Annex A

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@Arup (2021) Deep Geothermal Energy – Economic Decarbonisation Opportunities for the United Kingdom

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Ove Arup & Partners Limited
Bedford House
3rd Floor
16-22 Bedford Street
Belfast BT2 7FD
United Kingdom
arup.com

Contents

A.1 UK Geothermal Assessment 1
A.1.1 Introduction 1
A.1.2 Approach 2
A.1.3 Deep Geothermal Heat Assessment 4
A.1.4 Power Assessment 7
A.1.5 Model findings 10

A.2 Modelling summaries 13
A.2.1 Overview 13

A.3 Wessex Basin (Portsmouth) 14
A.3.1 DoubletCalc Inputs 18
A.3.2 Doublet Calc Outputs 22

A.4 Cheshire Basin (Manchester Airport) 23
A.4.1 Doublet Calc Inputs 26
A.4.2 Doublet Calc Outputs 30

A.5 Northumberland & Solway Basin (Newcastle) 31
A.5.1 Doublet Calc Inputs 37
A.5.2 Doublet Calc Outputs 41

A.6 Glasgow & Clyde Basin (Edinburgh) 42
A.6.1 Doublet Calc Inputs 45
A.6.2 Doublet Calc Outputs 49

A.7 Northern Ireland Sedimentary Basin (Lough Neagh Basin, Antrim) 50
A.7.1 Doublet Calc Inputs 53
A.7.2 Doublet Calc Outputs 57

A.8 Cornish Granites 58
A.8.1 Doublet Calc Inputs 59
A.8.2 Doublet Calc Outputs 63

A.9 North Scotland Granites (Aberdeen) 64
A.9.1 Doublet Calc Inputs 65
A.9.2 Doublet Calc Outputs 69

References 70

Tables

Table 1: Inferred temperature change across the heat exchanger (ΔT) at various bottom hole temperatures 4
Table 2: Summary of UK geothermal targets used to inform the power assessment 7
Table 3: Summary of input parameters used for each power assessment for a given location and depth 7
Table 4: Summary of assumed electrical submersible pump power requirements 8
Table 5: Summary of Sedimentary aquifer geological parameters and thermal capacity estimates 11
Table 6: Summary of granite body geological parameters and thermal capacity estimates 12
Table 7: Power assessment summary 12

Table 8: Geological summary 14
Table 9: Inferred Ground Model 16
Table 10: Inputs for Greater Oolite Group 18
Table 11: Inputs for Sherwood Sandstone 20
Table 12: Geological summary 23
Table 13: Inferred ground model 25
Table 14: Inputs for Collyhurst Sandstone formation 26
Table 15: Inputs for Early Carboniferous Limestone 28
Table 16: Geological summary 31
Table 17: Inferred ground model Science Central 34
Table 18: Inferred ground model Kingston Park 36
Table 19: Inputs for Fell Sandstone - Science Centre 37
Table 20: Inputs for Fell Sandstone - Science Centre 39
Table 21: Geological summary 42
Table 22: Inferred ground model 44
Table 23: Inputs for the Kinnesswood Fm. 45
Table 24: Inputs for the Knox Pulpit Formation 47
Table 25: Geological summary 50
Table 26: Inferred ground model 52
Table 27: Inputs for the Sherwood Sandstone Group 53
Table 28: Inputs for the Lower Permian Sandstones 55
Table 29: Geological summary 58
Table 30: Inputs for the Granite 4km 59
Table 31: Inputs for the Granite 5km 61
Table 32: Geological summary 64
Table 33: Inputs for the Granite 4km 65
Table 34: Inputs for the Granite 5km 67

Figures

Figure 1: Geothermal Case Study Locations Summary (Adapted from the Deep Geothermal Energy White Paper [39]) 3
Figure 2: European geothermal heat plant capacities, flow rates, and production fluid temperature (after EGEC [21]) 5
Figure 3: Plot of Arup assessment across UK Sedimentary aquifers and Granite bodies; relative to European data (EGEC [21]) (zoomed in section of Figure 2, and inclusion of Arup data) 6
Figure 4: Plot of electrical outputs against Arup modelled outputs for the same system 9
Figure 5: European geothermal power plant capacities, flow rates, and production fluid temperature (after EGEC [21]). Arup net power values presented. 10
Figure 6: Site Location and local data 14
Figure 7: Inferred Ground model and geothermal gradient for Wessex Basin (Portsmouth) 15
Figure 8: Site location and local data 23
Figure 9: Inferred ground model and geothermal gradient 24
Figure 10: Site location and local data 31
Figure 11: Kingstone Park inferred ground model and geothermal gradient 32

Figure 12: Science Centre inferred ground model and geothermal gradient 33
Figure 13: Site location and local data 42
Figure 14: Inferred ground model and geothermal gradient 43
Figure 15: Site location and local data 50
Figure 16: Inferred ground model and geothermal gradient 51
Figure 17: Inferred extent of Cornish granites [19] 58
Figure 18: Inferred extent of Scottish granites [4][20] 64

A.1 UK Geothermal Assessment

A.1.1 Introduction

This appendix represents the initial step in addressing DESNZ's Research Question Nr. 06:

What are the costs for geothermal power and heat and combined heat and power in different geographic locations (including Manchester Basin, Portsmouth basin, Norfolk, and Cornwall), at different depths (e.g. 300m, 1km, 2km, 4km for heat and 4km and 5km for power).

The following sections provide details on our approach, methodology, and assessment outputs for both heat and power at different depths and geographical locations.

We extend our sincere gratitude to Professor Jon Gluyas and Dr. Mark Ireland for their invaluable technical review of this geothermal assessment. Their expertise and insights have provided a valuable appraisal of our work, and we are grateful to have benefitted from their comments and feedback.

A.1.1.1 Context

Deep Geothermal systems extract heat within the ground to deliver energy. The heat is used directly or converted to electricity. There are also methods to convert heat energy for cooling, however deep geothermal cooling systems have not yet extensively been commercially deployed.

To access the geothermal reservoir, deep wells are required. These wells are generally similar to oil and gas wells and utilise similar size drilling rigs and equipment.

The energy capacity of a geothermal reservoir depends on the following factors:

1. Temperature at depth (often referred to as the geothermal gradient)
2. Well yield (which depends on the permeability and thickness of the geologic target)
3. Presence of a low permeability 'cap' rock (which prevents the escape of reservoir pressure)

Of these factors, the well yield is typically the most uncertain. Deep drilling and testing is required to estimate well yield with any certainty, which requires an investment commitment where significant project risk exists.

A.1.1.1.1 Geothermal Geology & Reservoirs

The production of geothermal energy is often referred to as the reservoir 'enthalpy' which is the combination of fluid temperature and production rate. The geothermal geology drives the type of geothermal enthalpy. Volcanic systems can produce high enthalpy (most suitable for power); while hot dry rocks (i.e., granite) and hot wet rocks (i.e., sedimentary basins) have much lower enthalpy and may only be suitable for heat. Traditionally 'high enthalpy' reservoirs are found in places like Iceland, the United States, Indonesia, and the Philippines. Western Europe is typically characterised by lower enthalpy reservoirs.

A.1.1.1.2 Temperature gradients and Production Rates

Below the ground surface, the temperature increases with depth towards the Earth's core. The global temperature gradient is around 30°C/km. The gradient is a key parameter to understand if there are favourable conditions for geothermal use.

The other important aspect is the rate at which a well can produce the geothermal fluids. The well yield is influenced by several factors which include the pressure of the fluids in the geothermal reservoir and the permeability of the rock.

Of these three parameters: temperature gradient, pressure, and permeability, the permeability is by far the least certain parameter. This is because despite being able to generally identify the type of geology in a targeted reservoir, it is difficult to estimate the permeability unless a well has been installed and tested.

The other parameters (temperature gradient and pressure) can be more easily inferred and evaluated. For example, there are non-intrusive mapping techniques which can be used in combination with oil & gas exploration drilling data to evaluate temperature gradients. Pressure can be assumed to at least follow a hydrostatic gradient (that is, the pressure increases at a rate which is based on the weight or density of water, also known as the head of water).

A.1.1.1.3 Geothermal Energy Production

Regardless of the end-product (i.e., heat or power), geothermal energy requires: (i) the circulation of a geothermal fluids (in open loop systems the extraction of geothermal brine from wells and its reinjection back to the reservoir; in closed loop systems the circulation of a separate fluid within sealed pipework; (ii) conveyance to an energy plant.

The well field is a combination of production and reinjection wells. After energy has been extracted from the geothermal fluid, the fluid is reinjected to minimise loss of pressure in the reservoir.

A.1.1.1.4 Electricity Generation

High enthalpy systems, dominated by steam, may utilise direct steam generation. Low enthalpy systems, which are the most common geothermal system in Europe, utilises binary technologies most commonly based on the Organic Rankine Cycle (ORC). In other words, a heat exchanger is used to transfer the energy from the geothermal brine to a 'working' fluid. Then the working fluid drives the turbine. Electricity generation is calculated by geothermal system capacity (MWe) and plant availability (as a percentage of the year).

A.1.1.1.5 Geothermal Heat Generation

Direct heat use is becoming a more common use for geothermal reservoirs. Heat use may be the principal energy use for a project or may be an additional source of energy as a byproduct of waste heat from power generation. In some cases, the heat is used for building heating in the winter (as a supply to district heating networks), for greenhouse heating (which is becoming very common in The Netherlands), or for industrial heating uses.

Production of heat from a geothermal well field is completed by passing geothermal brine through a heat exchanger. At the heat exchanger a carrier or working fluid (often water) is then used to distribute the heat for heating or other use (e.g., within a district heating network).

Where the temperature is not suitable for direct use, the heating potential can be improved through the use of high-temperature heat pumps or temperature increased using more traditional water heating technologies.

A.1.2 Approach

A.1.2.1 Geological characterisation

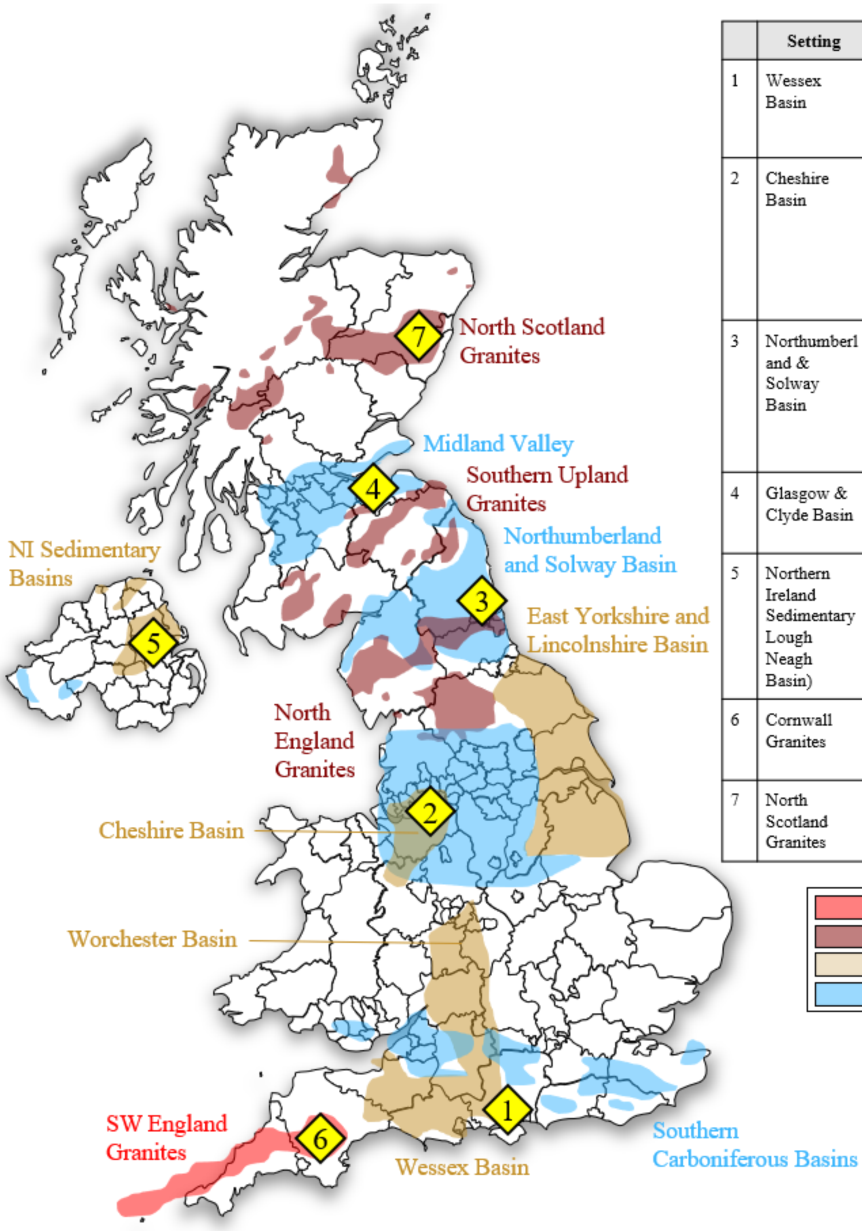
A literature review and modelling exercise was undertaken to infer the geological stratigraphy and produce ground models at seven selected locations in the UK (see Figure 1). These locations were selected to provide a broad geographic spread across the UK. The assessment was limited to seven locations and considered to be representative of deep basins across the UK, as agreed by DESNZ. Considering the geographical spread, a specific target location was used for each geological setting as shown in brackets:

1. Wessex Basin (Portsmouth)
2. Cheshire Basin (Manchester Airport)
3. Northumberland & Solway Basin (Newcastle)
4. Glasgow & Clyde Basin (Western Edinburgh)
5. Northern Ireland Sedimentary Basin (Lough Neagh Basin, Antrim)
6. Cornish granites (Cornwall)
7. North Scotland granites (Western Aberdeen)

Within the sedimentary basin environments, one or two potential hydrothermal target strata were selected. For each of the geothermal targets (sedimentary basin and granite bodies), a target depth, inferred temperature, and estimated permeability ranges were inferred from literature. These values were used to inform the heat assessment and power assessment. Further geographic specific detail is provided in Sections A.2 to A.9.

The levelised costs are considered representative of the UK as a whole, but localised variations of geothermal output are anticipated. In future studies, and as more data becomes available, further information can be included within the existing analysed data set to widen the areas considered for the levelised cost calculation.

One notable exclusion is the East Midlands Basin (East Yorkshire and Lincolnshire Basin). Whilst this basin has not been explicitly assessed as part of this study, its geological conditions are expected to fall within the ranges of the other UK sedimentary basins.



	Setting	Location	Target	Depth (m)
1	Wessex Basin	Portsmouth	Great Oolites	1150 - 1300
			Sherwood Sandstone	1800 - 1920
2	Cheshire Basin	Manchester Airport	Collyhurst Sandstone Formation	1600 - 1900
			Early Carboniferous Limestone	3850 - 4350
3	Northumberland & Solway Basin	Newcastle, Science Central	Fell Sandstone	1420 - 1795
		Newcastle, Kingstone Park	Fell Sandstone	2000 - 2375
4	Glasgow & Clyde Basin	Western Edinburgh	Kinnesswood Fm.	1700 - 2000
			Know Pulpit Fm.	2000 - 2150
5	Northern Ireland Sedimentary Lough Neagh Basin)	Antrim	Sherwood Sandstone	2200 - 2650
			Lower Permian Sandstones	2900 - 3200
6	Cornwall Granites	Cornwall	4000m depth	Cornwall Granites
			5000m depth	
7	North Scotland Granites	West Aberdeen	4000m depth	North Scotland Granites
			5000m depth	

Figure 1: Geothermal Case Study Locations Summary (Adapted from the Deep Geothermal Energy White Paper [39])

A.1.2.2 Heat and power assessments

This work included an assessment of shallow and deep geothermal technologies. Many of these technologies are either location agnostic, where they broadly work in comparable ways irrespective of geological conditions (such as closed loop boreholes); or the assessment included generic assumptions based on literature, stakeholder engagement, and professional experience. Therefore, the UK geothermal assessment as outlined in this Appendix, pertains exclusively to the assessment of heat and power associated with deep geothermal technologies. Details of assessment of the other technologies is presented in Appendix B – LCOH Assessment.

A.1.3 Deep Geothermal Heat Assessment

This section provides a summary of some of the standard assumptions used for the deep geothermal assessment of the seven selected geothermal locations.

Outcomes from the Heat assessment are presented in Section A.1.5.

