical demands

Future electrical loads

In addition to the existing electrical loads derived from the metered data as summarised in the previous section, this section focuses on estimating the potential future electrical demand resulting from existing site demands and additional demands that may appear in the future.

Through discussion with CMSL, the most reliable summary of potential future electrical demands is the *Analysis of Future Demand Requirements* section of the CDMM UK Ltd. Report [4], which summarises future predicted loads expected to be connected to the Day Lodge sub-station, the White Lady Sheiling sub-station, and the West Wall sub-station. Using this information, a potential future overall site load, demand build-up is estimated for each area and item, shown in **Table 1**.

Many of the future loads are based on peak demand (kW) figures, which are also noted as continuous loads, in the CDMM UK Ltd. Report [4]. The report does not contain estimates of annual consumption (kWh) for these items. It has therefore been necessary to make significant assumptions regarding the operational profiles of these items which, whilst based on feedback from CMSL where possible, still introduces a high degree of uncertainty to the annual consumption estimates. A particular observation on the data in the CDMM report are the high loads associated with each of the new lifts, noted as a continuous load of 354 kW, which results in very high annual consumption estimates based on the usage profiles assumed.

Noting the above considerations, estimates of the overall site peak and annual consumption loads have been estimated and are as summarised below:

- Total site annual electrical consumption: 5,860,000 kWh, or 1,993,000 kWh excluding lifts; and
- Total site diversified peak load: 1500 kW, or 862 W excluding lifts.

A diversity of 60% has been applied to the sum of the peak loads to estimate the overall diversified load.

Given the high impact on the overall loads resulting from the future site additions, it would be recommended to gain greater confidence in these numbers if these are to form a key part in decision-making as part of this project, or any future work.

Area/Item	Annual Consumption (kWh)	Peak (kW)	Source/Assumption
Current Loads:			
Day Lodge & Base Station	534,036	159	Dec. 2018 - Nov. 2019 metered data provided to Arup in Oct. 2022
Ptarmigan	296,480	159	Dec. 2018 - Nov. 2019 metered data provided to Arup in Oct. 2022
Funicular	364,000	100	Peak assumed as 100kW. Consumption estimated as continuous peak for 10hr operation per day, 364 days per year
White Sheiling	170,000	169	Peak and consumption based on 2013 metered data as represented graphically in CDMM UK Ltd report [4]
Future Loads:			
Day Lodge sub-station supply:			
Snow Cannons (6)	14,400	144	Peak based on CDMM report [4]; assumed 2hr operation for 50 days per year
Snow Factory	272,304	186	Peak based on CDMM report [4]; assumed 24hr continuous operation for 2 months (Nov-Dec)
Lift no.1	1,289,000	354	Peak based on CDMM report [4]; 10hr operation per day for 364 days per year
Carpet Conveyor (3)	101,920	28	Peak based on CDMM report [4]; 10hr operation per day for 364 days per year
Mountain Coaster	91,000	25	Peak based on CDMM report [4]; 10hr operation per day for 364 days per year
White Lady Sheiling sub-station supply:			
Snow Cannons (17)	40,800	408	Peak based on CDMM report [4]; assumed 2hr operation for 50 days per year
Lift 2	1,289,000	354	Peak based on CDMM report [4]; 10hr operation per day for 364 days per year
Sheiling Restaurant	108,150	58	Peak based on CDMM report [4]; consumption pro-rata from Ptarmigan consumption based on ratio of peak demands
West Wall sub-station supply:			
Lift 3	1,289,000	354	Peak based on CDMM report [4]; 10hr operation per day for 364 days per year

Table 1: Future Electrical Loads – annual consumption, peak and sources/assumptions.

4. Energy demands

4.2 Heat demands

All current requirements for space heating and hot water within the buildings across the site are understood to be met through direct electric means, e.g. electric convector heaters and point-of-use or stored hot water. The demand for heat in the buildings is therefore a portion of the electrical demand summarised in the previous section. Further to this, the space heating and hot water requirements are not sub-metered, and so it is not possible to estimate the heating demand from the available metered data.

The main demands for heat on the site will be for the Day Lodge and Base Station buildings, served via the Day Lodge sub-station, and the Ptarmigan building, served from one of the Ptarmigan sub-stations. In order to estimate the scale of heat demands associated with these buildings, an estimate has been made of the portion of the electrical monthly consumption, and maximum demand, that is attributable to heat requirements. These have been assumed to vary based on a low of 20% in peak summer, to 60% in peak winter. Based on this notable assumption, the monthly heat load profile for the Day Lodge and Base Station, combined, and the Ptarmigan, have been estimated, see **Figure 12**.

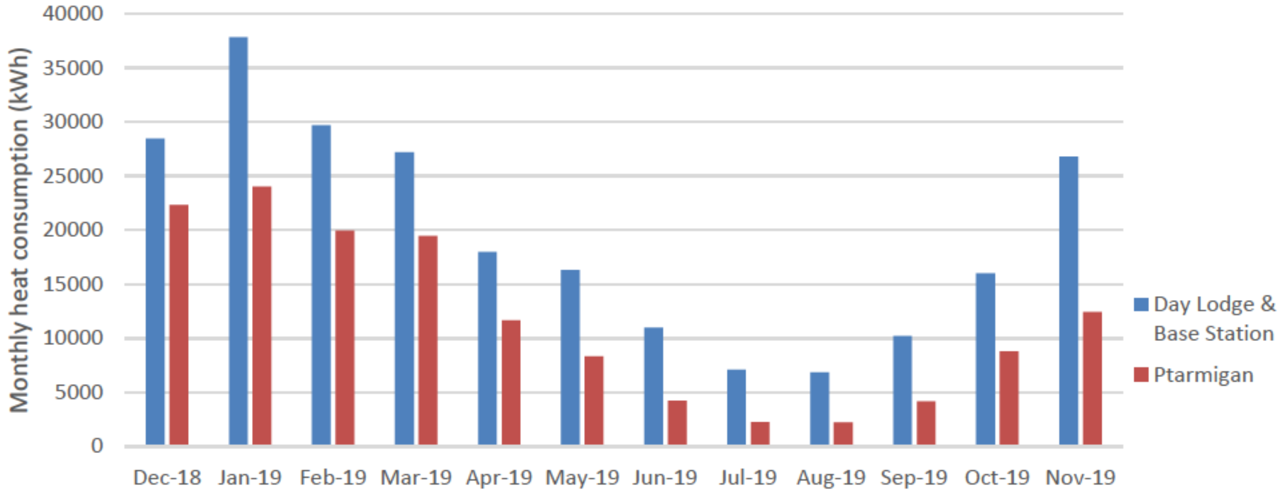

Figure 12: Monthly heat consumption estimates for the Day Lodge/Base Station and Ptarmigan buildings.

Similarly, the peak monthly load profiles for heat in these buildings is as illustrated in **Figure 13** below.

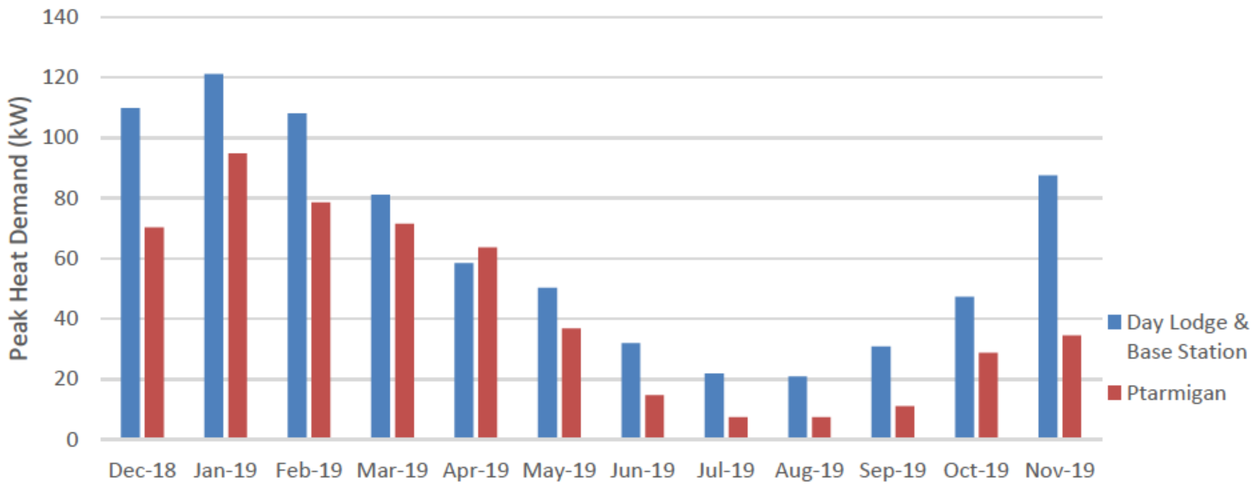

Figure 13: Monthly peak heat demand for the Day Lodge/Base Station and Ptarmigan buildings.

Based on this approach, the estimated overall annual and peak heat loads for the Day Lodge & Base Station buildings, and the Ptarmigan Building are as noted:

- Day Lodge & Base Station annual consumption: 303,000kWh;
- Day Lodge & Base Station peak load: 121kW;
- Ptarmigan annual consumption: 189,000kWh; and
- Ptarmigan peak load: 95kW.

The 121kW peak load estimate for the Day Lodge/Base Station compares favourably with the heat load of an estimate of 120kW made of these buildings within the renewable energy options appraisal [24].

4. Energy demands
4.3 Future Work

The electrical and heat demand assessments described in the preceding sections have been undertaken based on the level of information available during the course of this work, and for the purposes of providing an indication of the scale of demand at the site to inform the potential for geothermal-based heat and/or electricity.

With regard to the buildings on the Site, it has been noted during the course of discussions on the project that the Day Lodge building is likely to be replaced in the near future, with a new multi-purpose building at the same location. If one of the technology options presented in this report are to be developed further, it will be necessary to further review and determine the final loads against which any heat or electricity supply technologies are sized. This should include a detailed appraisal of the heat and/or electricity demands of both any current and future buildings.

Given the potential for new buildings on the Site, there is also potential to reduce the demand for heat and electricity in the first instance through careful design consideration of any new buildings, before applying and sizing any renewable technologies.

As noted previously, a particularly high proportion of the future electrical demand is due to the anticipated site-wide infrastructure (ski lifts, tows etc.). If these loads are to form a key part of the decision-making for any potential deep geothermal electricity scheme, then it is strongly recommended that further confidence is developed in the peak and year-round demands resulting from these loads.

5. Geothermal opportunity assessment

5.1 Geothermal systems

Geothermal systems

In this feasibility assessment deep geothermal, and ground source heat pump (GSHP) systems; vertical closed loop borehole, and dual purpose deep coaxial wells have been considered. These systems are outlined in **Figure 14** and detailed in the subsequent sections.

Vertical closed loop boreholes

Closed loop systems run thermal exchange fluids through piping installed in the ground. The piping can be installed within boreholes, piles or other structures. Water, sometimes with an antifreeze added, is pumped through the piping and the thermal exchange occurs within the boring. Where heat to the buildings is required, the fluid extracts heat from the ground, and where cooling is required, the fluid rejects heat to the ground. For this reason, closed loop systems are typically operated so that the annual heating and cooling loads are balanced to avoid long-term changes in ground temperatures and to optimise electricity use.

Dual purpose deep coaxial wells

Dual purpose deep coaxial wells are a type of hybrid system where water is continually circulated through a borehole.

Deep geothermal (Enhanced Geothermal Systems, EGS)

EGS are a type of open-loop systems within which the natural permeability of the rock has been enhanced. They utilise pumping and reinjection wells to directly abstract water, pass the water through the heat pump, or binary plant, and then reinject back to the abstracted formation. The pumping and reinjection well fields must be spaced far enough apart to minimise thermal interference and short-circuiting.

Flow rates need to be proven during hydraulic testing, and abstraction licences are required.

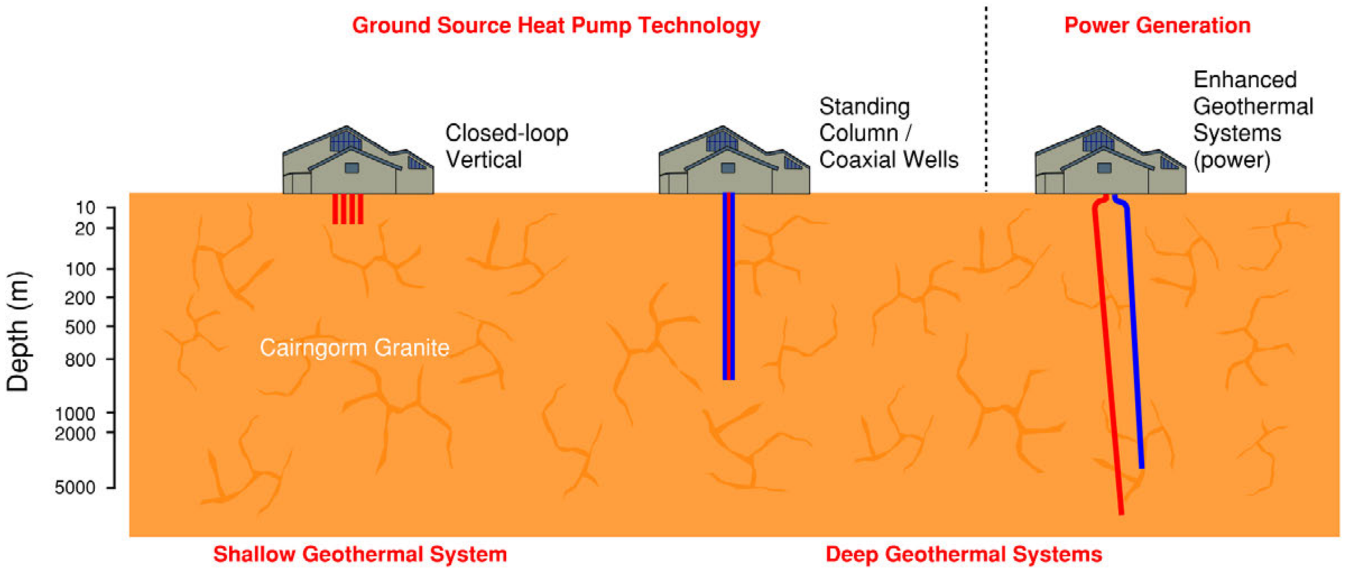

Figure 14: Summary diagram of geothermal options, highlighting ground source heat pump technologies: closed-loop vertical and standing column/dual purpose deep coaxial wells, and power generation technologies – enhanced geothermal systems (EGS). EGS require extensive fracture networks to sustain productive flowrates

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5. Geothermal opportunity assessment
5.2 Vertical closed loop boreholes

Vertical closed loop boreholes

A closed-loop boring is typically comprised of high-density polyethylene (HDPE) tubing that is arranged in a loop configuration installed within a boring to depths of 150 to 200m. Boreholes are usually suitably spaced to minimize thermal interference in the borefield. The number of borings are often maximized within the available site area, or are constrained by available project budget. Hundreds of borings are not uncommon for multiple building projects. These systems are typically installed for heating and cooling, balanced systems, as this allows for a long-term sustainable and efficient system operation, by maintaining ground temperatures. Imbalanced, e.g. heating-only, systems can drive down ground temperatures over long periods of time eventually reducing the efficiency of the heat pumps, which then drives up electricity use, and cost.

They benefit from no licence requirements and relatively low maintenance and monitoring. However, need careful design if to be operated with imbalanced loads. It is inferred that the building requirements at the Site are heating dominated and thus imbalanced.

To ensure that the use of vertical closed loop boreholes is feasible, a design assessment over the full operational project life, for example for 50 years or longer, would be required. The combination of an appropriate design assessment coupled with operational monitoring, even limited monitoring, will provide confidence for sustainable operation to maintain low carbon and low electricity usage.

There is plenty of UK experience installing these types of systems. Installation costs vary based on a multitude of factors including, but not limited to, ground conditions, site location, and contractor availability. A single vertical closed-loop borehole to 200m depth may cost around £20k. Contractor costs may vary and this value should be used for information only.

The thermal conductivity of the Cairngorm Granite is assumed at 3.5$Wm^{-1}K^{-1}$,based on published literature [6], which could provide thermal energy per m of borehole of around 70Wm^{-1}. Therefore, a closed loop borehole to 200m has the potential to provide around 14kWth from the ground, and around 20kWth to buildings, with the use of a ground source heat pump (GSHP) with a coefficient of performance (COP) of 3.2 and a delta T of 5°C.

The number of borehole can be scaled to meet heat demands. For example, based on a borehole spacing of 10m, a borefield of ten, 200m deep, boreholes would require around 0.1ha of space and could provide around 140kW from the ground and around 200kW to buildings with used of a GSHP with a COP of 3.2 and delta T of 5°C.

A borefield of this scale may be suitable to meet peak heat demands for an individual Hub, based on the heat demand assessment, see **Section 4.2**.