A.1.3.1 Temperature assumptions

Geothermal heat plant operational parameters will vary on a site-by-site basis; depending on thermal demands, operational constraints, seismic risk, and geothermal reservoir and brine conditions. One of the key components of geothermal capacity estimates is the change in temperature across the heat exchanger (often referred to as ΔT). The greater the ΔT, the greater the capacity (assuming all other variables remain constant). Generally, ΔT increases with production fluid temperature. Table 1 presents a summary of Arup's ΔT assumptions, relative to inferred bottom hole temperatures (and production fluid temperature). These assumptions have been benchmarked against global projects. The table presents the inferred bottom-hole temperature (i.e., the temperature of the fluid within the reservoir). This is abstracted to the surface where it is passed through a heat exchanger (ΔT is the amount of heat taken out of the fluid at this step). The fluid is then reinjection back into the target formation (the reinjection temperature is presented; this is bottom hole temperature, minus ΔT).

Table 1: Inferred temperature change across the heat exchanger (ΔT) at various bottom hole temperatures

Inferred bottom hole temperature (°C)	Temperature change across Heat Exchanger (ΔT)	Reinjection temperature (°C)
30	15	15
40	20	20
50	25	25
60	25	35
70	30	40
80	35	45
90	35	55
100	40	60
120	50	70
135	60	75
150	70	80
170	80	90

A.1.3.2 Benchmarking

As part of Arup's assessment, a benchmarking exercise was undertaken to check that the capacity estimates fall within a reasonable range.

The recent European Geothermal Energy Council (EGEC) 2023 market report [21] presents a summary of all European operational thermal and power plants. This dataset has been used to benchmark the Arup assessment of UK geothermal potential.

Figure 2 presents a summary of EGEC data on geothermal district heating systems. Figure 3 presents a plot of Arup assessment for UK sedimentary and granite bodies relative to the EGEC data. As can be seen there is large variability of geothermal plant capacity with ranges of flow rates and production fluid temperatures. Arup's assessment is comparable to European operational plants.

Thermal capacity is directly related to flow rate and ΔT, which broadly correlates with production fluid temperature; with greater fluid temperatures facilitating greater heat extraction. Thermal capacity of the system is a function of flow rate (l/s), specific heat capacity (J/kg°C) of the fluid, fluid density (kg/m^3), and the amount of heat extracted across the heat exchanger (ΔT, °C). Within a given reservoir, the fluid properties, specific heat capacity, and fluid density are constant; and therefore, thermal capacity of a system is largely determined by the flow rate and the ΔT. Greater the flow rate, or ΔT, greater the thermal capacity.

These variables are site specific and need to be monitored for sustainable use of the thermal reservoir over its operational life. Over pumping (flow rate), or over extraction (high ΔT), can thermally deplete the geothermal reservoir overtime reducing system performance. Figure 2 demonstrated this variability in flow rate between European systems.

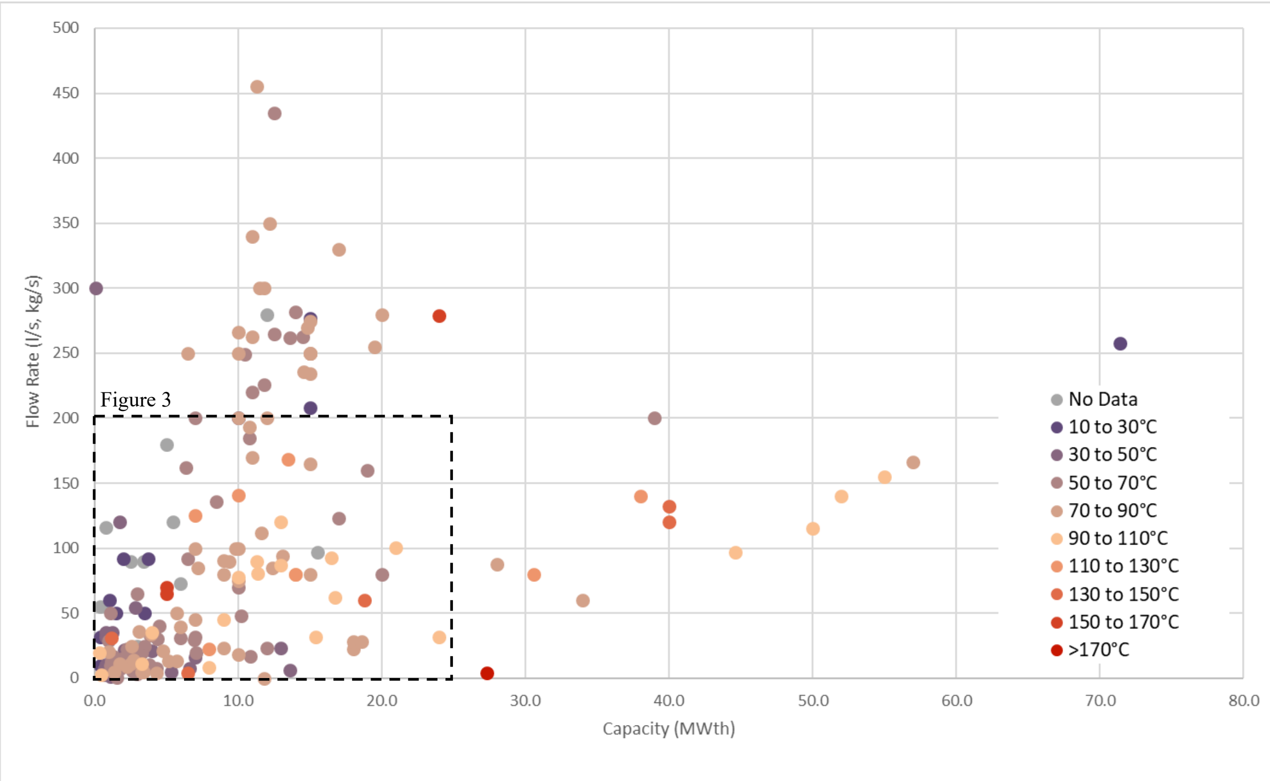


Figure 2: European geothermal heat plant capacities, flow rates, and production fluid temperature (after EGEC [21])

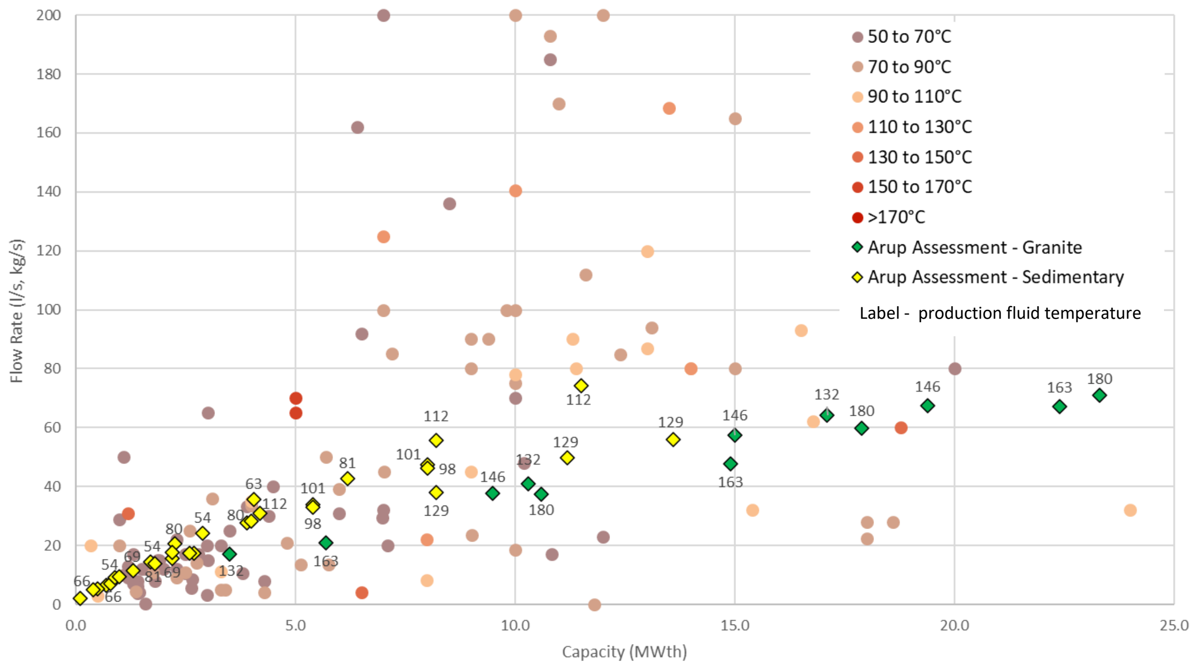


Figure 3: Plot of Arup assessment across UK Sedimentary aquifers and Granite bodies; relative to European data (EGEC [21]) (zoomed in section of Figure 2, and inclusion of Arup data)

A.1.3.3 Discussion

Permeability and effective aquifer thickness are the two most important geological parameters for sedimentary basins which impact upon modelled thermal output. Effective aquifer thickness is a combination of gross aquifer thickness and net-to-gross ratios of productive horizons. For example, an aquifer may be 300m thick, however if only 50% of the unit is sufficiently permeable to contribute flow, then it would be inappropriate to model the full 300m thickness. This has been captured within the DoubletCalc models; with net-to-gross set at 0.4, 0.5, and 0.8 for low, medium, and high, respectively. Based on our assessment of the data these numbers were considered appropriate to represent UK reservoirs.

The exit temperature at the heat exchanger, a function of ΔT, is the most important operational parameter for modelled thermal output; this was standardised in Table 1.

A.1.4 Power Assessment

For the hydrothermal targets, only reservoirs which were estimated with a bottom hole temperature (BHT) of greater than 100°C were considered. Table 2 presents a summary of the assessed geothermal reservoirs. Reservoirs suitable for power generation were inferred to be present at four of the seven selected sites. At the other three sites, the target reservoirs were either too shallow, or the geothermal gradient too low for fluid temperatures of more than 100°C to be present. Therefore, they were not suitable for power generation.

Table 2: Summary of UK geothermal targets used to inform the power assessment

Location	Target	Depth (m)	Inferred BHT (°C)
Cheshire	Early Carboniferous Limestone	3850 - 4350	109 – 149
Northern Ireland	Lower Permian Sandstone	2900 - 3200	106 – 119
Cornwall	Cornwall Granite	4000	142 – 173
Cornwall	Cornwall Granite	5000	175 – 185
North Scotland	North Scotland Granite	4000	122 – 138
North Scotland	North Scotland Granite	5000	150 – 170

A.1.4.1 Power modelling

An in-house Organic Rankine Cycle (ORC) binary plant modelling tool was utilised for the sedimentary basin assessment, while the publicly available GEOPHIRES tool [22] was employed for the granite assessment. Details of the low, medium, and high variables applied to each power assessment for the inhouse ORC modelling tool is provided in Table 3. Details of the GEOPHIRES modelling input are not provided. Default parameters were used in the modelling tool for GEOPHIRES, other than site specific details such as reservoir depth, geothermal gradient, etc., which are outlined in this Appendix.

ORC systems adopt thermodynamic cycle for power production which uses an organic fluid with a low vaporisation temperature. They are commonly used in geothermal power production as they have the ability to convert low temperature heat to electricity efficiently.

For each assessment, only the brine flow rate and plant efficiency were varied to represent low, medium, and high-power outputs. The other parameters remained constant for the assessed geothermal system. Parasitic power, which accounts for pumping power and plant load, was included in the power estimations. The Net power values were used for the LCOE assessment.

Table 3: Summary of input parameters used for each power assessment for a given location and depth

Variable	Unit	Low	Medium	High	Comment
Brine flow rate	l/s	Variable			DoubletCalc was used to estimate the flow rates for each of the geothermal targets (see Table 5 and Table 6).
No. Production wells	-	1			Assessment of single production well only. Within the LCOE assessment, the power output for this single system was scaled up. Further details in Appendix C
Abstraction depth	m	Constant			Constant and set to the locations geothermal target.
Geothermal gradient	°C/km	Constant			Constant and set to the locations inferred gradient.
Inlet temperature	°C	Constant			Constant and set to the BHT.

Variable	Unit	Low	Medium	High	Comment
Brine density	kg/m³	Constant			Constant and set relative to the BHT [23]
Temperature change across the heat exchanger (dT)	°C	Constant			Constant and set relative to the BHT (see Table 1)
Plant efficiency	%	8%	10%	13%	Plant efficiency inferred to range from 8% to 13% from experience and stakeholder feedback. Low and high value represents 25th to 75th percentile values.
Parasitic power (pumps)	kW	Variable			Pumping power set relative to the target depth. Deeper target requiring greater power load (see Table 4). The model was run with low, medium, and high inputs.
Parasitic power (plant)	%	17%	19%	21%	Plant parasitic loads a factor of the gross produced power. Estimates based on literature [24][25][26]. These values are direct from the three sources, Low, medium, and high are minimum, average, and maximum, respectively. given the limited data, these values were assumed to be consistent across all depths/ system thermal capacities assessed.

Table 4 presents a summary of the electrical submersible pump (ESP) assumptions applied to the power model. As part of the power models, ESP power is considered a parasitic load and detracted from the Gross power output. The values presented are based on experience and stakeholder information and are relatively high compared to the overall geothermal system outputs (c. 1 to 3MWe, see A.1.4.3). Estimating the pumping power requirements is difficult without detailed information on the target geological reservoir pressure, which is usually obtained only after the first geothermal well is installed and tested. Since this data is not available for this assessment, we have chosen to use conservatively high values. Given the typically high-power demands of ESPs, geothermal power plants usually supply this power directly during operation. Consequently, the ESP load is subtracted from the gross power outputs to determine the net power value.

Table 4: Summary of assumed electrical submersible pump power requirements

Depth (m)	Low (kW)	Medium (kW)	High (kW)
2000	300	350	400
2500	325	375	425
3000	350	400	450
3500	375	425	475
4000	400	450	500
4500	425	475	525
5000	450	500	550

A.1.4.2 Benchmarking

The Arup in-house geothermal binary plant power modelling tool has been used on various feasibility projects, and validated against several constructed systems, across the globe, and as a result, the outcomes are considered to be reasonable estimates. However, no two geothermal systems are identical, and due to various geothermal conditions and plant configurations, plant outputs will vary.

As part of this task, Arup compared the result against European Organic Rankine Cycle (ORC) plants [27][40]. The model was run for 10 German plants, the French Soultz-sous plant and Belgium Mol plant, which ranged in electrical capacity from 0.5 to 5.5 MWe, production flow rates of 60 to 168.6 l/s, and maximum temperatures of 120 to 165°C. These conditions are comparable to those anticipated in the UK.

The European plant input parameters (flow rate, max temperature) were input into the Arup model, and general assumptions were made for the remaining parameters. For example, ΔT across the heat exchanger (Table 1).

Figure 4 presents a comparison between Arup net model power values and actual values. The Arup model appears to be reasonable, with the majority of data points falling within 30% of actual values. Generally, the Arup model overestimates capacities for <2MWe plants and underestimates for >3MWe plants (shown by the liner trend lines). This is a basic model, and improvements could be made. This may include an adjustment factor to fit the model closer to the trend line seen in actual plants; however, for the purpose of this assessment and in the context of the UK it is considered appropriate.

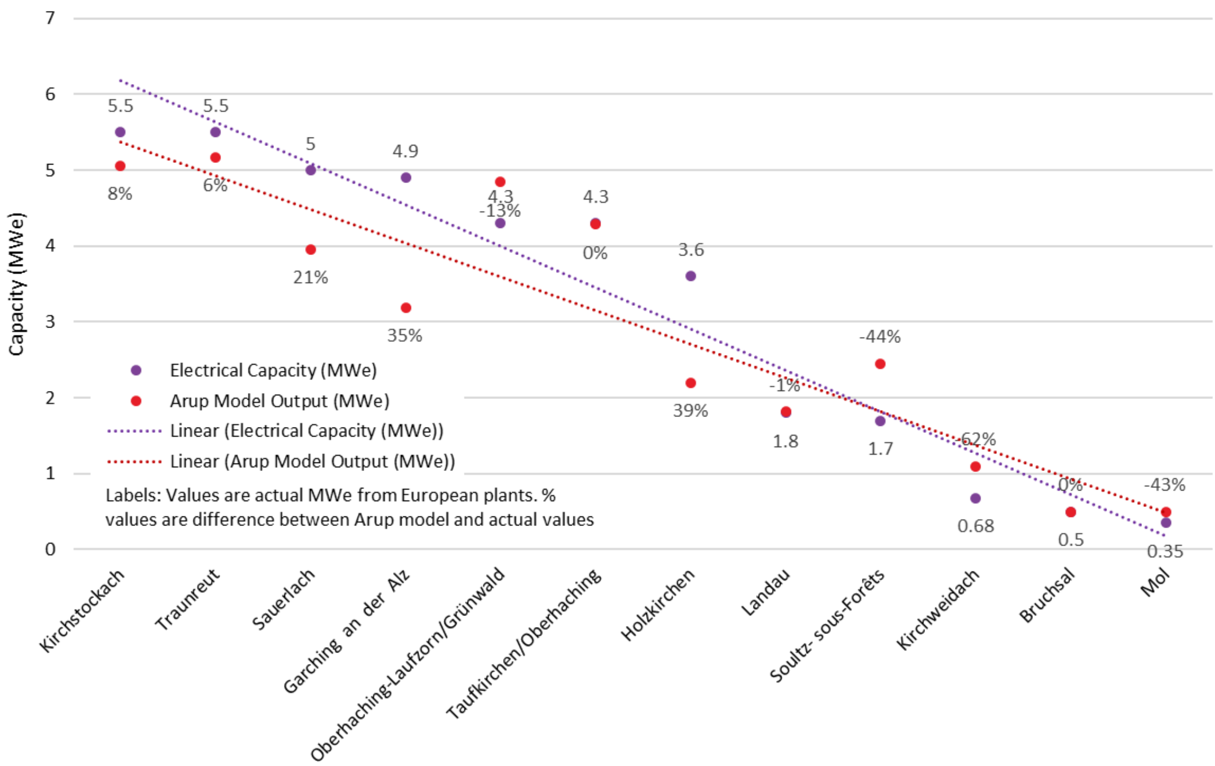


Figure 4: Plot of electrical outputs against Arup modelled outputs for the same system

Figure 4 reveals that while the Arup model aligns well with many cases, there are some differences for example, the Kirchweidach plant, Soultz-sous and Mol plants. This may be a result of different ΔT's used or other operational plant parameters. This underscores the difficulty in generalising plant outputs and the uniqueness of each plant.