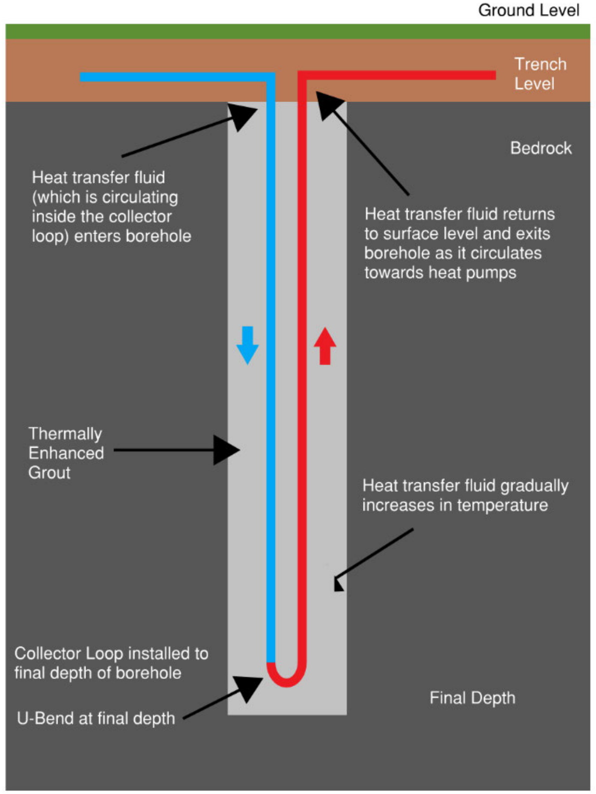

Figure 15: Typical design of a closed loop borehole

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5. Geothermal opportunity assessment

5.3 Dual purpose deep coaxial well

Dual purpose deep coaxial wells

Dual purpose deep coaxial wells are a type of hybrid system where water is continually circulated through a borehole. As illustrated in **Figure 16**, the well is constructed with a pipe placed within a well. Water is pumped from the inside of the pipe to the surface, passed through the heat pump, and then sent back to the well, but on the outside of the pipe.

Typically, the systems are closed as they are not expected to produce water from the ground but are technically in direct contact with target geology. In some cases, dual purpose deep coaxial well performance is improved by discharging a portion of the circulated water, known as bleeding-off, thereby inducing groundwater to provide a partially convective source of energy.

Systems which incorporate bleed require an abstraction licence from SEPA, as the system involves consumptive use of groundwater. Bled dual purpose deep coaxial well systems also need a suitable disposal option and top-up system, this may be via water mains/sewers, or local streams. Engagement with SEPA will be required. Non-bleed options do not require a licence as they do not consume groundwater. For this assessment, the system is assumed to be dual purpose deep coaxial without bleed/discharge. System considerations include:

- Systems are typically run for heating and cooling, balanced loads.
- Systems can more easily lose productivity, relative to closed loop borefields, if not operated within design requirements and monitoring is required to ensure sustainable operation.
- Have no licencing requirements, where no bleed occurs.
- Limited UK installation experience, on both design and installation sides.
- System can be vertical or inclined and have very small land footprints.

In-house empirical models have been used to infer the thermal yields from dual purpose deep coaxial wells at the Site. Modelling assumptions include: 1000m well length, 3l/s flow rate, 25°C/km ground temperature at 1000mbgl, based on published data, see **Section 3.2**, no bleeding, Delta T of 10°C.

Modelling outputs, which include long-term use and cooling, infer the base of the 1000m dual purpose deep coaxial well will stabilise at around 21°C, and output temperatures at around 19°C. Assuming a dT of 10°C reinjection temperature is assumed to be around 9°C. A dual purpose deep coaxial well without bleed to 1000m is inferred to yield around 100 - 120kW with a flow rate of 3l/s. With use of a GSHP, with a COP of 3.5, this could yield around 150 - 180kW per well.

A single dual purpose deep coaxial well may have a CAPEX around 20% greater than that of a closed loop borefield with comparable thermal outputs.

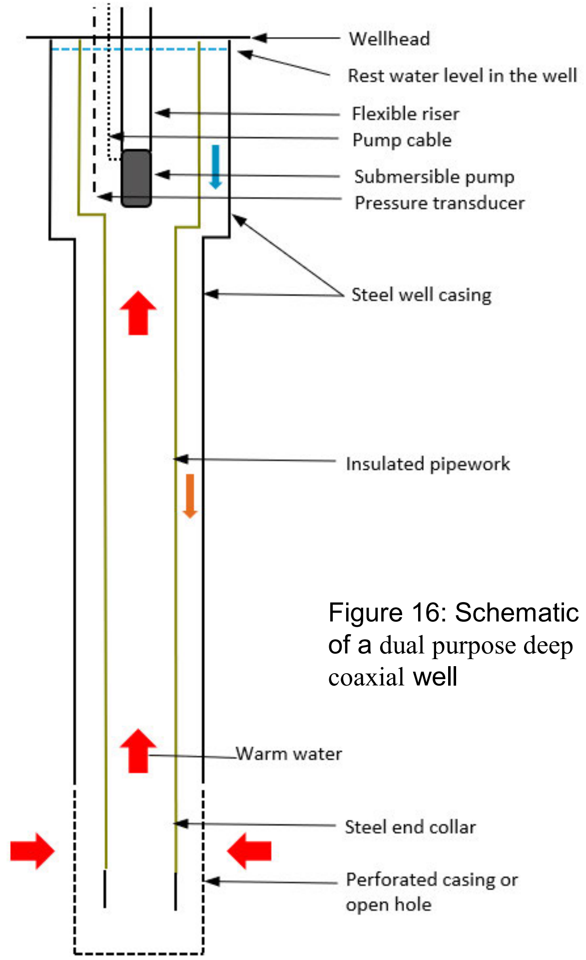

Figure 16: Schematic of a dual purpose deep coaxial well

Figure 16: Typical design of a dual purpose deep coaxial well

5. Geothermal opportunity assessment

5.4 Deep geothermal

Deep geothermal

Deep geothermal systems (i.e., Enhanced Geothermal Systems, EGS) use the deep subsurface as a source of heat for the production of heat or electricity. Deep geothermal systems require boreholes that are typically greater than 4km depth, depending on the geothermal gradient and the temperature required for heating/ power. The natural permeability of the rocks at these depths is usually insufficient for natural fluid to transport this heat to the surface and therefore deep geothermal systems are often referred to as hot dry rock (HDR) systems. Permeability can be higher where naturally occurring faults have resulted in open discontinuities, such as the Porthtowan fault in Cornwall - United Downs Deep Geothermal Power (UDDGP) site, however, hydraulic stimulation is usually needed to enhance the natural permeability. Hydraulic stimulation is injection of fluids at high flow rates into a reservoir to develop new fractures or reactivate and enhance the hydraulic performance of existing fractures.

As outlined in **Section 3**, there is a lack of deep geological data for the Site and a geothermal gradient has been inferred from shallow data. The following assumptions have been used to inform on a site specific deep geothermal system:

- Geothermal gradient of 25^{o}C /km;
- Minimum temperature of 120^{o}C entering the binary plant ,discussed further on the next page; and
- Up well thermal losses of greater than 10^{o}C

Based on the assumptions above, it is anticipated an abstraction well of greater than 5km depth would be required, however, it is considered that depths of around 7km may be more appropriate; to account for geological uncertainty and potentially high up well thermal losses. At these depths, any natural fractures are inferred to be very tight and natural permeability, low. It may be very challenging to achieve suitable flow rates required for a successful deep geothermal system at these depths.

While small, c. 0.2ha, well pads may be suitable for shallow wells <1km, deeper, >2.5km, boreholes may require well pads up to 1 to 2ha. A geothermal binary plant will require an additional 0.6 to 1ha of land.

Scale of economy principals apply with binary plants with larger plants providing relatively cheaper cost per CAPEX values. For <1.5MW plants, thought to be of appropriate scale for this project, global existing binary plants range in cost from \$6,500 to \$9,000 per kW [22] (equivalent to around £5,600 to £7,800). Based on the values provided, a plant with a 1.5MW capacity may cost around £8.5M to £12M. For context the cost of installing the 4MW binary plant at the UDDGP project was around £15M.

The site has a relatively small heat demand with heat use distributed amongst several small buildings/Hubs separated by distances of around 1km. Given the main energy use on the site is electricity based, a deep geothermal system would need to be capable of providing power.

Figure 17: The drilling rig used for the United Downs Deep Geothermal Project (UDDGP)

5. Geothermal opportunity assessment

5.4 Enhanced geothermal systems

Binary power plant

Binary plants are closed loop systems. Heat from geothermal fluids causes secondary fluid, within the closed loop system, to flash to vapour. This vapour then drives turbines and generators.

These plants can either be water-cooled, or air cooled. Water cooling is more efficient, but requires a constant source of water. Water cooling also generates water vapour, which may lead to a visual impact and planning limitations. An example 4MW plant is presented in **Figure 18**.

Air cooled systems use elevated cooling fans, typically situated around 5m off the ground, housed in acoustic-proofed buildings. These may cause a visual impact, which may need to be mitigated.

Binary plants require sufficient flow rates of around 20 l/s to 40 l/s and can operate at relatively low temperatures, c.120^{o}C and upwards. The efficiency of power conversion is typically between 9%, for lower temperature resources, c.120^{o}C, to 18%, for higher temperatures, c.180^{o}C. Total gross power production will depend upon temperature and flow rate. Net power is normally two thirds of gross power as electricity is used to drive the well pumps and cooling fans.

A binary power plant up to around 5MW gross power will take up between c. 0.6 to 1ha of land. The flat area of carparking around Hub 2 may be suitable in terms of land space but, until deep wells are drilled, there will be substantial geological uncertainty regarding temperature and flow rate. The lack of deep geological knowledge for the area will mean that any deep geothermal project for potential electricity generation must, at this point, be viewed as an R&D project, not as a commercial proposition. We have suggested a number of steps that can be taken towards such a project later in this report.

Sizing of the binary plant is dependent on the energy potential from the ground, sized such that the maximum amount of energy can be extracted sustainably over the project lifetime. The size of the binary plant is not typically sized to meet site loads as this may result in an undersized system, resulting in underutilised geothermal energy.

Figure 18: Example of 4MW binary plant from Denizli Tosunlar ORC geothermal power plant, Turkey [20] [21].

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6. Site constraints and opportunities

This section reviews site constraints and opportunities which impact deep geothermal and GSHP systems (vertical closed loop borehole and dual purpose deep coaxial wells).

Constraint	Description	Deep geothermal system	GSHP systems
Access	Access to Hub 1 and Hub 2 is via the Cairngorm Road	Low impact: sufficient access for large drilling rigs	Low impact: sufficient access for drilling rigs
	Access to Hub 3 and Hub 4 is via a gravel track	High impact: unsuitable for large drilling rigs	Moderate impact: tracked rigs will be required and rig size may be limited
Topography / available space	Hub 1 and Hub 2 have around 1.5ha and 2.7ha of flat space available respectively	Low impact: sufficient space for drilling rig and equipment, 1 to 2ha required, and binary plant, c. 0.5 to 1ha. Hub 2 is least impacted by space	Low impact: sufficient space for shallow (<1km) drilling rigs, c. 0.2ha
	Hub 3 and Hub 4 are inferred to have around 0.2 to 0.4ha of flat space available respectively	High impact: will required complicated design for rig and binary plant	Moderate impact: scale, and thus, thermal output, of geothermal system may be limited by available space
Weather	Sub-artic conditions with strong winds, cold temperatures, and snowfall. Engineering solutions to mitigate against weather may be available, however the weather may risk shutdown which may incur (significant) delay costs, typically burdened by the operator (i.e. HIE, CMSL).	High impact: drilling to the depths required for a deep geothermal system will take a number of months to a year(s). Continuous drilling is recommended and weather conditions may cause programme delays; with work only feasible in summer months. High wind conditions will be a Health and safety concern and rigs may not be suitable. Cold temperatures may limit drilling as freezing temperatures and snowdrifts are unworkable.	Moderate impact: drilling of GSHP geothermal systems may take a couple of weeks. Drilling may be limited to the summer months
Water supply/scale	Drilling operations require a supply of water. Coaxial systems with bleed also require 'top-up' water. Deep systems need large scale lagoons.	Moderate impact: large volumes of water will be required while drilling to the depths required for a deep geothermal system. This may be sourced from local streams or water network and stored in a man-made lagoon onsite (ideally around 5,000m^3)	Low impact: vertical closed loop borehole systems will require water during drilling but not during operation Low impact: coaxial wells may need a couple 10,000L tanks
Power	The site is supplied by an 11kV power line. The site grid network and local SSEN substation must have sufficient capacity to accept electricity generated at the deep geothermal binary plant	Moderate impact: during drilling, power supply for long-term drilling may put strain on the existing network. Supplementary diesel generators may be required. Deep drilling rigs may have peak energy demands of 3MW. High impact during binary plant operation, there must be sufficient capacity at the local substation to accept electricity generated at the binary plant	Low impact: Rigs typically use diesel generators, however can be operated with electricity (c. 100's kW peak demand). Power supply may put short-term strain on the existing network.

6. Site constraints and opportunities

Constraint	Description	Deep geothermal system	GSHP systems
Water disposal	Discharge of abstracted brines will be required during hydraulic testing and operation of a deep geothermal system Abstracted brine will have high temperature and elevated salinity, and therefore discharge to a surface receptor is unlikely to be permitted. It is likely SEPA's preferred option will be to reinject the brine back to the abstracted formation, non-consumptive use. This will require both an abstraction well and reinjection well	Moderate impact: hydraulic tests are required to evaluate well/system performance. These pumping tests will abstract large volumes of brine which will need disposal. Disposal options include disposal to the wastewater network, either via tanker, or sewage connection, subject to the local wastewater treatment works accepting the brine; or reinjection back into granite formation, likely SEPA preferred option The granite/deep geothermal system must have sufficient permeability for discharge. Permeability of the deep granite is unknown. Permeability can be higher where naturally occurring faults have resulted in open discontinuities however, hydraulic stimulation is usually needed to enhance the natural permeability. During operation of the binary plant, water disposal will likely be limited to reinjection back into the granite. A waste treatment works is present on Site, however it may be insufficient to treat the highly saline abstracted brines. If used, the treatment works may require modifications. A licence to deal with NORMs may be required to handle abstracted brines.	Low impact: vertical closed loop borehole systems do not require a water supply following installation and operation Moderate impact: Coaxial wells benefit from bleeding, where abstracted water is disposed off, replaced with new water. Bleed will likely be limited to the sewage network. Daily bleed volumes are relatively low, around 260m^3/day, assuming a continuous flow rate of 3 l/s. Given the coaxial well is in contact with the formation, the circulating fluid may comprise a mixture of freshwater and groundwater brines. Low impact for non-bleed coaxial systems.
Drilling/ Capital costs	Drilling through competent granite is a slow process. Drilling to shallow depths, <1000m, may take a couple of weeks, however drilling to the depths required for a deep geothermal system could take many months. Drilling is most efficient if continuous drilling can be achieved. This may be challenging based on site conditions and may result in long periods of 'standing-time', time during which the equipment is set up, however if drilling is not ongoing; e.g. as a result of inclement weather. Standing time is also typically costed at the same rate as drilling time and could cost a significant amount of money	High impact: Drilling of deep boreholes is costly and the relationship between depth and cost is non-linear. For depths of greater than 1km, a dedicated deep drilling rig will likely be required. The cost of drilling through deep competent granite is also expensive and can cost around £30k per day. Standing time is also typically costed at the same rate. Drilling costs at the United Downs Deep Geothermal Power (UDDGP) were around £30M [19], and comprised the drilling of 2 boreholes to 5275m and 2393m. The drilling conditions for the UDDGP project were more favourable than at the Cairngorms, with mild weather, enabling continuous drilling, and higher geothermal gradients, allowing shallower borehole. Relative to the UDDGP project, drilling boreholes suitable for a deep geothermal system are likely to be more expensive owing to harsh weather conditions, limiting drilling periods, and increasing potential 'standing time', a reduced geothermal gradient, requiring deeper boreholes to yield the same temperatures, and a poorer deep geological understanding, may not intersect a suitably permeable fault, like UDDGP did, resulting in lower flow rates Total costs of the United Downs Deep Geothermal Power (UDDGP) project were around £45M; indicating that subsequent to drilling; testing, construction, and operation of the binary plant cost a further £15M. Pumping costs are significant and will reduce total generation	Moderate impact: Individual closed loop boreholes are relatively low-cost systems with each borehole costing c.<£20k. There is plenty of UK experience installing these systems. The system, number of boreholes and spacing, can be scaled to meet energy demands. The scale of the system will determine CAPEX cost Moderate impact: Limited UK installation experience, for both design and installation. Depth of wells, up to 1km, will require multiple weeks of drilling. A dedicated deep drilling rig is unlikely to be required saving on daily drilling cost, relative to deep geothermal drilling

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6. Site constraints and opportunities