A.1.4.3 Outcomes

A summary of the power assessment is presented in Section A.1.5. The UK sedimentary basins targets are shallower and generally have lower geothermal gradients, and as a result exhibit lower power capacities compared to the granites.

These estimates underscore the significant variations in power potential based on different geothermal targets and depths. Notably, the granites, with their greater depths and elevated geothermal gradients, generally offer higher power potential.

A.1.4.4 Benchmarking

The recent European Geothermal Energy Council (EGEC) 2023 market report [21] presents a summary of all European operational Geothermal power plants. This dataset has been used to benchmark the Arup assessment of UK geothermal power potential.

Figure 5 presents a summary of EGEC data on geothermal power plants compared to Arup's assessment. While Arup's assessment aligns with European operational plants, it shows relatively low-capacity estimates.

This lower capacity is mainly due to the relatively low geothermal gradients and permeabilities, which result in lower flow rates.

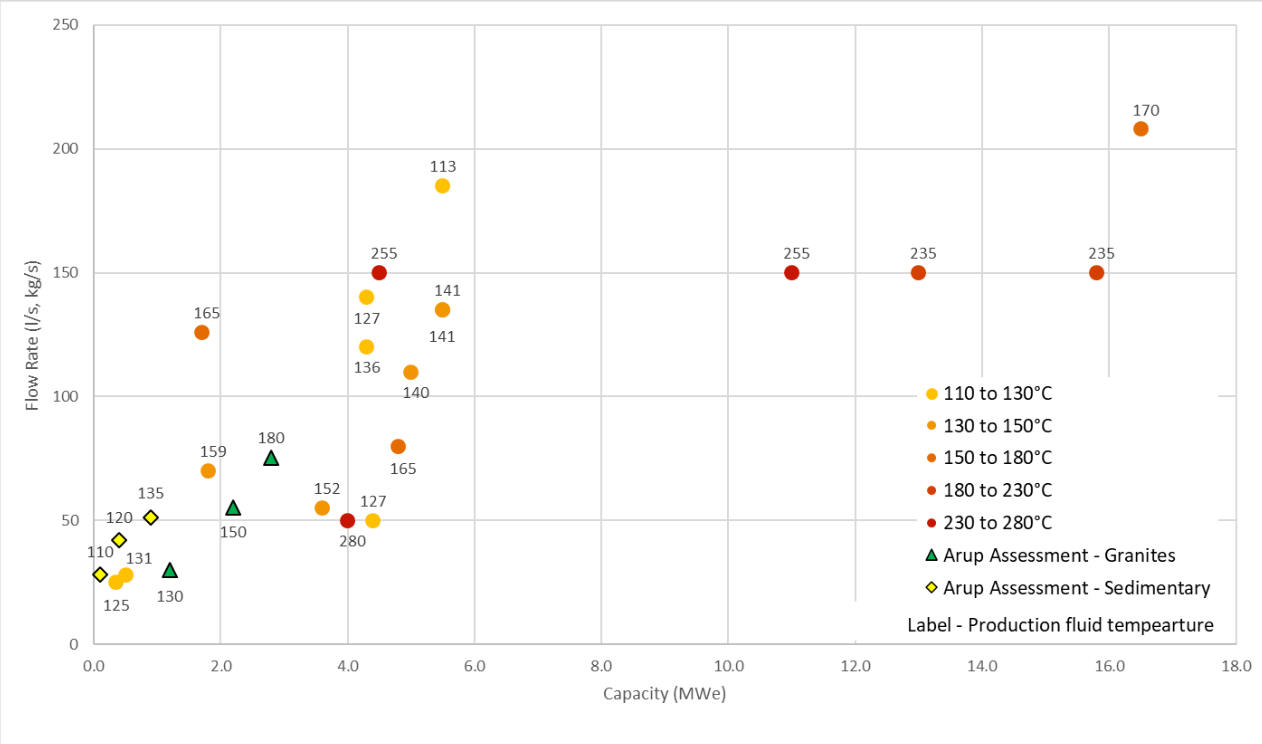


Figure 5: European geothermal power plant capacities, flow rates, and production fluid temperature (after EGEC [21]). Arup net power values presented.

A.1.4.5 Discussion

The power data presented has been used to inform the low, medium, and high-capacity estimates within the LCOE model. The model comprises a sedimentary, granite, and 'general' deep geothermal power plant.

A.1.5 Model findings

Table 5 and Table 6 present a summary of the geothermal heat assessments. Table 7 presents a summary of the geothermal power assessment. The heat and power capacities presented were used to inform the levelised cost models.

Table 5: Summary of Sedimentary aquifer geological parameters and thermal capacity estimates

Setting	Location	Aquifer / granite	Depth (m)	Thickness (m)	Gradient (°C/km)	Permeability (mD)[1] [most likely]	Flow (l/s)			Thermal Capacity (MWth)[2]			Confidence[3]
							P90	P50	P10	P90	P50	P10	
Wessex Basin	Portsmouth	Great Oolites	1150 - 1300	150	35 – 40	1 – 400 [150]	6.4	14.4	24.3	0.7	1.7	2.9	Low-medium
		Sherwood Sandstone	1800 - 1920	120	35 – 40	1 – 400 [150]	7	15.7	27.6	0.8	2.2	3.9	Medium-high
Cheshire Basin	Manchester Airport	Collyhurst Sandstone Formation	1600 - 1900	300	25 – 35	1 – 300 [100]	9.2	20.5	35.6	0.9	2.25	4.05	Medium
		Early Carboniferous Limestone	3850 - 4350	500	25 – 35	1 – 400 [150]	38.1	49.9	56.1	8.2	11.2	13.6	Low-medium
Northumberland & Solway Basin	Newcastle, Science Central	Fell Sandstone	1420 - 1795	375	35 – 40	1 – 250 [100]	13.9	28.4	42.8	1.8	4.0	6.2	Medium-high
	Newcastle, Kingstone Park	Fell Sandstone	2000 - 2375	375	35 – 40	1 – 250 [100]	17.5	33.8	47.5	2.7	5.4	8.0	Medium
Glasgow & Clyde Basin	Western Edinburgh	Kinnesswood Fm.	1700 - 2000	300	28 – 32	1 – 100 [50]	5.3	11.5	17.6	0.5	1.3	2.2	Low
		Know Pulpit Fm.	2000 - 2150	150	28 – 32	1 – 100 [40]	2.2	5.1	9.3	0.1	0.4	1.0	Low
Northern Ireland Sedimentary Basin (Lough Neagh Basin)	Antrim	Sherwood Sandstone	2200 - 2650	450	30 – 34	1 – 400 [150]	30.9	55.6	74.3	4.2	8.2	11.5	Low
		Lower Permian Sandstones	2900 - 3200	300	30 – 34	1 – 300 [100]	17.4	32.9	46.3	2.6	5.4	8.0	Low

[1] Permeability is a very challenging parameter to assess. Core measurements can be used where available; however, these only reflect primary permeability, ignoring fracture influence. Owing to their depth, deep geothermal reservoir permeability is often dominated by secondary (fracture) permeability. Therefore, the permeability estimates presented are often an order of magnitude greater than core measurements recorded in literature. Permeability is reported in mD (Millidarcy).

[2] The calculated thermal capacity estimates are high level used to inform the levelised cost models only. The values are not to be relied upon for more detailed site assessments. Sedimentary basins target depths ranged from 1,150 to 4,350 metres; P50 thermal capacities ranged from 0.4 to 11.2 MWth.

[3] Relative confidence based on geological data availability. Many locations have ‘low’ confidence, which reflects the lack of literature, deep well data, or seismic data available in the area.

Table 6: Summary of granite body geological parameters and thermal capacity estimates

Setting	Location	Depth (m)	Gradient (°C/km)	Permeability (mD) [most likely]	Flow (l/s)			Thermal Capacity (MWth)[1]			Confidence[2]
					P90	P50	P10	P90	P50	P10	
Cornwall Granites	Cornwall	4000	33 – 35	1 – 5000 [200]	37.6	57.3	67.6	9.5	15.0	19.4	Low
		5000	33 – 35	1 – 5000 [150]	37.5	59.9	70.9	10.6	17.9	23.3	Low
North Scotland Granites	West Aberdeen	4000	28 – 32	1 – 5000 [100]	17	40.9	64.3	3.5	10.3	17.1	Low
		5000	28 – 32	1 – 5000 [100]	20.9	47.7	67.3	5.7	14.9	22.4	Low

[1] The calculated thermal capacity estimates are high level used to inform the levelised cost models only. The values are not to be relied upon for more detailed site assessments. Granites target depths assessed at 4,000 and 5,000 metres; P50 thermal capacities ranged from 10.3 to 17.9 MWth.

[2] Relative confidence based on geological data availability. ‘low’ confidence locations, reflect the lack of literature, deep well data, or seismic data available in the area.

Table 7: Power assessment summary

Setting	Location	Aquifer / granite	Depth (m)	Gradient (°C/km)	Bottom-hole Temperature estimate (°C)	Flow (l/s)			Power Capacity (MWe)[1]			Confidence[2]
						P90	P50	P10	P90	P50	P10	
Cheshire Basin	Manchester Airport	Early Carboniferous Limestone[1]	3850 - 4350	25 – 35	109 – 149	38.1	49.9	56.1	<0.1	0.4	1	Low
Northern Ireland	Antrim	Lower Permian Sandstones[1]	2900 - 3200	30 – 34	106 – 119	17.4	32.9	46.3	<0.1	0.3	0.8	Low
Cornwall	Cornwall	Granite[2]	4000	33 – 35	142 – 173	40	60	80	1.3	1.9	2.5	Low
		Granite[2]	5000	33 – 35	175 – 185	40	60	80	2.2	3.3	4.2	Low
North Scotland Granites	West Aberdeen	Granite[2]	4000	28 – 32	122 – 138	20	50	70	0.5	1.3	1.4	Low
		Granite[2]	5000	28 – 32	150 – 170	20	50	70	0.9	2.1	2.9	Low

[1] The calculated thermal capacity estimates are high level used to inform the levelised cost models only. The values are not to be relied upon for more detailed site assessments. Sedimentary basin power targets ranged from c. 3km to 4km; P50 power capacity estimates ranged from 0.3 to 0.4 MWe. Granites target depths assessed at 4,000 and 5,000 metres; P50 power capacities ranged from 1.3 to 3.3 MWe. [2] Relative confidence based on geological data availability. ‘low’ confidence locations, reflect the lack of literature, deep well data, or seismic data available in the area.

A.2 Modelling summaries

A.2.1 Overview

The following appendix sections pertain to the deep geothermal modelling work for each UK location. At each location available data was assessed, this is evidenced by a map figure. Subsequently, a ground model was inferred. The level of confidence of each ground model varies; as the availability and quality of data within each region varies. For example, the Wessex Basin has existing oil and gas wells and a UK seismic section which can help to refine geological models, whereas Newcastle has far less data available.

A summary of the selected geothermal reservoir is provided in a table. Selection of the geothermal reservoir was based on depth, and inferred productivity. The productivity of a reservoir is a result of porosity, permeability, thickness, net-to-gross ratios (i.e., what portion of the unit thickness will contribute flow, i.e., mudstone units are low permeability relative to sandstone units), and hydraulic conductivity values. Assessment of permeability is very challenging and remains uncertain until a well is drilled. Publications, BGS aquifer designation, professional judgement, and peer review was all considered in selecting the target reservoir.

BGS aquifer designations include:

- Principal aquifer: strategically important rock units that have high permeability and water storage capacity;
- Secondary A aquifer: a permeable layer of rock that can support local water supplies and may be an important source of base flow to rivers;
- Secondary B aquifer: mainly lower permeability layers that may store and yield limited amounts of groundwater through characteristics like thin cracks (called fissures); and,
- Unproductive aquifer: rocks which have negligible significance for water supply.

Generally, principal aquifers are targeted. Secondary A aquifers were targeted where principal aquifers are absent.

References to the source of information used to inform the DoubletCalc models are presented within the Calculation Input tables.

Well system design, casing diameters, distance between wells, etc are standard across all models. Temperature difference across the heat exchanger is based on Table 1. Reservoir pressures are unknown and therefore left as default.

The model tables contain summaries of the direct inputs used for the DoubletCalc; which outputs probabilistic estimations of geothermal thermal capacities (MWth). At the end of each section, these model inputs and associated model outputs and graphs are presented. Modelled pumping power is one model outputs. However, given the uncertainty of the reservoir pressure, and use of generic default values; Arup decided to use more conservative values for the pumping power (see Table 4).

DoubletCalc is not suited to modelling granites, as DoubletCalc is for use for hydrothermal systems in sedimentary aquifers. As a result, key and highly inferred assumptions were made. These include permeability and porosity. These are based on geological professional judgement; however, in reality the system is highly permeable if a fracture network is encountered, and highly impermeable if no fractures exist. The thickness of the unit and net-to-gross ratios again are not really suitable for granites. In a granite setting these could be the thickness of the contributing vertical extent of the fracture network, and net-to-gross the proportion of productive fractures and no-productive native rock. The granite DoubletCalc assessment remains highly uncertain, and professional judgement of inferred flow rates, benchmarked against active projects (like United Downs) was undertaken.