Constraint	Description	Deep geothermal system	GSHP systems
Environmental designations	The site is not located within any environmental land designations. The following are within 1km of the site: These designations include: National Nature Reserve, Special Areas of Conservation, Special Protected Areas, Sites of Special Scientific Interest, and Geological Conservation Review site	Low impact: Not within a land designation. May need to consider off site impacts	Low impact: Not within a land designation. May need to consider off site impacts
Operating costs	GSHP systems are relatively low cost and comprise relatively minor operational (OPEX) and replacement (REPEX) costs. The deep geothermal system will have larger installation costs, for the binary plant, and much larger REPEX costs. Deep geothermal systems for electricity generation have significant pumping requirements. This parasitic power requirement can be of MW scale and typically 20% of power generated is taken up for pumping.	Low impact: Following initial capital costs to set up the binary plant, operation is relatively inexpensive as the plant powers itself with the electricity generated.	Low impact: Vertical closed loop borehole systems are relatively low maintenance, and, if designed to supply sustainable heat for the life of the project, can be operated for decades
Induced seismicity	Reinjection undertaken at high pressure has the potential to induce seismicity at depth. Similarly hydraulic stimulation where fluid is injected at high pressure to induce fissuring with the objective of increasing flow rates, can cause induced seismicity. Relative to oil and gas projects which measure induced seismicity with magnitude, geothermal projects measure induced seismicity from surface acceleration. Surface acceleration is less onerous than magnitude measurements and therefore geothermal projects could be thought to generally carry less induced seismicity liability compared to oil and gas projects. If pressurised injection is proposed it is important to undertake suitable tests to reduce potential seismicity. Community engagement with regards to potential seismicity is also very important and strongly recommended if pressurised injection is proposed.	Moderate impact: potential for induced seismicity during reinjection and hydraulic stimulation, however there are relatively few receptors given the isolated nature of the site. Community engagement is important and recommended	Low impact: induced seismicity is unlikely
Geological certainty	There is large uncertainty with deep geological conditions beneath the site, and estimates have been based on the shallow 300m BGS well on site. The GSHP systems are shallower and therefore a greater confidence can be attributed to the geological conditions for these systems	High impact: System feasibility strongly linked with a good geological understanding. There remains a large uncertainty within the deep geology. Geothermal gradients have been estimated and the presence of fractures or other permeable features are unknown.	Low impact: Site geological conditions impact GSHP less than for deep geothermal systems. Shallow conditions to 300m are also known based on the on site 300m deep BGS well
Constraint summary		**Highly impacted by various constraints**	**Low / moderate impact from constraints**

6. Site constraints and opportunities

6.1 Confidence profile

Confidence profile

A project confidence profile for a typical deep geothermal project is presented in **Figure 19**.

As is presented, pre-surveys and exploration can be done at an initial stage to evaluate deep geological conditions. Following this, a decision is required on whether to commence with test drilling.

Test drilling often comprises a well to the ultimate target depth. This well is typically fit-for-purpose and following testing is used as the principal abstraction well. This stage will incur high costs, however it is required to evaluate the deep geological conditions.

Following the test drilling and hydraulic testing, a technological and economic feasibility assessment can be undertaken to evaluate if the project should commence.

Development of the well field and construction is costly however is paired with strong increase with project confidence.

Phasing

It could be considered appropriate to initially install a GSHP geothermal system, such as vertical closed loop boreholes or dual purpose deep coaxial wells. These systems could be sufficient to meet heat demands at the site and decarbonise heat supply.

Downhole surveys could also be undertaken within a dual purpose deep coaxial well, prior to its commission, providing further insight for the geothermal conditions beneath the site, and filling in the current data gap.

Following a review of further surface and downhole surveys, a decision on whether to commence with a deep geothermal system could be made.

Subsequent to the drilling of a deep geothermal exploratory well, further testing can be done to evaluate the technological and economic feasibility of a deep geothermal project. An overview of some of these investigations is presented in **Section 8**.

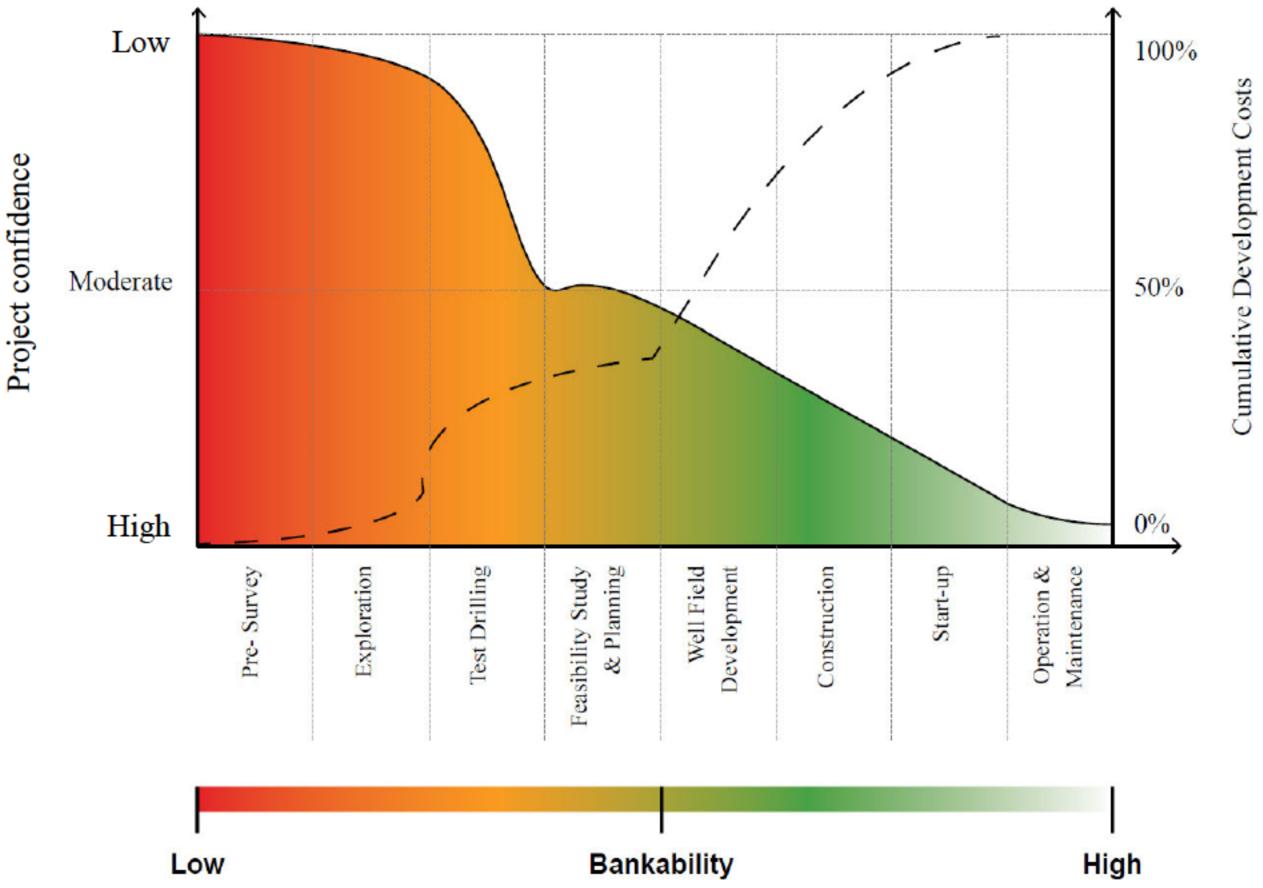

Figure 19: Example project confidence profile for a typical deep geothermal project

7. Investigation options and confidence analysis

Overview of potential investigation and impact on project confidence

This section will review the typical investigations which can be undertaken as part of a deep geothermal system and their impact on overall project confidence. To increase the confidence at a typical deep geothermal system the following could be considered. Indicative costs and inferred improvements in the level of confidence of a proposed deep geothermal system have been provided.

Investigation	Summary	Indicative cost*	Level of confidence#
Borehole siting survey	Field surveys to review possible constraints for drilling sites, such as slopes, and other obstructions. It may be prudent to undertake this work with a drilling contractor with knowledge of the size and space requirements of the drilling work.	<£10k	1
Surface geophysical techniques	Discussions with geophysical contractor is recommended to develop a cost effective technique to identify linear features, i.e. deep faults. Magnetotelluric surveys are commonly used in deep geothermal exploratory investigations to identify deep permeable zones to assist in feasibility assessments and borehole design. Examples include electromagnetic radio wave techniques, such as the EM Adrok technique [17], or a local array of geophone and monitors to record micro seismicity back ground.	<£50k	2
Downhole geophysical surveys	It is recommended that any downhole geophysics undertaken includes collection of data on lithology, temperature, and well construction. Well condition/ well integrity data will be required to assess suitability for a deep well for abstraction and will be required by the SEPA to grant a groundwater abstraction/ discharge licence. Downhole geophysics can be used to collect stress measurements, which would be useful to confirm assumptions about the local stress regime to inform deep geothermal borehole design such as trajectory, orientation and hydraulic stimulation requirements. Televiewer logging (OTV/ATV) and calliper logging can be undertake to estimate the minimum horizonal stress orientation or provided information for a geomechanical model. **Prerequisite:** a suitably deep borehole. Could initially drill and survey a shallow, <1km borehole, to inform on a deeper geothermal well. Then repeat testing following completion of deep geothermal borehole too.	c.£200k for <1km borehole c.£750k for deep geothermal (5-7 km) boreholes	3
Geomechnical modelling	Geomechanical models incorporate downhole geophysical survey data and can be a useful tool ahead of in-situ stress regime measurement techniques **Prerequisite:** downhole geophysical survey data	<£10k	2

7. Investigation options and confidence analysis

Investigation	Summary	Indicative cost*		Level of confidence#	
Slim-hole drilling	Slim-hole drilling typically refers to drilling with a well casing size less than 6" for 90% of its depth. A slim-hole can be drilled to around 1km to 2.5km depth. It is cheaper to drill than standard borehole drilling and can be used to confirm geological thermal properties	£100k's		4	
Deep borehole drilling	Whilst geophysical testing may provide data to evaluate the presence and geometry of potential faults at depth, there is an inherent risk that these faults may be absent or do not provide sufficient permeability for an efficient power project. A deep borehole would be required to prove the presence of deep structures (e.g. faults) and investigate the temperature and assess flow rates and injection pressures	£Millions		5	
In-situ stress regime measurements	There are three main in-situ techniques used to estimate maximum horizontal stress in boreholes: hydraulic testing, overcoring, and borehole failure mechanisms [18]. A good understanding of the local stress regime is essential to developing a deep geothermal system (i.e. outlining target depths/structures). **Prerequisite:** a suitably deep borehole (and ideally downhole geophysical survey information and a geomechnical model)	c.£500k		3	
Pumping test	A pumping test, including installation of pumping test equipment, step tests, and discharge, is recommended following drilling of a deep geothermal well. Discharge of pumped water back to the formation may be required (for SEPA licence), requiring both an abstraction and discharge borehole. **Prerequisite:** deep geothermal borehole at target depth and within target feature (i.e. deep fault)	c.£900k		4	
Hydrogeological numerical modelling	Recommended to test the hydrogeological conceptual model, assess borehole configuration scenarios, and assess thermal losses. **Prerequisite:** pumping test data	<£10k		3	

* Indicative costs are high level and based on Arup experience. They are for information only.
# Level of confidence: 1 – Minimal improvement in system confidence, 2 – Minor improvement in geological understanding and system confidence, 3 – Moderate improvements in system confidence associated with more comprehensive geological data, 4 – Major improvements in system confidence with direct geothermal and hydrogeological measurements, 5 – Significant improvements in system confidence with a fit-for-purpose deep borehole to evaluate system feasibility.

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8. Deep geothermal roadmap

Economics assessment → Concept design → Detailed design → Construction

A typical deep geothermal system roadmap is presented below. Further details on investigation options, regulatory requirements, and funding options are presented in subsequent **Section 8**.

Dual purpose deep coaxial well

As outlined in Section 6, installation and testing of a dual purpose deep coaxial well may provide an opportunity to gather further deep geothermal data of the Cairngorm granite which could benefit subsequent development stages. This is project specific opportunity, and not a typical roadmap stage. This step could be undertaken ahead of concept design of a deep geothermal system.

Concept design

A comprehensive electrical demands and heat load survey should be undertaken. Discussions with local network suppliers, such as SSEN, should be undertaken to review current infrastructure capacity to accept exported power and understand grid curtailment for economic models.

Geological requirements for a successful system should be outlined and outline well design and configurations drafted.

An outline technological and economic assessment for project feasibility is required to evaluate a range of possible project outcomes/ Internal Rate of Return (IRRs).

Detailed design

If decided to proceed, the following investigations could be considered as part of concept design:

- Borehole siting survey with drilling contractor to review possible constraints for drilling sites.
- Up to 1km depth drilling campaign to better constrain temperature gradient and stress regime. Data from this can inform on detailed system design, site layout and rig requirements.
- Surface geophysical surveys to evaluate and refine an understanding of the deep geology.

Hold initial discussions and prepare documentation with local planning and regulatory authorities. At the Site this would likely be Cairngorms National Park Authority (CNPA), Scottish Environmental Protection Agency (SEPA) and Health & Safety England (HSE):

- Planning application and potential Environmental Impact Assessment (EIA), CNPA.
- Borehole construction, CAR licence, SEPA and HSE.
- Abstraction and discharge licence (for testing and operation), SEPA.
- Assess Naturally occurring radioactive material (NORM), SEPA

As outlined in **Section 5.3**, based on a lack of deep geological knowledge this project has a need for more data to inform decision making for a deep geothermal project. Such a project should be considered an R&D project at this stage and not a commercial proposition. Therefore, a number of R&D funding options may apply. These are outlined in **Section 9.3**.

If Planning Permission is successful then can consider construction.

Construction

The construction will likely comprise the following:

- Funding opportunities should be explored to fund the drilling campaign;
- Drilling and testing of the well(s);
- Presentation of drilling data to gain funding for construction of the power plant; and
- Construction and commission of the power plant.

8. Deep geothermal roadmap

Roadmap costs and timings for deep geothermal projects are project-specific and provision of generic costs and timescales is challenging. The table below comprises general ranges for deep geothermal projects, for information only. A detailed tender is required to obtain better price and timescale estimates. In addition, during deep drilling (particularly very deep drilling) unforeseen conditions will occur which should be expected to cause project delays and cost increases. For this reason, contingency in cost and programme in proportion to the scale of the drilling is required to manage deep drilling risks.

Constraint	Typical costs	Anticipated timescales
Economics assessment	c. £20k	3 months
Concept design	c. £50k	4 – 6 months
Detailed design		
Borehole siting survey	<£10k	1 – 3 weeks
Surface geophysics	<£50k	1 month
Drilling campaign (up to 1km)	£100k's	2 – 4 months
Planning applications and EIA	<£10k	1 year
Licensing from regulators	Na	1 to 2 years
Construction		
Funding	NA	3 to 5 years
Drilling and testing	£Millions	1 year
Power plant funding campaign	NA	3 to 5 years
Construction of power plant	£Millions	1 to 2 years

9. Regulator, planning, and funding considerations

9.1 Environmental regulation

Environmental regulations

Closed loop boreholes and non-bled dual purpose deep coaxial wells, are non-consumptive and therefore have few regulatory requirements. However, deep geothermal systems have a number of regulatory requirements [25].

General

The Scottish Environmental Protection Agency (SEPA) regulates activities that may cause pollution or that pose another risk to the environment.

With regards to geothermal SEPA regulates abstractions from and discharges of pollutants to the water environment, including those associated with geothermal energy, through the Water Environment Controlled Activities, Scotland, Regulations 2011 (CAR).

Depending on the type of geothermal energy scheme this can involve the following activities which may require control under the CAR:

- construction and operation of a borehole or boreholes;
- abstraction of groundwater; and
- subsequent return of the abstracted groundwater to the water environment.

As SEPA's regulatory processes are complex pre-application discussions with the SEPA are recommended to ensure the regulatory route and requirements are clear.

Health and Safety Executive (HSE) take a risk-based approach to the drilling of boreholes for geothermal exploitation. The broad framework of the Health and Safety at Work etc Act 1974, which applies to all workplaces will be utilised in assessing geothermal developments.

Borehole

The construction and operation of boreholes to depths of greater than or equal to 200m require a CAR licence. This may be the case for the vertical closed loop borehole option.

The construction of boreholes <200m in depth are normally authorised via CAR General Binding Rule 3 (GBR). The borehole should be designed to prevent:

- pollution;
- unacceptable mixing of water between layered aquifer systems; or
- loss of water from artesian aquifers.

Groundwater abstraction

There are no abstractions or discharges to the water environment from a closed loop geothermal system and therefore no authorisation for the abstraction or discharge from SEPA will be required.

The abstraction and discharge, of a open loop system, can be authorised by GBR17 the open loop system

- does not abstract more than 10m^3 per day which is not subsequently returned;
- returns water to same geological formation from which it was abstracted; and
- the chemical composition of the abstracted water has not been altered, by for example, addition of chemicals from a cooling process.

Where GBR17 does not apply, as the conditions cannot be complied with, the abstraction may be authorised by GBR2 if it is less that 10m^3/day or by registration or CAR licence for abstractions if over 10m^3/day.

9. Regulator, planning, and funding considerations

9.1 Environmental regulation

Naturally occurring radioactive materials (NORM)

Removing and managing radioactive scales and precipitates from equipment associated with boreholes may result in naturally occurring radioactive material (NORM) being encountered.

Under the Environmental Authorisations (Scotland) Regulations 2018 (EASR), SEPA regulate activities within an authorisation framework designed to ensure that suitable controls are in place that are proportionate to the nature of the activity and any associated risks to human health and the environment.

In order to allow for proportionate regulation based on the risk an activity poses to human health and the environment SEPA issue four levels of authorisation under EASR:

- General Binding Rules
- Notification
- Registration
- Permit

The application process for each differs and is outlined in SEPA's 'Authorisation guide for radioactive substances activities' [1]

9. Regulator, planning, and funding considerations

9.2 Planning application

Definition of development - Town and Country Planning (Scotland) Act 1997

The Town and Country Planning, Scotland, Act 1997 states that development includes any building, engineering, mining or other operations in, on, over or under land. It also includes changes in the use of buildings and land'.