A.3 Wessex Basin (Portsmouth)

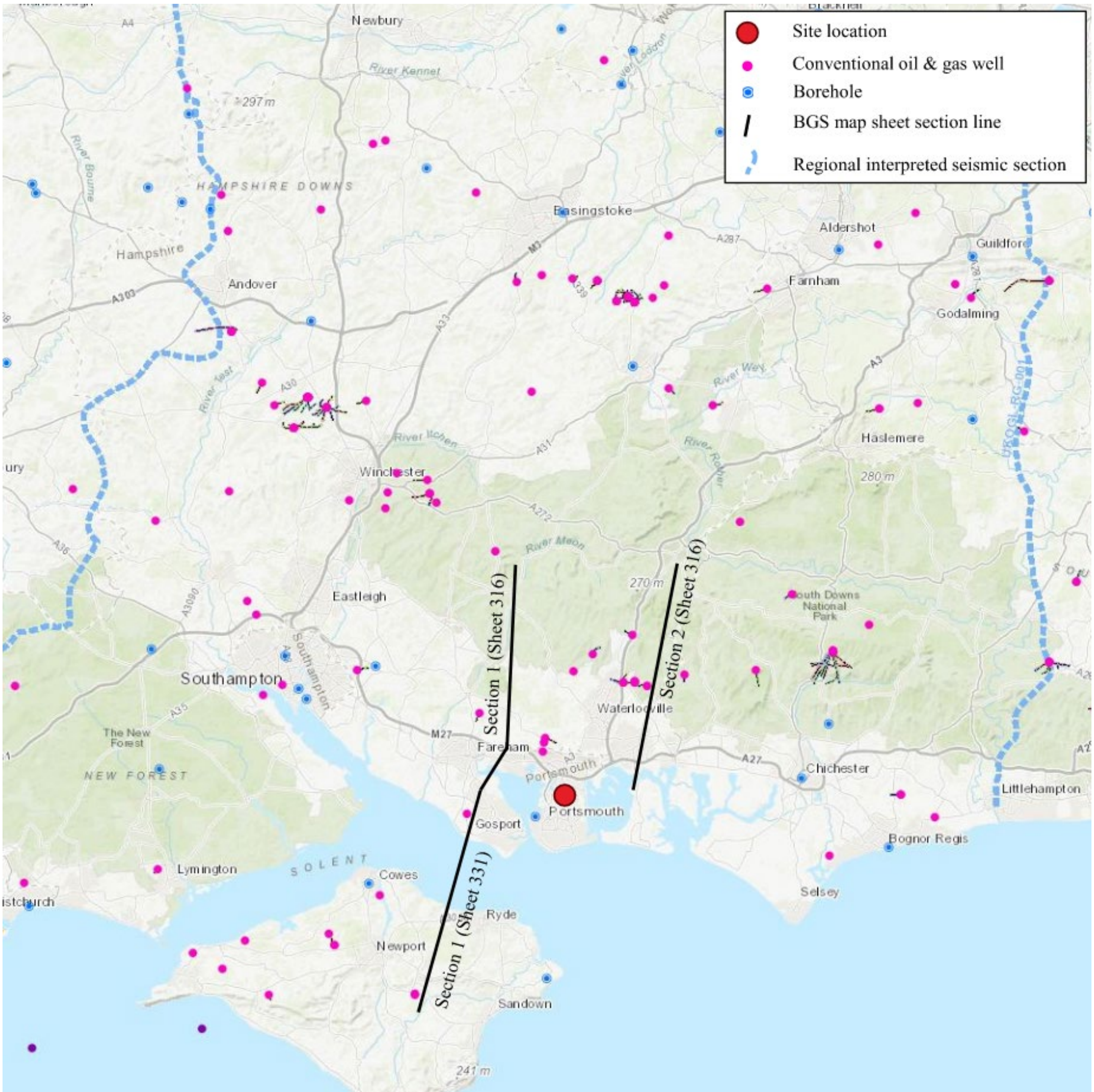


Figure 6: Site Location and local data

Table 8: Geological summary

Parameter	Value
Geothermal gradient	Between 35 to 40°C/km
Potential deep geothermal reservoirs	Great Oolite Group – Principal aquifer – 1150 to 1300m depth
	Inferior Oolite Group – Principal aquifer – 1300 – 1440m depth
	Sherwood Sandstone Group – Principal aquifer – 1800 to 1920m depth

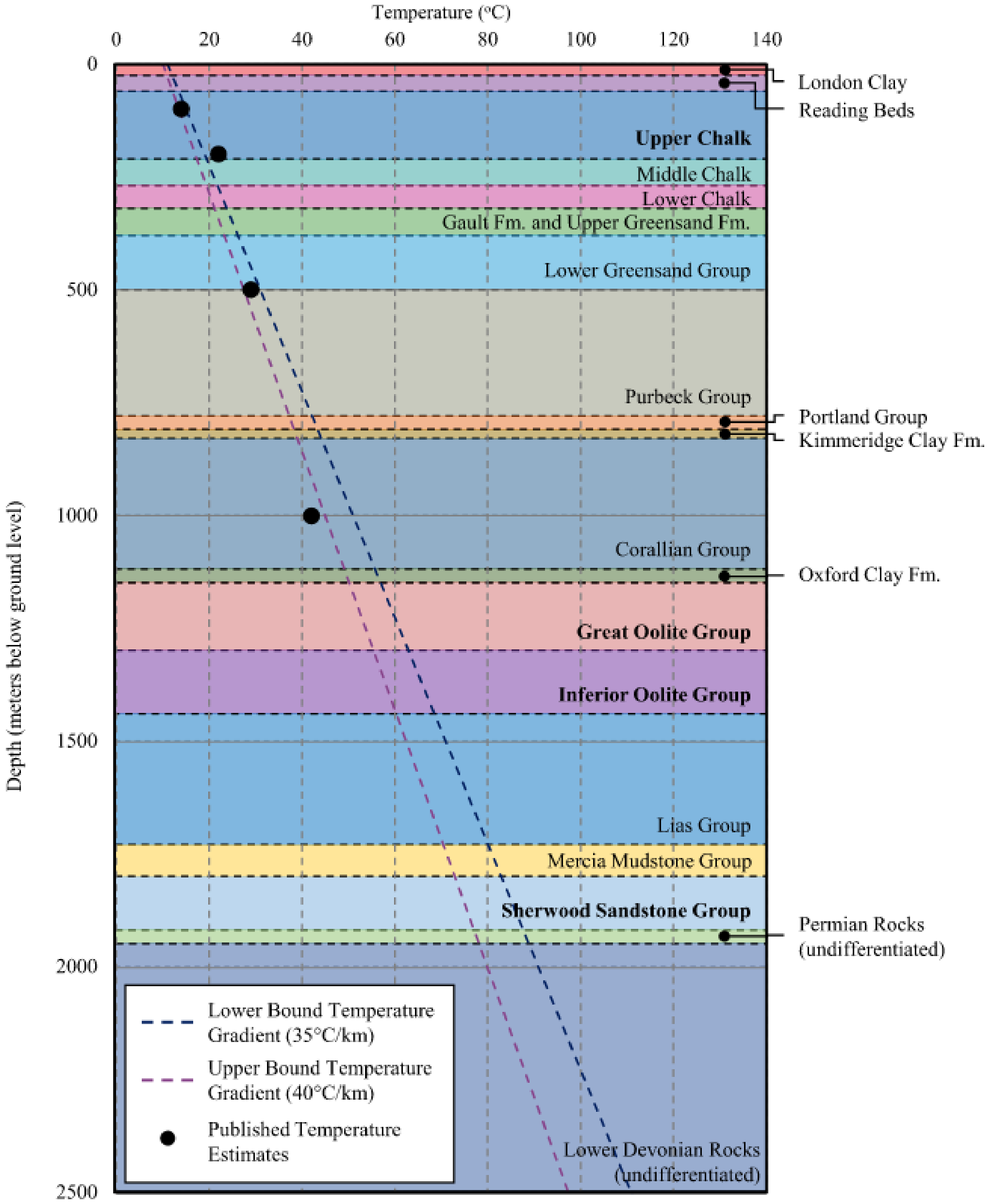


Figure 7: Inferred Ground model and geothermal gradient for Wessex Basin (Portsmouth)

Table 9: Inferred Ground Model

Aquifer	Formation	Period	Lithology	Depth to top (mbgl)	Depth to base (mbgl)	Thickness (m)	Temperature Range (base) (°C)	Aquifer condition	Estimated hydraulic conductivity*	
									m/s	mD
Unproductive	London Clay	Eocene	Clay	0	25	25	10.9 to 11	Unproductive		
Secondary U	Reading Beds	Palaeocene	Sandstone And Mudstone	25	60	35	12.1 to 12.4	Moderately Productive		
Principal	Upper Chalk	Cretaceous	Chalk	60	210	150	17.4 to 18.4	Highly Productive		
Principal	Middle Chalk	Cretaceous	Chalk	210	270	60	19.5 to 20.8	Highly Productive		
Principal	Lower Chalk	Cretaceous	Chalk	270	320	50	21.2 to 22.8	Moderate to High Productive		
Unproductive	Gault Formation and Upper Greensand Formation	Cretaceous	Mudstone, Sandstone and Limestone	320	380	60	23.3 to 25.2	Unproductive		
Principal	Lower Greensand Group	Cretaceous	Sandstone And Mudstone	380	500	120	27.5 to 30	Significant intergranular-highly productive		
Secondary U	Purbeck Group	Jurassic T	Interbedded Limestone and Mudstone	500	780	280	37.3 to 41.2	Moderately Productive		
Secondary A	Portland Group	Jurassic	Limestone And Calcareous Sandstone	780	810	30	38.4 to 42.4	Moderately Productive		
Unproductive	Kimmeridge Clay Formation	Jurassic	Mudstone	810	830	20	39.1 to 43.2	Essentially No Groundwater		
Secondary A	Corallian Group	Jurassic	Limestone, Sandstone, Siltstone and Mudstone	830	1120	290	49.2 to 54.8	Moderately Productive		
Secondary B	Oxford Clay Formation	Jurassic	Mudstone, Siltstone and Sandstone	1120	1150	30	50.3 to 56	Essentially No Groundwater		
Principal	Great Oolite Group	Jurassic	Sandstone, Limestone and Argillaceous Rocks	1150	1300	150	55.5 to 62	Highly Productive (Predominantly secondary, fracture, permeability)		
Principal	Inferior Oolite Group	Jurassic	Limestone, Sandstone, Siltstone and Mudstone	1300	1440	140	60.4 to 67.6	Highly Productive (Predominantly secondary, fracture, permeability)	3x10-11 to 5.8x10-6	0.1 to 500

Aquifer	Formation	Period	Lithology	Depth to top (mbgl)	Depth to base (mbgl)	Thickness (m)	Temperature Range (base) (°C)	Aquifer condition	Estimated hydraulic conductivity*	
									m/s	mD
Secondary U	Lias Group	Jurassic	Mudstone, Siltstone, Limestone and Sandstone	1440	1730	290	70.6 to 79.2	Highly Productive (Predominantly secondary, fracture, permeability)		
Secondary B	Mercia Mudstone Group	Triassic	Mudstone, Siltstone and Sandstone	1730	1800	70	73 to 82	Essentially No Groundwater		
Principal	Sherwood Sandstone Group	Triassic	Sandstone, Siltstone and Mudstone	1800	1920	120	77.2 to 86.8	Highly Productive	6.9 x 10-9 to 5.1x10-6	0.1 to 300
Secondary B	Permian Rocks (Undifferentiated)	Permian	Mudstone, Siltstone and Sandstone	1920	1950	30	78.3 to 88	Low productivity		
Secondary A	Lower Devonian Rocks (Undifferentiated)	Devonian	Mudstone, Siltstone and Sandstone	1950	2600	650	101 to 114	Essentially no groundwater		
* Estimated permeabilities based on published data sources [1][2][3]										
Highlighted	Key aquifers beneath the Site which have potential for deep geothermal									

A.3.1 DoubletCalc Inputs

Table 10: Inputs for Greater Oolite Group

Parameter	Value			Units	Comment
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	1	150	400	mDarcey	Permeability data has been inferred from and published literature [1][2][3]
Aquifer porosity	0.05	0.15	0.25	-	Porosity inferred from published literature [1][2]
Aquifer net to gross	0.5	0.6	0.8	-	Aquifer assumed to be heterogeneous. General net-to-gross of 50% to 80% assumed. Insufficient data to suggest otherwise.
Aquifer gross thickness	120	150	180	m	Inferred from local O&G well data [4] and BGS datasets [5][6], and publications [7]. Applied +/- 20% error margin for min/max
Aquifer top at producer	1161	1290	1419	m TVD	Inferred from local O&G well data [4] and BGS datasets [5][6], and publications [7]. Located at 10m from base of aquifer. Applied +/- 10% error margin for min/max
Aquifer top at injector	1044	1160	1276	m TVD	Inferred from local O&G well data [4] and BGS datasets [5][6], and publications [7]. Located at 10m from top of aquifer. Applied +/- 10% error margin for min/max
Aquifer water salinity	50k	80k	150k	ppm	General assumption
Aquifer net transmissivity	-			Dm	
Aquifer kh/kv ratio	0.5			-	Inferred to be 50% anisotropic.
Surface temperature	11			°C	Based on published data for the UK [8]
Geothermal gradient	0.037			°C/m	Inferred from publications [9]
Mid Aquifer temperature producer	-			°C	
Initial aquifer pressure at producer	-			Bar	
Initial aquifer pressure at injector	-			Bar	
Heat capacity rock matrix at 20°C	855			$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix	2710			kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix	2.5			$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix	0.0000011			m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation	-			-	
Doublet and pump properties					
Exit temperature heat exchanger	35.0			°C	

Parameter	Value			Units	Comment
	Min	Ave	Max		
Output temperature from wells	61.1			°C	
Delta T across doublet	26.1			°C	
Distance wells at aquifer level	2000			m	
Pump system efficiency	0.6			-	
Production pump depth	300			m	
Pump pressure difference	30			bar	
Cooling as fraction of initial	0.1			ΔT	
Yearly full operational hours	6000			Hours	
Well properties					
Calculation length subdivision	50			m	
Producer					
Outer diameter producer	7			Inch	
Skin producer	2			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
Injector					
Outer diameter producer	7			Inch	
Skin producer	0.5			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
General					
Segment	1			-	
Pipe segment sections	1290 (Prod), 1160 (Reinj)			mAH	
Pipe segment depth	1290 (Prod), 1160 (Reinj)			m TVD	
Pipe inner diameter	6			Inch	
Pipe roughness	1.38			milli-inch	

 Page 19

Table 11: Inputs for Sherwood Sandstone

Parameter	Value			Units	Comment
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	1	150	400	mDarcey	Permeability data has been inferred from published literature [2][3]
Aquifer porosity	0.05	0.15	0.25	-	Porosity inferred from published literature [1][2]
Aquifer net to gross	0.5	0.6	0.8	-	Aquifer assumed to be heterogeneous. General net-to-gross of 50% to 80% assumed. Insufficient data to suggest otherwise.
Aquifer gross thickness	96	120	144	m	Inferred from local O&G well data [4] and BGS datasets [5][6], and publications [7]. Applied +/- 20% error margin for min/max
Aquifer top at producer	1719	1910	2101	m TVD	Inferred from local O&G well data [4] and BGS datasets [5][6], and publications [7]. Located at 10m from base of aquifer. Applied +/- 10% error margin for min/max
Aquifer top at injector	1629	1810	1991	m TVD	Inferred from local O&G well data [4] and BGS datasets [5][6], and publications [7]. Located at 10m from top of aquifer. Applied +/- 10% error margin for min/max
Aquifer water salinity	50k	80k	150k	ppm	General assumption
Aquifer net transmissivity		-		Dm	
Aquifer kh/kv ratio		0.5		-	Inferred to be 50% anisotropic.
Surface temperature		11		°C	Based on published data for the UK [8]
Geothermal gradient		0.037		°C/m	Inferred from publications [9]
Mid Aquifer temperature producer		-		°C	
Initial aquifer pressure at producer		-		Bar	
Initial aquifer pressure at injector		-		Bar	
Heat capacity rock matrix at 20°C		855		$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix		2710		kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix		2.5		$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix		0.0000011		m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation		-		-	
Doublet and pump properties					
Exit temperature heat exchanger		45.0		°C	
Output temperature from wells		83.5		°C	
Delta T across doublet		38.5		°C	
Distance wells at aquifer level		2000		m	
Pump system efficiency		0.6		-	
Production pump depth		300		m	
Pump pressure difference		30		bar	
Cooling as fraction of initial		0.1		ΔT	
Yearly full operational hours		6000		Hours	
Well properties					

 Page 20

Parameter	Value			Units	Comment
	Min	Ave	Max		
Calculation length subdivision		50		m	
Producer					
Outer diameter producer		7		Inch	
Skin producer		2		-	
Penetration angle producer		-		° Degrees	
Skin due to penetration angle		0		-	
Total skin producer		0		-	
Injector					
Outer diameter producer		7		Inch	
Skin producer		0.5		-	
Penetration angle producer		-		° Degrees	
Skin due to penetration angle		0		-	
Total skin producer		0		-	
General					
Segment		1		-	
Pipe segment sections		1910 (Prod), 1810 (Reinj)		mAH	
Pipe segment depth		1910 (Prod), 1810 (Reinj)		m TVD	
Pipe inner diameter		6		Inch	
Pipe roughness		1.38		milli-inch	

 Page 21

A.3.2 Doublet Calc Outputs

Oolites

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	1	150	350
aquifer porosity (-)	0.05	0.15	0.25
aquifer net to gross (-)	0.5	0.6	0.8
aquifer gross thickness (m)	120	150	180
aquifer top at producer (m TVD)	1035	1150	1265
aquifer top at injector (m TVD)	1170	1300	1430
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