It is known that the development of a deep geothermal powerplant will be considered as development requiring planning permission in line with the above.

A definitive answer as to whether vertical closed loop boreholes and dual purpose deep coaxial wells are considered as such will be provided by the Planning authorities, see below, at pre-application stage. It is considered that both will likely require a grant of planning permission.

Planning application

The planning system in the Cairngorms National Park is managed by the **Cairngorms National Park Authority** (CNPA) and the five local authorities which operate in the Park - Aberdeenshire, Angus, Highland, Moray and Perth & Kinross. The proposal site lies within the joint jurisdiction of CNPA and **Highland Council Planning Authority**.

All planning applications within the National Park are made to the relevant local authority, in this case Highland Council. The majority of applications are decided by the local authority. If, however, the proposal is deemed to be of a size or nature that is potentially impactful on the key characteristics, or function of the National Park, then it can be 'called-in' and decided by the CNPA.

The CNPA has 21 days to decide whether to 'call in' and determine a planning application. If an application is called in, The CNPA notifies the council, the applicant and any consultees that it has called in the application.

The planning application requirements including supporting studies, surveys and documentation will vary depending on the size and scale of the proposed development. It is recommended that pre-application discussions are sought with both the CNPA and the Highland Council Planning Authority at an early stage to confirm the following:

- Whether the proposal constitutes development requiring planning permission in accordance with the 1997 Act, only relevant to closed loop options as deep geothermal will require a grant of full planning permission;
- The scope and requirements of the application supporting studies including environmental studies/Environmental Statement.

All planning applications in the National Park are assessed against the Cairngorms National Park Local Development Plan 2021 (LDP) regardless of whether the CNPA or the local authority that makes the decision.

Major vs local application

All development proposals into one of three categories:

1. national development, not relevant to this project;
2. major development;
3. local development.

Vertical closed loop boreholes and dual purpose deep coaxial wells will likely be considered Local Developments as the site area will be < 2ha.

A deep geothermal powerplant may exceed the 2ha site threshold and be considered a major development.

The statutory determination period are:

- local development – 2 months;
- major development – 4 months.

Major developments are subject to statutory pre-application public consultation requirements, see **Community Engagement** section below for further details.

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9. Regulator, planning, and funding considerations
9.2 Planning application

Environmental impact assessment - The Town and Country Planning (Environmental Impact Assessment) (Scotland) Regulations 2017

It is not expected that vertical closed loop boreholes or dual purpose deep coaxial wells would be subject to EIA requirements in line with the regulations.

Development of a deep geothermal powerplant is likely to exceed the thresholds for Schedule 2 development under the regulations where a binary plant exceeds 1,000 sqm floorspace or the area of deep drilling works exceeds 1ha.

The requirement for an EIA for the proposed development would need to be determined through EIA screening and EIA scoping with the determining local authority.

The scope of an EIA may include the following topics:

- Landscape and visual impact assessment;
- Noise and vibration assessment;
- Ecology assessment;
- Transport assessment;
- Air quality;
- Water resources and flood risk;
- Water quality and aquatic ecology assessment;
- Geology and land contamination.

Community engagement

If the proposal is considered a Major Development pre-application consultation (PAC) is statutorily required consisting of, as a minimum:

- Consult the Community Council(s) affected by your proposal;
- Hold two public events which have been advertised prior to the event.

In certain circumstances the Council may request additional notification and consultation.

Often a hybrid approach of digital and in person engagement is best for reaching across the community demographic and geographic spread.

The statutory engagement requirements for major developments can also be considered as a starting point as to best practice community engagement for local developments which may have widespread potential impacts or which may generate local interest.

Community consultation and stakeholder engagement is likely to be vital in successfully delivering the project. The development consenting process can be heavily influenced by public perception and discourse, and as such it is vitally important that a full and detailed community engagement process is undertaken.

If a decision is taken to move forward with a deep geothermal project then community engagement and education programmes need to start prior to any Planning submission. An experienced team will need to be in place early and continue to be in place throughout the project. The developer should go above and beyond anything that is required in the Planning application. Therefore, an appropriate budget needs to be ring fenced for this work from the beginning.

9. Regulator, planning, and funding considerations

9.2 Planning application

Planning Policy

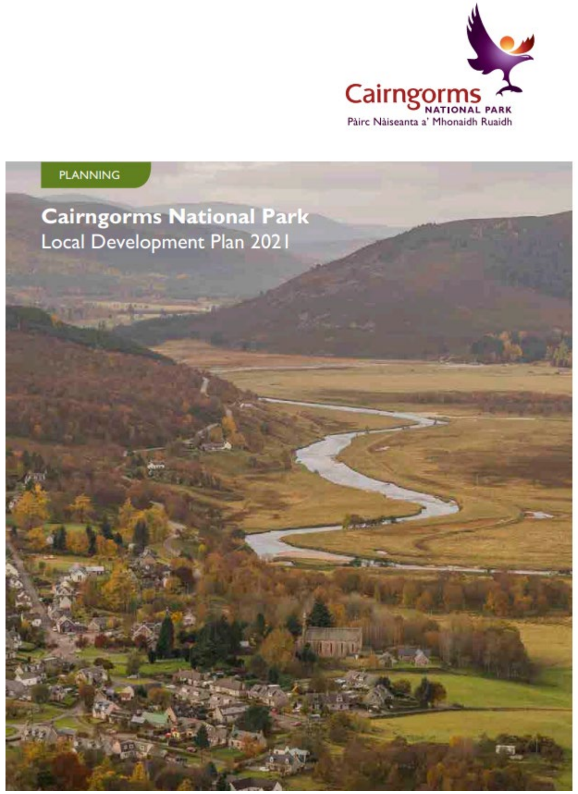
The Draft Fourth National Planning Framework (NPF4) details the Scottish Government's long term plan for what Scotland could be in 2045 and is scheduled to be adopted final quarter 2022. NPF4 includes support in principle for renewable energy projects and geothermal in particular, subject to detailed considerations and local constraints.

All planning applications in the National Park are assessed against the Cairngorms National Park Local Development Plan 2021 (LDP).

The LDP includes Policy 7: Renewable Energy which includes a presumption in favour of renewable energy projects where:

- they contribute positively to the minimisation of climate change;
- they complement the sustainability credentials of the development;
- they conserve and enhance the special qualities of the Park, including wildness;
- they include appropriate means of access and traffic management, including appropriate arrangements for construction areas and compounds;
- they adequately minimise all cumulative effects; and
- they adequately minimise detrimental impacts on local air quality.

The policy context is such that a proposed vertical closed loop borehole, dual purpose deep coaxial well or deep geothermal would benefit from support in principle. If it can be evidenced that any detailed proposal has an acceptable level of environmental impacts, post mitigation, it may benefit from Local Planning Authority support.



9. Regulator, planning, and funding considerations

9.3 Funding options

Funding options

The funding options, as outlined in **Section 8**, have been expanded upon below and further details are presented in **Appendix B**.

Funding round 1 - site investigation and permitting

As outlined in **Section 5.3**, given the lack of deep geological knowledge for the area, this will mean that any deep geothermal project for potential electricity generation must, at this point, be viewed as an R&D project, not as a commercial proposition. As a result R&D funding options have been considered.

It is considered that the following funding bodies/ grant applications may be suitable:

- Clean Growth Fund - £20 million BEIS funding to support a new clean technology early stage investment fund.
- Net Zero Innovation Portfolio - £1 billion BEIS funding to decrease costs of decarbonisation, create jobs and investment.
- Low Carbon Infrastructure Transition Programme - £400 million Scottish Government funding over the next five years in large-scale heat decarbonisation infrastructure.
- Green Heat Hub Challenge – Scottish Enterprise grant of up to £75,000 to help towards creating a green heat hub, closes 18 November 2022.
- Net Zero Technology Centre Funding - Up to £1m for 24 month projects with technology innovation, closes January 2023.
- Innovate UK funding - There are innovation grants available for businesses to develop new and novel products, processes or services.
- Horizon Europe - EU innovation programme, with a budget of €95 billion, which runs until 2027. The UK is associated to this programme.
- In addition, various business support and finance opportunities can be found through Scottish Enterprise and the Scottish Funding Portal.

The scope of this grant application may comprise the following:

- surface investigations, mapping lithology;
- Up to 1km depth drilling campaign drilling campaign to better better constrain temperature gradient and stress regime;
- detailed system design, site layout and rig requirements;
- permitting and planning.

Community and stakeholder engagement is recommended at an early stage in the project

Funding round 2 - drilling campaign

The drilling and testing of the deep wells will be challenging. At least £30m will be required and, given the lack of data at the site (and on-shore in Scotland as a whole) it will be difficult to attract any private funding. Further, if grant funding is used for the project then it will not be possible to claim CfDs (see below) for the revenue stream.

For the above reasons, a very high percentage of grant intervention rate will be required. High intervention rates are normally only allocated to Universities or other Research Institutions. It would therefore be worth considering involving a university at an early stage in any deep project.

Funding round 3 - powerplant

Support for renewable heat systems owned by business, public sector and non-profit organisations has in the past been provided through the Non-Domestic Renewable Heat Incentive (NDRHI), however this closed to new applicants on 31 March 2021. There has been no replacement scheme for non-domestic renewable heat announced to date.

The Contracts for Difference (CfD) scheme is the UK government's main mechanism for supporting low-carbon electricity generation. CfDs provide certainty for generators from volatile electricity markets through a theoretical guaranteed 'strike price'. The latest round (CfD 4) closed in January 2022, however rounds open approximately every two years. The most recent pot for geothermal was under the 'less established technologies' category, which has a total budget of £31 million. It should be noted that this is a competitive auction where the lowest bid price is successful. This price is not necessarily the strike price.

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10. Next steps and recommendations

Overview

Based on a review of the current data available; a combination of a low geothermal gradient, a lack of deep geological understanding, and highly impacting site constraints mean that the development of a deep geothermal system on the Site is likely to require deep, 7km, wells. These will have a large CAPEX, in excess of the £45M cost for UDDGP in Cornwall. As a result, this assessment concludes that there is a need for more data to inform decision making for a deep geothermal system at the Site. Alternative locations elsewhere in the Cairngorms may be more suitable for a deep geothermal scheme. For example at lower elevations with a milder climate and sited close to infrastructure, such as a substation with capacity to accept electricity generation.

GSHP geothermal systems, such as vertical closed loop boreholes or dual purpose deep coaxial wells are less impacted by site constraints, have fewer regulatory requirements, and are relatively simple to install and operate. These types of systems are thought to be suitable to meet heat demands at each of the Hubs and could provide an opportunity to decarbonise heat at the Site.

It could be considered to initially install a dual purpose deep coaxial well up to 1km in depth. Such a well could be dual-purpose: downhole surveys could be undertaken within the well, prior to its commission, providing further insight of the geothermal conditions beneath the Site, and filling in the current data gap; and following commission, the dual purpose deep coaxial well would provide low-carbon heat to the Site.

Peak heat demands per Hub are inferred to be <120kW. Based on the high-level closed loop and dual purpose deep coaxial well assessments, a borefield comprising ten, 200m deep, boreholes; or one, 1000m deep dual purpose deep coaxial well may be able to meet the peak heat demands per Hub. Note that these systems need to be designed to provide sustainable heat for the life of the project. The scale of the systems presented within this report are indicative. As all heat demands are electric with no submetering, further understanding and analysis would be required to determine the exact heat demands for each of the hub locations. Opportunities for geothermal heat pump systems should also be considered where new buildings at the Base Station are considered.

Deep geothermal next steps

As outlined, this assessment concludes a need for more data to inform decision making for a deep geothermal system at the Site. A next step may comprise the drilling and subsequent testing of a dual purpose deep coaxial well to help fil in current deep geothermal data gaps.

For completeness, a typical deep geothermal system roadmap may comprise the following:

An economics assessment (with full sensitivity analysis) to identify a number of scenarios. Following this, a concept design would be developed. This may comprise an outline for geological requirements for a successful system and outline well design configurations. A comprehensive electrical demand and heat load survey should also be undertaken to evaluate the Site demands.

As part of detailed design, site investigations could be considered. These may comprise borehole siting surveys, shallow drilling and testing campaigns and surface geophysical surveys. The data from these surveys will help refine the deep geological understanding at the Site. It is also considered pertinent at this stage to initiate dialogue with appropriate regulatory bodies about the proposed system. At this Site this may include Scottish Environmental Protection Agency (SEPA), and Health and Safety Executive (HSE)) and the local planning authority, Cairngorms National Park Authority (CNPA). R&D funding opportunities can also be explored at this stage.

The construction stage will likely comprise exploring R&D funding opportunities for drilling and testing of the well(s), followed by further fund raising for the binary plant construction and commissioning.

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Appendix

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Appendix A

Summary of geothermal funding options

UK Government (BEIS)

Support for renewable heat systems owned by business, public sector and non-profit organisations has been provided through the Non-Domestic Renewable Heat Incentive, however this closed to new applicants on 31 March 2021. There has been no replacement scheme for non-domestic renewable heat announced yet.

Current UK Government heat schemes include:

- Boiler Upgrade Scheme (residential heat pumps)
- Local Authority Delivery Scheme (local authorities to improve energy efficiency of low-income households)
- Social Housing Decarbonisation Fund (improve the energy performance of social homes in England)
- Home Upgrade Grant (residential energy efficiency where homes are off gas-grid)
- Green Gas Fund (anaerobic digestion)
- Green Heat Network Fund (heat networks in England)

However, none of these are suitable for commercial geothermal installations.

Current policy for low carbon heat in the UK is the Heat and Building Strategy. Alongside current government support (above), it mentions plans to develop a competitive, fit-for purpose green finance market providing a range of financing options (loans, mortgages, or other financing products) to meet the needs of different consumers. However no specifics/timescales are set out.

Alternative funding options that are not directly related to low-carbon heat which may be suitable are detailed in the table:

Name	Scheme Name	Description	Link
Contracts for Difference round	UK Government (BEIS, LCCC) subsidy scheme	Closed Jan 2022, run approx. every 2 years. Most recent pot with £31 million budget for less established technologies (inc. geothermal).	Link
Clean Growth Fund	Clean Growth Fund (in partnership with BEIS) investment fund	£20 million of BEIS funding to support a new clean technology early stage investment fund. Investment in early-stage disruptive products and services in clean growth sectors across power, transport, industry, buildings, waste and water.	Link
Net Zero Innovation Portfolio	UK Government (BEIS) funding scheme	A £1 billion fund to decrease costs of decarbonisation, create jobs and investment. Geothermal is not a priority area, but could fit into disruptive technologies, homes and buildings, industry.	Link
Contracts for Difference round	UK Government (BEIS, LCCC) subsidy scheme	Closed Jan 2022, run approx. every 2 years. Most recent pot with £31 million budget for less established technologies (inc. geothermal).	Link

Appendix A

Summary of geothermal funding options

Scottish Government

The Scottish Government have previously run geothermal-specific funding rounds as part of the Low Carbon Infrastructure Transition Programme (Low Carbon Infrastructure Transition Programme: closed invitations - gov.scot (www.gov.scot), Geothermal Energy Challenge Fund), but does not appear to have anything currently open, with funding currently focussed on heat networks, such as the Heat Network Fund and District Heating Loan Fund.

Current Scottish policy for low carbon heating is the Heat in Buildings Strategy which commits £1.6 billion of capital funding over the next 5 years. Chapter 6 Kick-starting Investment in the Transition - Heat in buildings strategy - achieving net zero emissions: consultation - gov.scot (www.gov.scot) However, it states 'Larger businesses and organisations can access support on the open market to invest in decarbonising their property assets.'

Name	Scheme Name	Description	Link
Low Carbon Infrastructure Transition Programme	Scot Gov Programme	LCITP and its successor programme will invest £400 million over the next five years in large-scale heat decarbonisation infrastructure.	Link Link
SME Loan Scheme	Business Energy Scotland Loan scheme	Loans up to £100k are available to help pay for energy and carbon-saving upgrades in your business, cashback grant of up to £30k. Renewable heat technologies are eligible.	Link
Green Heat Hub Challenge	Scottish Enterprise Challenge	A grant of up to £75,000 to help towards creating a green heat hub – close 18th Nov 2022	Link
Clean Energy Transition Partnership programme (CETP)	Scottish Enterprise	Up to £6 million available for supporting projects, assigned on a competitive basis, however, needs two EU member partners. Deadline 23 November 2022.	Link
Scottish Growth Scheme	Backed by Scottish Government	Package of financial support of up to £500 million for Scottish businesses	Link
Net Zero Technology Centre Funding	Funding Competition	Up to £1m for 24 month projects with technology innovation – Jan 2023	Link
Future Fund	British Patient Capital	£375m UK-wide programme which encourages private investors to co-invest in high-growth, innovative firms.	Link
Innovate UK funding	Various funding opportunities	Various funding opportunities (no heat specific just now)	Link
Horizon Europe	EU funding programme	EU innovation programme, budget Euro 95bn, runs until 2027. UK is associated.	Link Link
Scottish Enterprise	Various funding opportunities	Details on business grants. Innovation funding and investment funding. Support with EU funding opportunities.	Link Link
Scottish funding portal	Various funding opportunities	Lists the EU and UK Funding that the UK can access in 2021 – 2027	Link