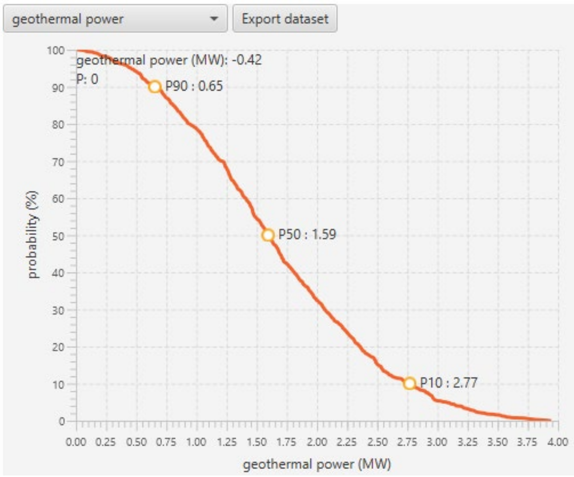
Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	11
geothermal gradient (°C/m)	0.037
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	1000
density rock matrix (kg/m^3)	2500
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	25
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	1290
pipe segment depth (m TVD)	1290
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	1160
pipe segment depth (m TVD)	1160
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	6.02	14.03	24.23
mass flow (kg/s)	6.28	14.26	23.72
pump volume flow (m^3/h)	21.7	49.2	81.1
required pump power (kW)	30.2	68.3	112.7
geothermal power (MW)	0.65	1.59	2.77
COP (kW/kW)	20.9	23.3	25.3
doublet life time (years)	985.9	1632.5	3628.1
doublet power over life time (PJ)	66.99	80.65	94.27
heat capacity rock matrix (J/Kg/K)	1063.4	1069.3	1074.4
aquifer pressure at producer (bar)	124.45	131.11	138.23
aquifer pressure at injector (bar)	110.41	117.75	125.27
pressure difference at producer (bar)	12.53	13.15	13.61
pressure difference at injector (bar)	16.6	17.29	17.69
aquifer temperature at producer * (°C)	53.95	56.33	58.72
temperature at heat exchanger (°C)	51.41	54.37	56.91
pressure at heat exchanger (bar)	13.48	15.13	15.94

base case (median value input)	value
aquifer kH net (Dm)	13.5
mass flow (kg/s)	13.92
pump volume flow (m^3/h)	48
required pump power (kW)	66.7
geothermal power (MW)	1.57
COP (kW/kW)	23.5
doublet life time (years)	1651.1
doublet power over life time (PJ)	81.83
heat capacity rock matrix (J/Kg/K)	1069.8
aquifer pressure at producer (bar)	130.86
aquifer pressure at injector (bar)	117.47
pressure difference at producer (bar)	13.18
pressure difference at injector (bar)	17.36
aquifer temperature at producer * (°C)	56.33
temperature at heat exchanger (°C)	54.6
pressure at heat exchanger (bar)	15.19

* @ mid aquifer depth



Sherwood Sandstone

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	1	150	400
aquifer porosity (-)	0.05	0.1	0.2
aquifer net to gross (-)	0.5	0.6	0.8
aquifer gross thickness (m)	96	120	144
aquifer top at producer (m TVD)	1719	1910	2101
aquifer top at injector (m TVD)	1629	1810	1991
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

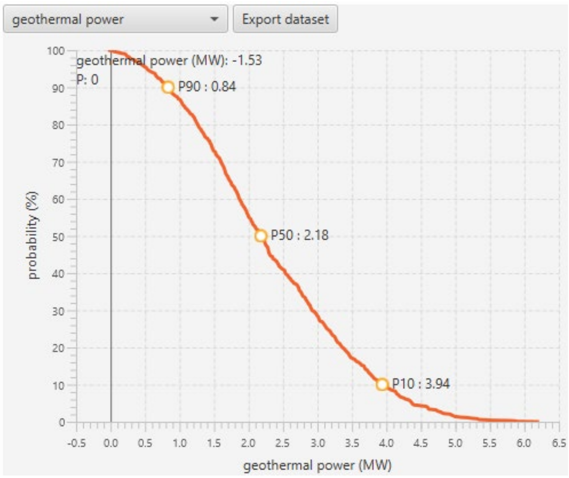
Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	11
geothermal gradient (°C/m)	0.037
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	930
density rock matrix (kg/m^3)	2500
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	45
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	1910
pipe segment depth (m TVD)	1910
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	1810
pipe segment depth (m TVD)	1810
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	4.82	11.09	21.73
mass flow (kg/s)	7.37	16.21	28.69
pump volume flow (m^3/h)	25.3	56.4	99.2
required pump power (kW)	35.1	78.3	137.8
geothermal power (MW)	0.84	2.18	3.94
COP (kW/kW)	23.1	27.2	30.6
doublet life time (years)	621.3	1098.2	2441.6
doublet power over life time (PJ)	57.63	73.12	87.88
heat capacity rock matrix (J/Kg/K)	1030.2	1039.7	1047.3
aquifer pressure at producer (bar)	181.24	192.17	203.65
aquifer pressure at injector (bar)	171.73	182.28	192.49
pressure difference at producer (bar)	12.18	13.38	13.97
pressure difference at injector (bar)	16.58	18.33	19.13
aquifer temperature at producer * (°C)	79.94	83.89	87.77
temperature at heat exchanger (°C)	74.19	79.59	84.02
pressure at heat exchanger (bar)	11.8	14.35	15.7

base case (median value input)	value
aquifer kH net (Dm)	10.8
mass flow (kg/s)	15.87
pump volume flow (m^3/h)	55.4
required pump power (kW)	77
geothermal power (MW)	2.12
COP (kW/kW)	27.6
doublet life time (years)	1107.3
doublet power over life time (PJ)	74.15
heat capacity rock matrix (J/Kg/K)	1040.3
aquifer pressure at producer (bar)	192.01
aquifer pressure at injector (bar)	181.85
pressure difference at producer (bar)	13.45
pressure difference at injector (bar)	18.39
aquifer temperature at producer * (°C)	83.89
temperature at heat exchanger (°C)	79.97
pressure at heat exchanger (bar)	14.54

* @ mid aquifer depth



 Page 22

A.4 Cheshire Basin (Manchester Airport)

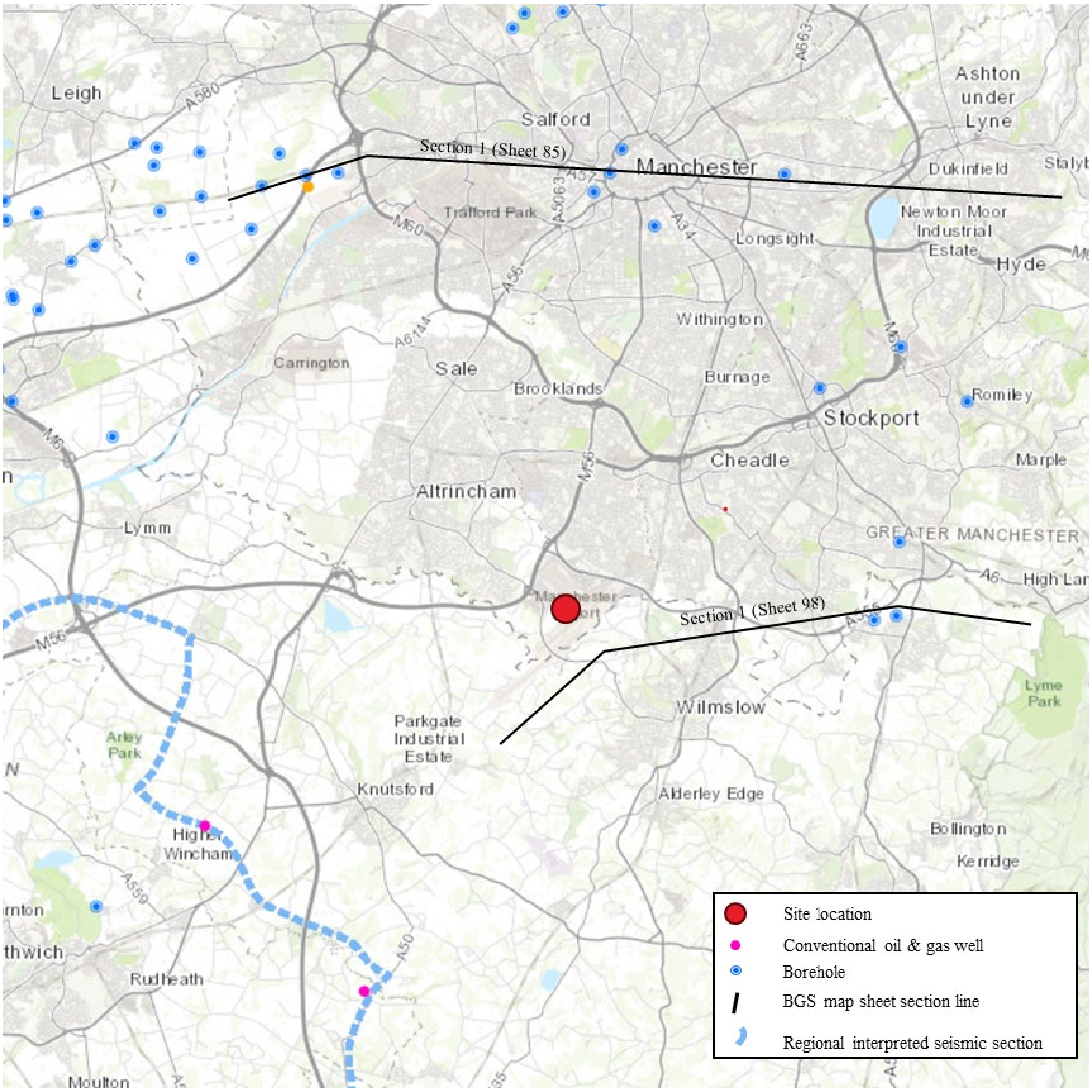


Figure 8: Site location and local data

Table 12: Geological summary

Parameter	Value
Geothermal gradient	Between 25 to 35 °C/km
Potential deep geothermal reservoirs	Appelby Group (Collyhurst Sandstone Fm.) – 1500 to 2000m depth
	Craven Group – 3100 to 4850m depth

 Page 23

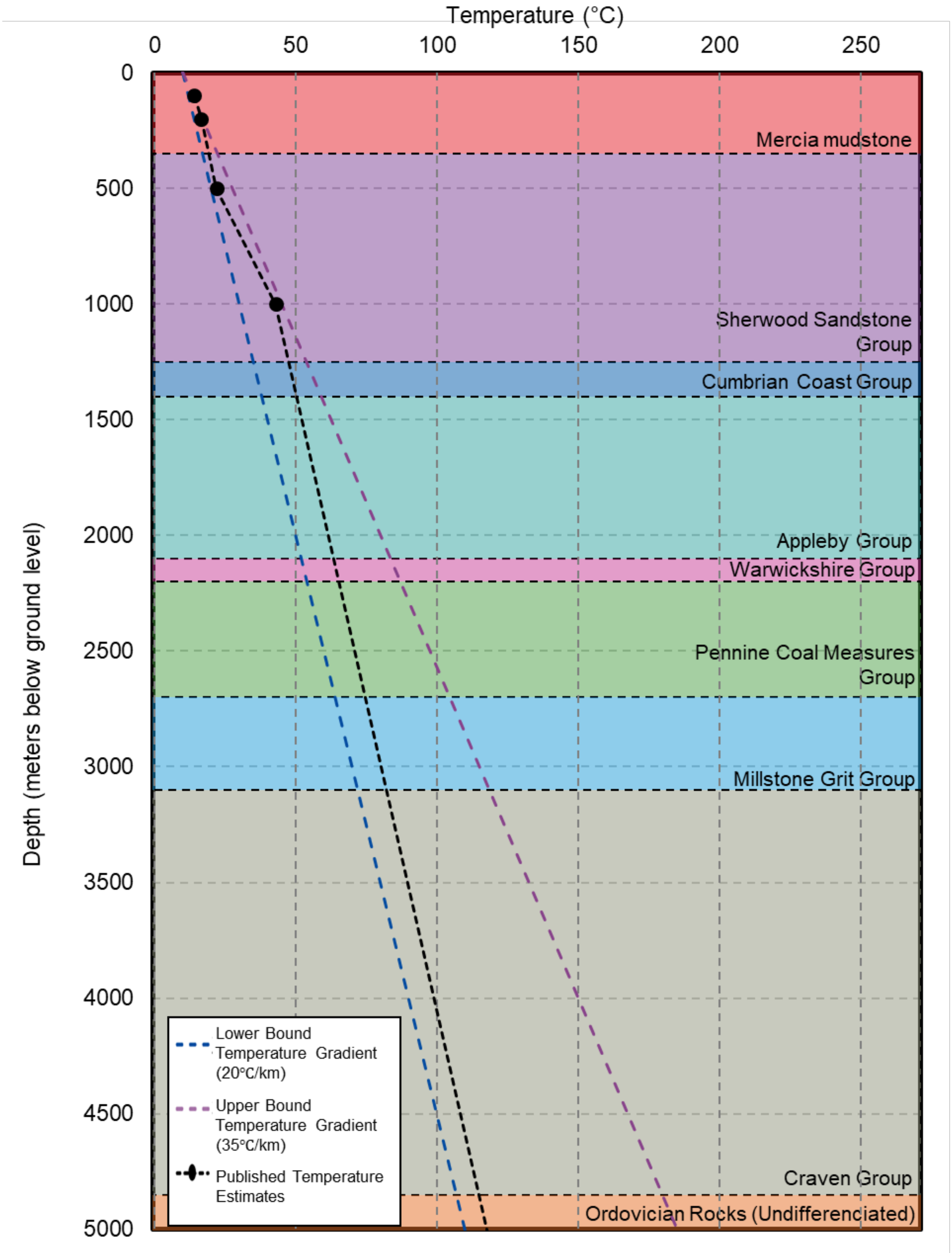


Figure 9: Inferred ground model and geothermal gradient

Table 13: Inferred ground model

Aquifer	Formation	Period	Lithology	Depth to top (mbgl)	Depth to base (mbgl)	Thickness (m)	Temperature Range (base) (°C)	Aquifer condition	Estimated hydraulic conductivity*	
									m/s	mD
Secondary B	Mercia mudstone	Permo-Triassic	Mudstone, siltstone, and sandstone	0	350	350	14 to 16	Predominantly fracture-low productivity	1x10-11 to 1x10-9	10-3 to 10-1
Principal	Sherwood Sandstone Group	Permo-Triassic	Sandstone	350	1250	900	30 to 38	Significant intergranular-highly productive	1x10-5 to 1x10-6	10-2 to 10-3
Secondary B	Cumbrian Coast Group (Manchester Marls)	Permian	Mudstone, siltstone, and sandstone	1250	1500	250	44 to 58	Essentially no groundwater	1x10-11	10-3 to 10-1
Principal	Appleby Group (Collyhurst Sandstone Fm.)	Permian	Interbedded sandstone and cobblestone	1500	2000	500	54 to 71	Significant intergranular-moderately productive	1x10-5 to 1x10-6	10-2 to 10-3
Secondary A	Warwickshire Group	Carboniferous	Mudstone, siltstone, sandstone, coal, ironstone, and ferricrete	2000	2200	200	63 to 84	Predominantly fracture-moderately productive	1x10-8 to 1x10-6	1 to 10-2
Secondary A	Pennine Coal Measures Group	Carboniferous	Mudstone, siltstone, and sandstone	2200	2700	500	71 to 96	Predominantly fracture-moderately productive	1x10-8 to 1x10-6	1 to 10-2
Secondary A	Millstone Grit Group	Carboniferous	Mudstone and sandstone	2700	3100	400	83 to 112	Predominantly fracture-moderately productive	1x10-8 to 1x10-6	1 to 10-2
Secondary A	Craven Group (undifferentiated)	Carboniferous	Mudstone and limestone interbedded	3100	3850	750	97 to 132	Predominantly fracture-moderately productive	1x10-5 to 1x10-6	10-2 to 10-3
Secondary A	Craven Group (early carboniferous)	Carboniferous	Mudstone and limestone interbedded	3850	4350	500	113 to 154	Predominantly fracture-moderately productive	1x10-5 to 1x10-6	10-2 to 10-3
Secondary A	Craven Group (undifferentiated)	Carboniferous	Mudstone and limestone interbedded	4350	4850	500	125 to 171	Predominantly fracture-moderately productive	1x10-5 to 1x10-6	10-2 to 10-3
Secondary B	Ordovician Rocks (Undifferentiated)	Ordovician	Mudstone, siltstone, and sandstone	4850	Unknown	Unknown	>131 to >180	Predominantly fracture-low productivity	1x10-11 to 1x10-9	10-3 to 10-1
* Estimated permeabilities based on published data sources [2][3]										
Highlighted	Key aquifers beneath the Site which have potential for deep geothermal									

Page 25

A.4.1 Doublet Calc Inputs

Table 14: Inputs for Collyhurst Sandstone formation

Parameter	Value			Units	Comment
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	1	200	400	mDarcey	Permeability data has been inferred from published literature [1][2][3]
Aquifer porosity	0.05	0.15	0.25	-	Porosity inferred from published literature [2]
Aquifer net to gross	0.5	0.6	0.8	-	Aquifer assumed to be heterogeneous. General net-to-gross of 50% to 80% assumed. Insufficient data to suggest otherwise.
Aquifer gross thickness	240	300	360	m	Inferred from local O&G well data [4] and BGS datasets [6][14], and publications [7]. Applied +/- 20% error margin for min/max
Aquifer top at producer	1,701	1,890	2,079	m TVD	Inferred from local O&G well data [4] and BGS datasets [6][14], and publications [7]. Located at 10m from base of aquifer. Applied +/- 10% error margin for min/max
Aquifer top at injector	1,449	1,610	1,771	m TVD	Inferred from local O&G well data [4] and BGS datasets [6][14], and publications [7]. Located at 10m from top of aquifer. Applied +/- 10% error margin for min/max
Aquifer water salinity	50k	80k	150k	ppm	*Generic assumption*
Aquifer net transmissivity	-			Dm	
Aquifer kh/kv ratio	0.5			-	Inferred to be 50% anisotropic.
Surface temperature	10			°C	Based on published data for the UK [8]
Geothermal gradient	0.027			°C/m	Inferred from publications [7]
Mid Aquifer temperature producer	-			°C	
Initial aquifer pressure at producer	-			Bar	
Initial aquifer pressure at injector	-			Bar	
Heat capacity rock matrix at 20°C	1,000			$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix	2,500			kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix	2.5			$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix	0.0000011			m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation	-			-	
Doublet and pump properties					
Exit temperature heat exchanger	35			°C	
Output temperature from wells	64.8			°C	
Delta T across doublet	29.8			°C	
Distance wells at aquifer level	2,000			m	
Pump system efficiency	0.6			-	*Generic assumption*
Production pump depth	300			m	*Generic assumption*
Pump pressure difference	30			bar	*Generic assumption*
Cooling as fraction of initial	0.1			ΔT	

Parameter	Value			Units	Comment
	Min	Ave	Max		
Yearly full operational hours	6,000			Hours	
Well properties					
Calculation length subdivision	50			m	
Producer					
Outer diameter producer	7			Inch	
Skin producer	2			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
Outer diameter producer	7			Inch	
Skin producer	0.5			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
General					
Segment	1			-	
Pipe segment sections	1,890 (Prod), 1,610 (Reinj)			mAH	
Pipe segment depth	1,890 (Prod), 1,610 (Reinj)			m TVD	
Pipe inner diameter	6			Inch	
Pipe roughness	1.38			milli-inch	*Default*

Table 15: Inputs for Early Carboniferous Limestone

Parameter	Value			Units	Comment
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	1	150	400	mDarcey	Permeability data has been inferred from published literature [2][3]
Aquifer porosity	0.05	0.15	0.25	-	Porosity inferred from published literature [1][2]
Aquifer net to gross	0.99	1	1.01	-	Entire aquifer inferred to have geothermally contributing layers. Insufficient data to suggest otherwise
Aquifer gross thickness	1,400	1,750	2,100	m	Inferred from local O&G well data [4] and BGS datasets [6][14], and publications [7]. Applied +/- 20% error margin for min/max
Aquifer top at producer	3,600	4,000	4,400	m TVD	Inferred from local O&G well data [4] and BGS datasets [6][14], and publications [7]. Located at 10m from base of aquifer. Applied +/- 10% error margin for min/max
Aquifer top at injector	2790	3100	3410	m TVD	Inferred from local O&G well data [4] and BGS datasets [6][14], and publications [7]. Located at 10m from top of aquifer. Applied +/- 10% error margin for min/max
Aquifer water salinity	50,000	80,000	150,000	ppm	
Aquifer net transmissivity	-			Dm	
Aquifer kh/kv ratio	0.5			-	Inferred to be 50% anisotropic.
Surface temperature	11			°C	Based on published data for the UK [8]
Geothermal gradient	0.028			°C/m	Inferred from publications [7]
Mid Aquifer temperature producer	-			°C	
Initial aquifer pressure at producer	-			Bar	
Initial aquifer pressure at injector	-			Bar	
Heat capacity rock matrix at 20°C	850			$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix	2,600			kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix	2.5			$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix	0.0000011			m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation	-			-	
Doublet and pump properties					
Exit temperature heat exchanger	70.0			°C	
Output temperature from wells	135.6			°C	
Delta T across doublet	65.6			°C	
Distance wells at aquifer level	2,000			m	
Pump system efficiency	0.6			-	*Generic assumption*
Production pump depth	300			m	*Generic assumption*
Pump pressure difference	30			bar	*Generic assumption*
Cooling as fraction of initial	0.1			ΔT	
Yearly full operational hours	6,000			Hours	

Parameter	Value			Units	Comment
	Min	Ave	Max		
Well properties					
Calculation length subdivision	50			m	
Producer					
Outer diameter producer	7			Inch	
Skin producer	2			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
Outer diameter producer	7			Inch	
Skin producer	0.5			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
General					
Segment	1			-	
Pipe segment sections	4,000 (Prod), 3,100 (Reinj)			mAH	
Pipe segment depth	4,000 (Prod), 3,100 (Reinj)			m TVD	
Pipe inner diameter	6			Inch	
Pipe roughness	1.38			milli-inch	*Default*

A.4.2 Doublet Calc Outputs

Collyhurst Sandstone Fm.

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	1	100	300
aquifer porosity (-)	0.05	0.15	0.25
aquifer net to gross (-)	0.5	0.6	0.8
aquifer gross thickness (m)	240	300	360
aquifer top at producer (m TVD)	1701	1890	2079
aquifer top at injector (m TVD)	1449	1610	1771
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

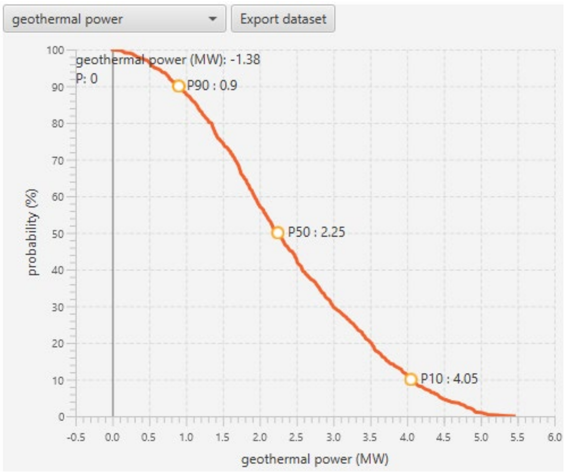
Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	10
geothermal gradient (°C/m)	0.027
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	1000
density rock matrix (kg/m³)	2500
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	35
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	1890
pipe segment depth (m TVD)	1890
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	1610
pipe segment depth (m TVD)	1610
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	8.07	19.11	39.47
mass flow (kg/s)	9.61	21.38	37.01
pump volume flow (m³/h)	33	73.8	128
required pump power (kW)	45.8	102.5	177.8
geothermal power (MW)	0.9	2.25	4.05
COP (kW/kW)	18.9	21.8	24.1
doublet life time (years)	1284.5	2198.5	4793.3
doublet power over life time (PJ)	124.49	152.09	181.69
heat capacity rock matrix (J/Kg/K)	1078.5	1085.4	1091
aquifer pressure at producer (bar)	180.19	191.13	202.39
aquifer pressure at injector (bar)	153.55	162.36	172
pressure difference at producer (bar)	11.02	13.08	13.89
pressure difference at injector (bar)	13.73	16.38	17.48
aquifer temperature at producer * (°C)	62.29	65.11	67.97
temperature at heat exchanger (°C)	58.99	62.51	65.42
pressure at heat exchanger (bar)	10.63	13.24	14.49

base case (median value input)	value
aquifer kH net (Dm)	18
mass flow (kg/s)	20.42
pump volume flow (m³/h)	70.7
required pump power (kW)	98.2
geothermal power (MW)	2.16
COP (kW/kW)	22
doublet life time (years)	2275.8
doublet power over life time (PJ)	155.13
heat capacity rock matrix (J/Kg/K)	1085.8
aquifer pressure at producer (bar)	190.8
aquifer pressure at injector (bar)	162.14
pressure difference at producer (bar)	13.16
pressure difference at injector (bar)	16.48
aquifer temperature at producer * (°C)	65.08
temperature at heat exchanger (°C)	62.72
pressure at heat exchanger (bar)	13.4

* @ mid aquifer depth



Early Carboniferous (of Craven Group) output

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	0	150	400
aquifer porosity (-)	0.05	0.15	0.25
aquifer net to gross (-)	0.5	0.6	0.8
aquifer gross thickness (m)	400	500	600
aquifer top at producer (m TVD)	3906	4340	4774
aquifer top at injector (m TVD)	3474	3860	4246
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

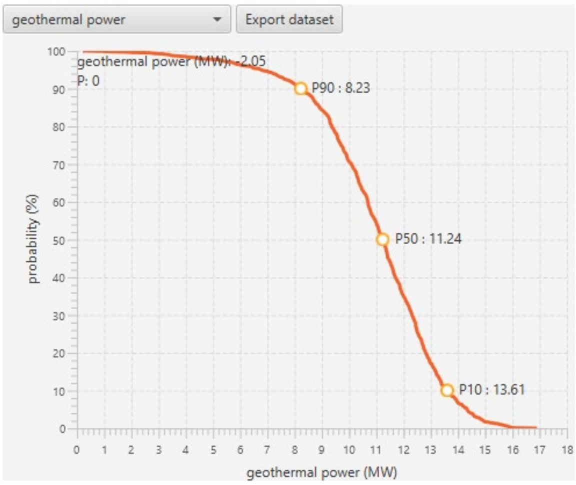
Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	10
geothermal gradient (°C/m)	0.027
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	1000
density rock matrix (kg/m³)	2500
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	70
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	4340
pipe segment depth (m TVD)	4340
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	3860
pipe segment depth (m TVD)	3860
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	20.62	46.69	87.16
mass flow (kg/s)	38.47	50.04	55.94
pump volume flow (m³/h)	137.3	179.8	201.9
required pump power (kW)	190.7	249.8	280.4
geothermal power (MW)	8.23	11.24	13.61
COP (kW/kW)	40.5	45.4	50.2
doublet life time (years)	1479.8	1717.2	2281.4
doublet power over life time (PJ)	509.49	609.1	714.38
heat capacity rock matrix (J/Kg/K)	1192.9	1203.8	1213.8
aquifer pressure at producer (bar)	407.75	432.55	458.32
aquifer pressure at injector (bar)	363.13	384.94	407.19
pressure difference at producer (bar)	3.84	6.51	11.29
pressure difference at injector (bar)	5.8	9.72	17.14
aquifer temperature at producer * (°C)	127.34	133.92	140.33
temperature at heat exchanger (°C)	122.34	128.99	135.26
pressure at heat exchanger (bar)	7.25	12.91	16.32

base case (median value input)	value
aquifer kH net (Dm)	45
mass flow (kg/s)	49.72
pump volume flow (m³/h)	179.5
required pump power (kW)	249.3
geothermal power (MW)	11.42
COP (kW/kW)	45.8
doublet life time (years)	1706.7
doublet power over life time (PJ)	614.91
heat capacity rock matrix (J/Kg/K)	1204.3
aquifer pressure at producer (bar)	431.99
aquifer pressure at injector (bar)	384.23
pressure difference at producer (bar)	6.65
pressure difference at injector (bar)	10.07
aquifer temperature at producer * (°C)	133.93
temperature at heat exchanger (°C)	129.29
pressure at heat exchanger (bar)	13.27

* @ mid aquifer depth



A.5 Northumberland & Solway Basin (Newcastle)

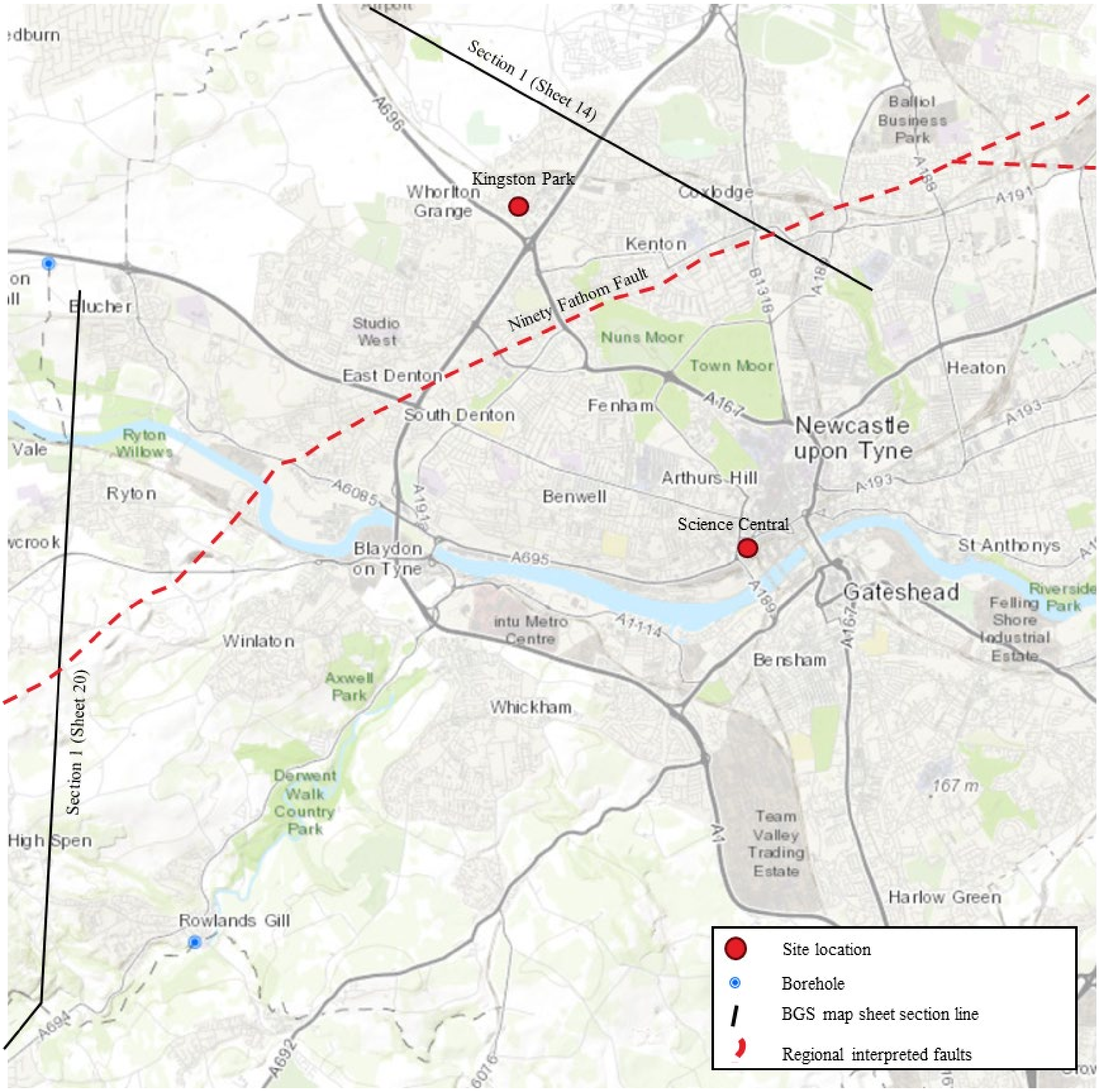


Figure 10: Site location and local data

Table 16: Geological summary

Parameter	Value
Geothermal gradient	35 to 40 °C/km
Potential deep geothermal reservoirs	Fell Sandstone – Principal aquifer – 2000 to 3000m depth (Kingston Park)
	Fell Sandstone – Principal aquifer – 1420 to 1795m depth (Science Central)

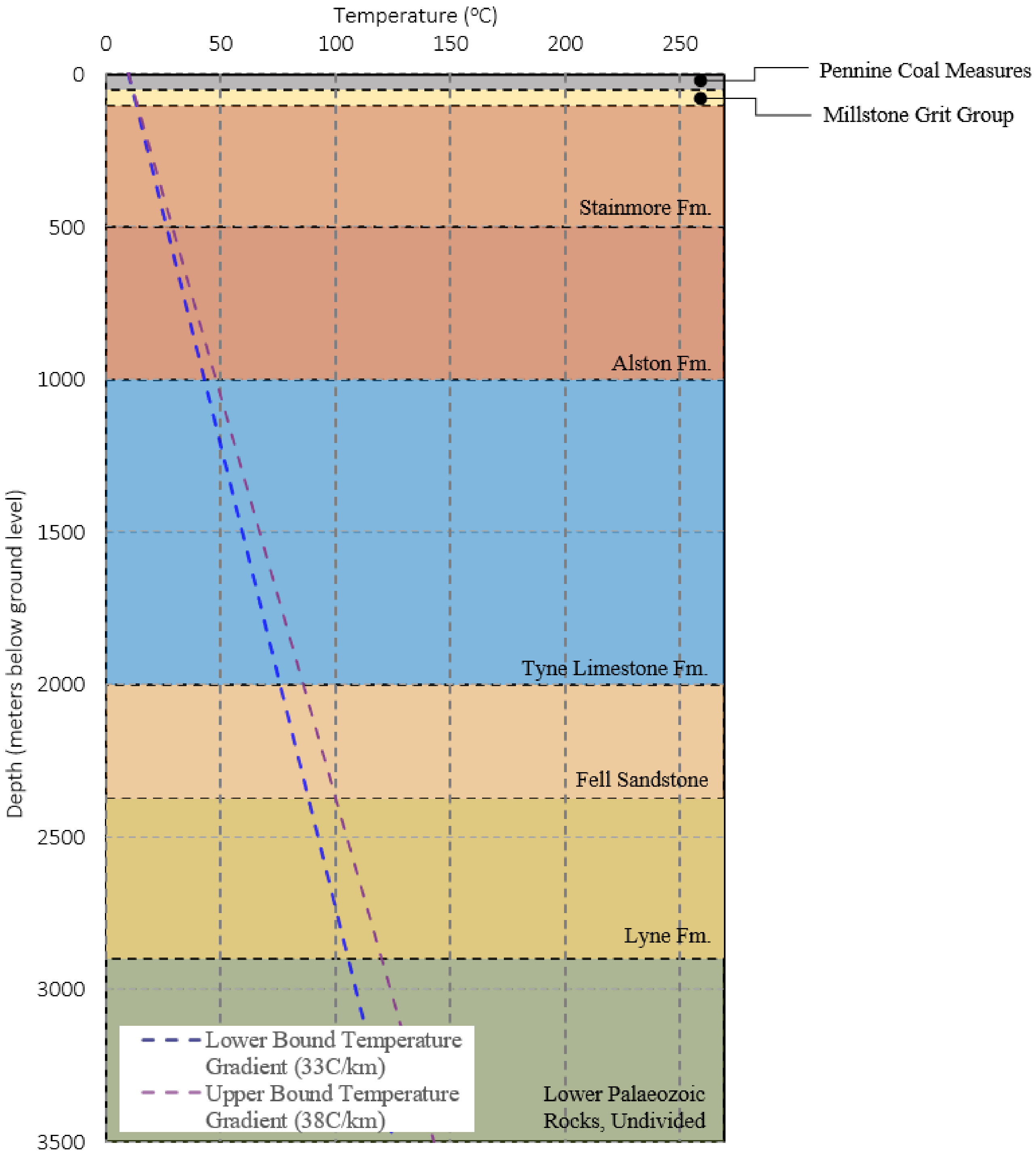


Figure 11: Kingstone Park inferred ground model and geothermal gradient

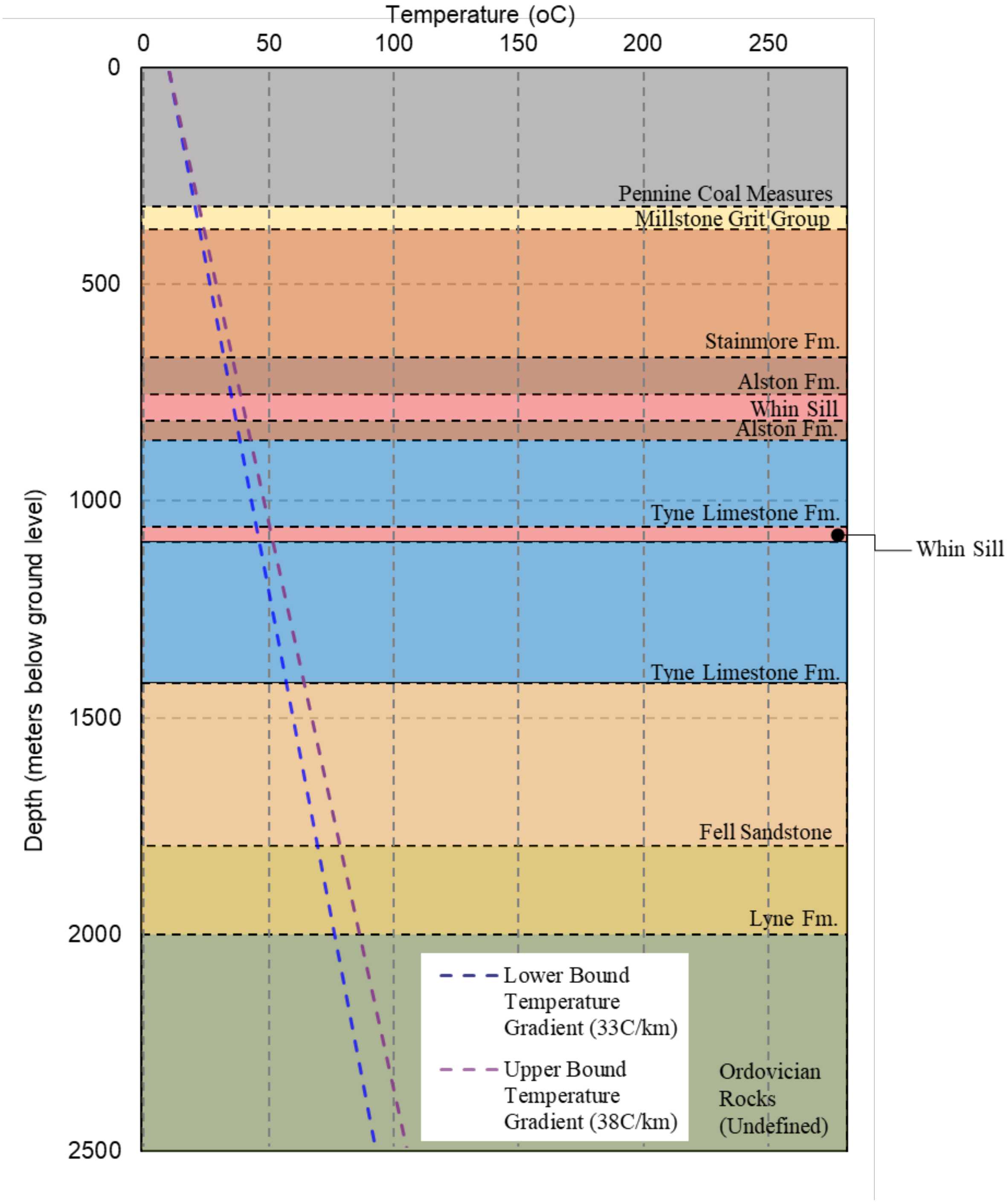


Figure 12: Science Centre inferred ground model and geothermal gradient

Table 17: Inferred ground model Science Central

Aquifer	Formation	Period	Lithology	Depth to top (mbgl)	Depth to base (mbgl)	Thickness (m)	Temperature Range (base) (°C)	Aquifer condition	Estimated hydraulic conductivity*	
									m/s	mD
Secondary A	Pennine Coal Measures	Carboniferous	mudstone, siltstone, sandstone, coal, ironstone and ferricrete	0	320	320	21.2 to 22.8	Predominantly fracture-moderately productive		
Secondary A	Millstone Grit Group	Carboniferous	Sandstones, siltstones, and mudstones	320	375	55	23.1 to 25	Predominantly fracture-moderately productive		
Secondary A	Stainmore Fm.	Carboniferous	Limestone, sandstone, siltstone, and mudstone	375	670	295	33.5 to 36.8	Predominantly fracture-moderately productive		
Secondary A	Alston Fm.	Carboniferous	Limestone with subordinate sandstone and argillaceous rocks	670	755	85	36.4 to 40.2	Predominantly fracture-moderately productive		
Secondary B	Whin Sill	Carboniferous	Dolerite and tholeiitic basalt	755	815	60	38.5 to 42.6	Predominantly fracture-low productivity		
Secondary A	Alstone Fm.	Carboniferous	Limestone with subordinate sandstone and argillaceous rocks	815	860	45	40.1 to 44.4	Predominantly fracture-moderately productive		
Secondary A	Tyne Limestone Fm.	Carboniferous	Limestone, argillaceous rocks, and subordinate sandstone, interbedded	860	1,060	200	47.1 to 52.4	Predominantly fracture-moderately productive		
Secondary B	Whin Sill	Carboniferous	Dolerite and tholeiitic basalt	1,060	1,095	35	48.3 to 53.8	Predominantly fracture-low productivity		
Secondary A	Tyne Limestone Fm.	Carboniferous	Limestone, argillaceous rocks, and subordinate sandstone, interbedded	1,095	1,420	325	59.7 to 66.8	Predominantly fracture-moderately productive		
Principal	Fell Sandstone	Carboniferous	Sandstone with subordinate argillaceous rocks and limestone	1,420	1,795	375	72.8 to 81.8	Significant intergranular-moderately productive		0.01 to 200

Aquifer	Formation	Period	Lithology	Depth to top (mbgl)	Depth to base (mbgl)	Thickness (m)	Temperature Range (base) (°C)	Aquifer condition	Estimated hydraulic conductivity*	
									m/s	mD
Secondary A	Lyne Fm.	Carboniferous	Siltstone, sandstone, dolostone and anhydrite	1,795	2,000	205	80 to 90	Predominantly fracture-moderately productive		Inferred thickness
Secondary B	Ordovician Rocks (Undefined)	Ordovician	Mudstone, siltstone, and sandstone	2,000	Unknown	-	-	Predominantly fracture-low productivity		
* Estimated permeabilities based on published data sources										
Highlighted	Key aquifers beneath the Site which have potential for deep geothermal									

Table 18: Inferred ground model Kingston Park

Aquifer	Formation	Period	Lithology	Depth to top (mbgl)	Depth to base (mbgl)	Thickness (m)	Temperature Range (base) (°C)	Aquifer condition	Estimated hydraulic conductivity*	
									m/s	mD
Secondary A	Pennine Coal Measures	Carboniferous	mudstone, siltstone, sandstone, coal, ironstone and ferricrete	0	50	50	11.8 to 12	Predominantly fracture-moderately productive		
Secondary A	Millstone Grit Group	Carboniferous	Sandstones, siltstones, and mudstones	50	100	50	13.5 to 14	Predominantly fracture-moderately productive		
Secondary A	Stainmore Fm.	Carboniferous	Limestone, sandstone, siltstone, and mudstone	100	500	400	27.5 to 30	Predominantly fracture-moderately productive		
Secondary A	Alston Fm.	Carboniferous	Limestone with subordinate sandstone and argillaceous rocks	500	1,000	500	45 to 50	Predominantly fracture-moderately productive		
Secondary A	Tyne Limestone Fm.	Carboniferous	Limestone, argillaceous rocks, and subordinate sandstone, interbedded	1,000	2,000	1,000	80 to 90	Predominantly fracture-moderately productive		
Principal	Fell Sandstone	Carboniferous	Sandstone with subordinate argillaceous rocks and limestone	2,000	2,375	375	93.1 to 105	Significant intergranular-moderately productive		0.01 to 100
Secondary A	Lyne Fm.	Carboniferous	Siltstone, sandstone, dolostone and anhydrite	2,375	2,900	500	132.5 to 150	Predominantly fracture-moderately productive		
Secondary B	Lower Palaeozoic Rocks, Undivided	Cambrian	Mudstone, siltstone, and sandstone	2,900	Unknown	-	-	Predominantly fracture-low productivity		
* Estimated permeabilities based on published data sources										
Highlighted	Key aquifers beneath the Site which have potential for deep geothermal									

A.5.1 Doublet Calc Inputs

Table 19: Inputs for Fell Sandstone - Science Centre

Parameter	Value			Units	Comment
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	1	100	250	mDarcey	Permeability data has been inferred from published literature [15][1][2][3]
Aquifer porosity	0.05	0.15	0.25	-	Porosity inferred from published literature [15][1][2]
Aquifer net to gross	0.5	0.6	0.8	-	Aquifer assumed to be heterogeneous. General net-to-gross of 50% to 80% assumed. Insufficient data to suggest otherwise.
Aquifer gross thickness	300	375	450	m	Inferred from local O&G well data [4] and BGS datasets [16][17][6], and publications [7]. Applied +/- 20% error margin for min/max
Aquifer top at producer	1,615.5	1,795	1,974.5	m TVD	Inferred from local O&G well data [4] and BGS datasets [16][17][6], and publications [7]. Located at 10m from base of aquifer. Applied +/- 10% error margin for min/max
Aquifer top at injector	1,278	1,420	1,562	m TVD	Inferred from local O&G well data [4] and BGS datasets [16][17][6], and publications [7]. Located at 10m from top of aquifer. Applied +/- 10% error margin for min/max
Aquifer water salinity	50,000	80,000	150,000	ppm	
Aquifer net transmissivity	-			Dm	
Aquifer kh/kv ratio	0.5			-	Inferred to be 50% anisotropic.
Surface temperature	10			°C	Based on published data for the UK [8]
Geothermal gradient	0.037			°C/m	Inferred from publications [9]
Mid Aquifer temperature producer	-			°C	
Initial aquifer pressure at producer	-			Bar	
Initial aquifer pressure at injector	-			Bar	
Heat capacity rock matrix at 20°C	855			$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix	2,500			kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix	2.5			$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix	0.0000011			m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation	-			-	

Parameter	Value			Units	Comment
	Min	Ave	Max		
Doublet and pump properties					
Exit temperature heat exchanger	45.0			°C	
Output temperature from wells	83.4			°C	
Delta T across doublet	38.4			°C	
Distance wells at aquifer level	2,000			m	
Pump system efficiency	0.6			-	Generic assumption
Production pump depth	300			m	Generic assumption
Pump pressure difference	30			bar	Generic assumption
Cooling as fraction of initial	0.1			ΔT	
Yearly full operational hours	6,000			Hours	
Well properties					
Calculation length subdivision	50			m	
Producer					
Outer diameter producer	7			Inch	
Skin producer	2			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
Injector					
Outer diameter producer	7			Inch	
Skin producer	0.5			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
General					
Segment	1			-	
Pipe segment sections	1,795 (Prod), 1420 (Reinj)			mAH	
Pipe segment depth	1,795 (Prod), 1420 (Reinj)			m TVD	
Pipe inner diameter	6			Inch	
Pipe roughness	1.38			milli-inch	Default

Table 20: Inputs for Fell Sandstone - Science Centre

Parameter	Value			Units	Comment / Reference
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	1	100	250	mDarcey	Permeability data has been inferred from published literature [15][1][2][3]
Aquifer porosity	0.05	0.15	0.25	-	Porosity inferred from published literature [15][1][2]
Aquifer net to gross	0.5	0.6	0.8	-	Aquifer assumed to be heterogeneous. General net-to-gross of 50% to 80% assumed. Insufficient data to suggest otherwise.
Aquifer gross thickness	300	375	450	m	Inferred from local O&G well data [4] and BGS datasets [16][17][6], and publications [7]. Applied +/- 20% error margin for min/max
Aquifer top at producer	2137.5	2375	2612.5	m TVD	Inferred from local O&G well data [4] and BGS datasets [16][17][6], and publications [7]. Located at 10m from base of aquifer. Applied +/- 10% error margin for min/max
Aquifer top at injector	1,800	2,000	2,200	m TVD	Inferred from local O&G well data [4] and BGS datasets [16][17][6], and publications [7]. Located at 10m from top of aquifer. Applied +/- 10% error margin for min/max
Aquifer water salinity	50,000	80,000	150,000	ppm	Generic range
Aquifer net transmissivity	-			Dm	
Aquifer kh/kv ratio	0.5			-	Inferred to be 50% anisotropic.
Surface temperature	10			°C	Based on published data for the UK [8]
Geothermal gradient	0.037			°C/m	Inferred from publications [9]
Mid Aquifer temperature producer	-			°C	
Initial aquifer pressure at producer	-			Bar	
Initial aquifer pressure at injector	-			Bar	
Heat capacity rock matrix at 20°C	855			$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix	2,500			kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix	2.5			$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix	0.0000011			m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation	-			-	
Doublet and pump properties					
Exit temperature heat exchanger	60			°C	

Parameter	Value			Units	Comment / Reference
	Min	Ave	Max		
Output temperature	104.8			°C	
Delta T	44.8			°C	
Distance wells at aquifer level	2,000			m	
Pump system efficiency	0.6			-	Generic assumption
Production pump depth	300			m	Generic assumption
Pump pressure difference	30			bar	Generic assumption
Cooling as fraction of initial	0.1			dT	
Yearly full operational hours	6,000			Hours	
Well properties					
Calculation length subdivision	50			m	
Producer					
Outer diameter producer	7			Inch	
Skin producer	2			-	
Penetration angle producer	-			°C Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
Injector					
Outer diameter producer	7			Inch	
Skin producer	0.5			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
General					
Segment	1			-	
Pipe segment sections	2375 (Prod), 2000 (Reinj)			mAH	
Pipe segment depth	2375 (Prod), 2000 (Reinj)			m TVD	
Pipe inner diameter	6			Inch	
Pipe roughness	1.38			milli-inch	Default

A.5.2 Doublet Calc Outputs

Fell Sandstone Doublet Calc Output - Science Centre

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	0	100	250
aquifer porosity (-)	0.05	0.15	0.25
aquifer net to gross (-)	0.5	0.6	0.8
aquifer gross thickness (m)	300	375	450
aquifer top at producer (m TVD)	1616	1795	1974
aquifer top at injector (m TVD)	1278	1420	1562
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

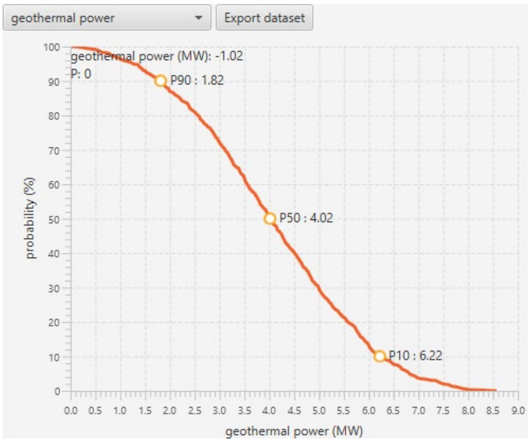
Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	10
geothermal gradient (°C/m)	0.037
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	855
density rock matrix (kg/m³)	2500
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	45
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	1795
pipe segment depth (m TVD)	1795
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	1420
pipe segment depth (m TVD)	1420
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	10.2	23.61	42.14
mass flow (kg/s)	14.32	29.43	44.1
pump volume flow (m³/h)	49.9	102.2	154.1
required pump power (kW)	69.3	141.9	214
geothermal power (MW)	1.82	4.02	6.22
COP (kW/kW)	25.1	28.1	31.1
doublet life time (years)	1199.9	1801.1	3877.1
doublet power over life time (PJ)	188.07	227.1	267.93
heat capacity rock matrix (J/Kg/K)	951.4	957.8	963.9
aquifer pressure at producer (bar)	170.93	181.11	191.53
aquifer pressure at injector (bar)	134.84	142.93	150.92
pressure difference at producer (bar)	10.21	12.37	13.66
pressure difference at injector (bar)	13.23	16.02	17.87
aquifer temperature at producer * (°C)	79.71	83.37	86.99
temperature at heat exchanger (°C)	76.82	80.84	84.72
pressure at heat exchanger (bar)	11.82	14.22	15.56

base case (median value input)	value
aquifer kH net (Dm)	22.5
mass flow (kg/s)	28.83
pump volume flow (m³/h)	100.8
required pump power (kW)	139.9
geothermal power (MW)	3.99
COP (kW/kW)	28.5
doublet life time (years)	1830.3
doublet power over life time (PJ)	230.57
heat capacity rock matrix (J/Kg/K)	958.4
aquifer pressure at producer (bar)	180.69
aquifer pressure at injector (bar)	142.61
pressure difference at producer (bar)	12.42
pressure difference at injector (bar)	16.15
aquifer temperature at producer * (°C)	83.35
temperature at heat exchanger (°C)	81.19
pressure at heat exchanger (bar)	14.43

* @ mid aquifer depth



Fell Sandstone Doublet Calc Output - Kingston

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	0	100	250
aquifer porosity (-)	0.05	0.15	0.25
aquifer net to gross (-)	0.5	0.6	0.8
aquifer gross thickness (m)	300	375	450
aquifer top at producer (m TVD)	2138	2375	2612
aquifer top at injector (m TVD)	1800	2000	2200
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

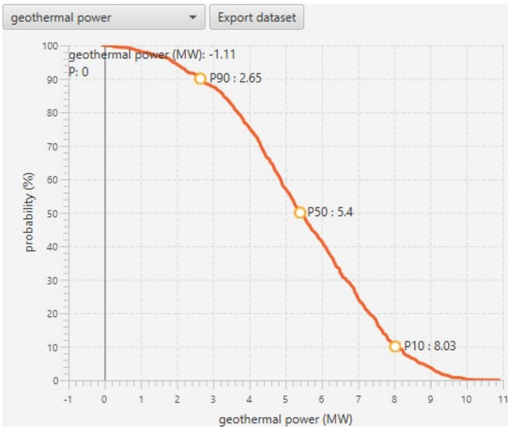
Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	10
geothermal gradient (°C/m)	0.037
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	855
density rock matrix (kg/m³)	2500
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	60
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	2375
pipe segment depth (m TVD)	2375
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	2000
pipe segment depth (m TVD)	2000
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	10.22	23.01	42.19
mass flow (kg/s)	18.07	34.39	48.22
pump volume flow (m³/h)	63.1	121.5	171.1
required pump power (kW)	87.7	168.7	237.7
geothermal power (MW)	2.65	5.4	8.03
COP (kW/kW)	28	32.3	36.3
doublet life time (years)	1127.3	1573.7	2952.9
doublet power over life time (PJ)	220.43	269.95	323.96
heat capacity rock matrix (J/Kg/K)	981.3	989.5	997.2
aquifer pressure at producer (bar)	224.23	238.48	252.37
aquifer pressure at injector (bar)	189.36	200.59	211.71
pressure difference at producer (bar)	8.79	11.79	14.01
pressure difference at injector (bar)	11.8	15.62	18.84
aquifer temperature at producer * (°C)	100.07	104.81	109.7
temperature at heat exchanger (°C)	95.98	101.38	106.62
pressure at heat exchanger (bar)	11.08	14.2	15.98

base case (median value input)	value
aquifer kH net (Dm)	22.5
mass flow (kg/s)	34.23
pump volume flow (m³/h)	121.1
required pump power (kW)	168.2
geothermal power (MW)	5.5
COP (kW/kW)	32.7
doublet life time (years)	1582.6
doublet power over life time (PJ)	274.49
heat capacity rock matrix (J/Kg/K)	990.1
aquifer pressure at producer (bar)	237.87
aquifer pressure at injector (bar)	200.1
pressure difference at producer (bar)	11.81
pressure difference at injector (bar)	15.76
aquifer temperature at producer * (°C)	104.81
temperature at heat exchanger (°C)	101.81
pressure at heat exchanger (bar)	14.49

* @ mid aquifer depth



A.6 Glasgow & Clyde Basin (Edinburgh)

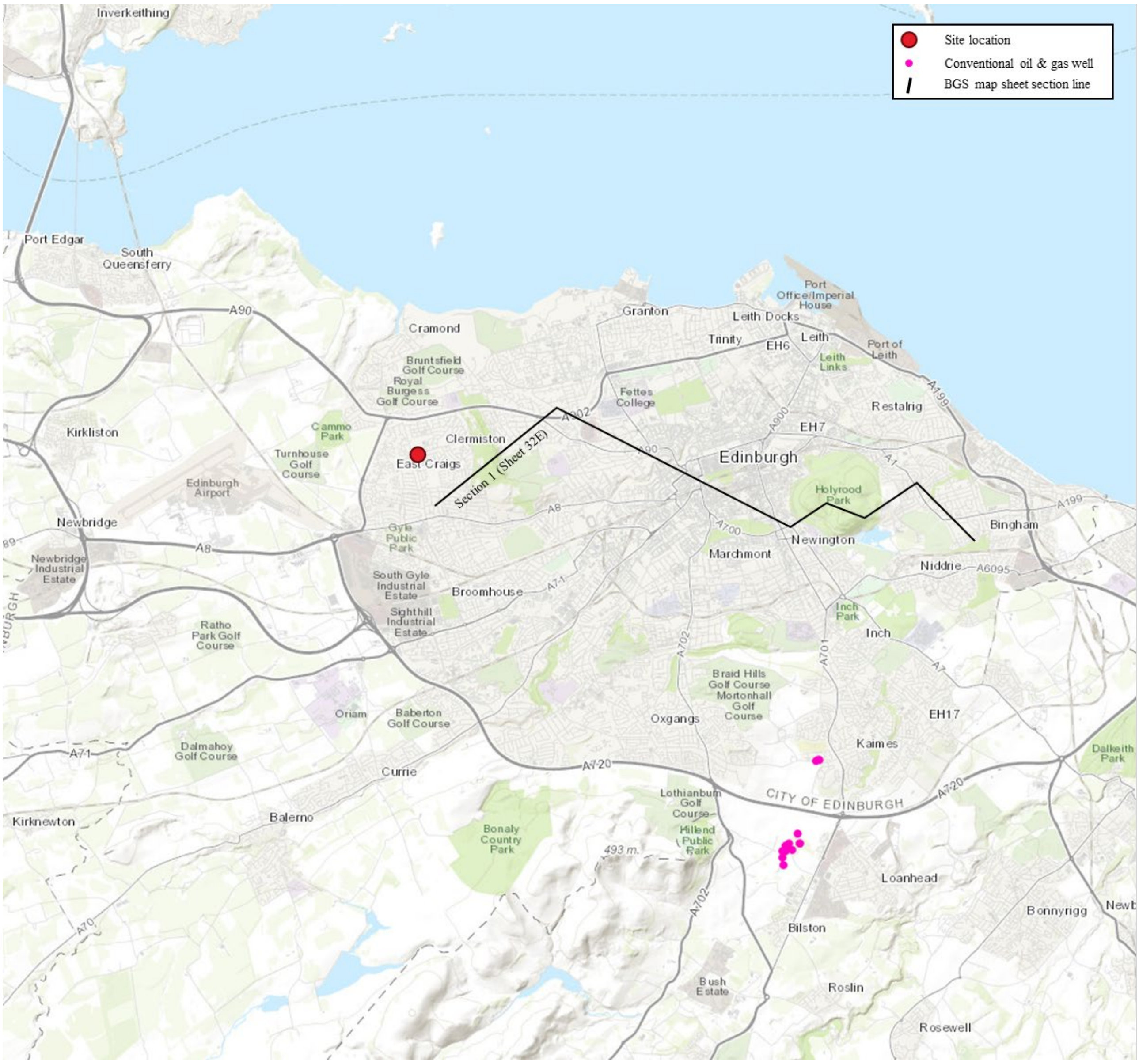


Figure 13: Site location and local data

Table 21: Geological summary

Parameter	Value
Geothermal gradient	Between 28 to 32 °C/km
Potential deep geothermal reservoirs	Kinnesswood Fm. – Secondary A – 1700 to 2000m depth
	Know Pulpit Fm. – Secondary A – 2000 – 2150m depth

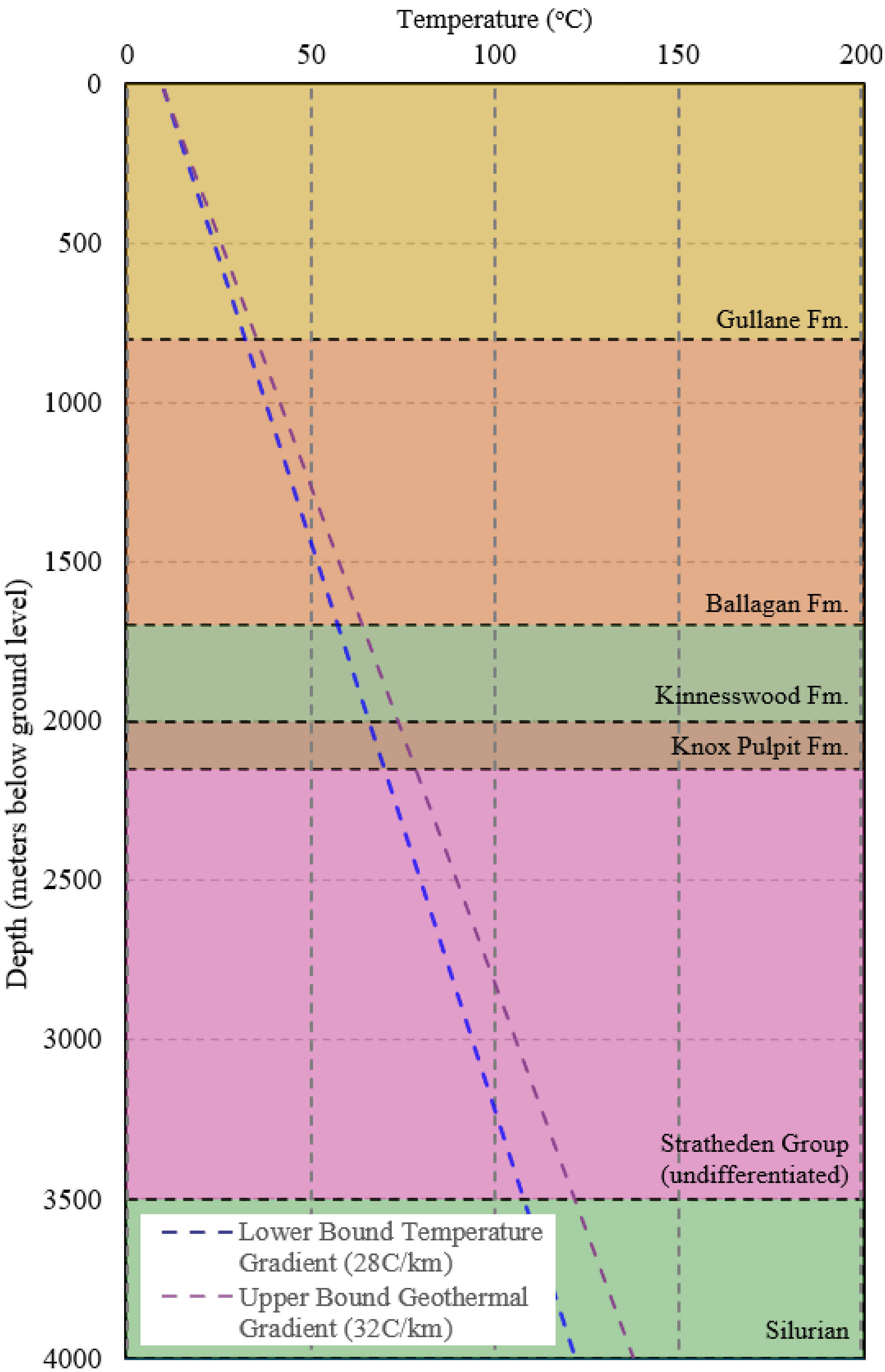


Figure 14: Inferred ground model and geothermal gradient

Table 22: Inferred ground model

Aquifer	Formation	Period	Lithology	Depth to top (mbgl)	Depth to base (mbgl)	Thickness (m)	Temperature Range (base) (°C)	Aquifer condition	Estimated hydraulic conductivity*	
									m/s	mD
Secondary A	Gullane Fm	Carboniferous	Sandstone, Siltstone, mudstone	0	800	800	32.4 to 35.6	Predominantly fracture-moderately productive		
Secondary A	Ballagan Fm	Carboniferous	Mudstone and siltstone	800	1700	900	57.6 to 64.4	Predominantly fracture-moderately productive		
Secondary A	Kinnesswood Fm	Carboniferous	Sandstone and conglomerates	1700	2000	300	66 to 74	Predominantly fracture-moderately productive	1x10-10 to 7x10-6	0.01 to 150
Secondary A	Knox Pulpit Fm	Devonian	Sandstone, Siltstone, mudstone	2000	2150	150	70 to 79	Predominantly fracture-moderately productive	1x10-10 to 1x10-6	0.01 to 100
Secondary A	Stratheden Group	Devonian	Sandstone, Siltstone, mudstone	2000	3500	1500	108 to 122	Predominantly fracture-moderately productive	1x10-10 to 1x10-6	0.01 to 100
Secondary A	Silurian	Silurian	Mudstones and siltstones	>3500		unknown				
* Estimated permeabilities based on published data sources										
Highlighted	Key aquifers beneath the Site which have potential for deep geothermal									

A.6.1 Doublet Calc Inputs

Table 23: Inputs for the Kinnesswood Fm.

Parameter	Value			Units	Comment
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	1	50	100	mDarcey	Permeability data has been inferred from published literature [3][34]
Aquifer porosity	0.03	0.15	0.25	-	Porosity inferred from published literature [3][34]
Aquifer net to gross	0.5	0.6	0.8	-	Entire aquifer inferred to have geothermally contributing layers. Insufficient data to suggest otherwise
Aquifer gross thickness	240	300	360	m	Inferred from local O&G well data [4] and BGS datasets [6], and publications [7][28][29][30][31][32][33]. Applied +/- 20% error margin for min/max
Aquifer top at producer	1,800	2000	2,200	m TVD	Inferred from local O&G well data [4] and BGS datasets [6], and publications [7][28][29][30][31][32][33]. Located at 10m from base of aquifer. Applied +/- 10% error margin for min/max
Aquifer top at injector	1,530	1700	1,870	m TVD	Inferred from local O&G well data [4] and BGS datasets [6], and publications [7][28][29][30][31][32][33]. Located at 10m from top of aquifer. Applied +/- 10% error margin for min/max
Aquifer water salinity	50,000	80,000	150,000	ppm	
Aquifer net transmissivity	-			Dm	
Aquifer kh/kv ratio	0.5			-	Inferred to be 50% anisotropic.
Surface temperature	9			°C	Based on published data for the UK [8]
Geothermal gradient	0.0305			°C/m	Inferred from publications [9]
Mid Aquifer temperature producer	-			°C	
Initial aquifer pressure at producer	-			Bar	
Initial aquifer pressure at injector	-			Bar	
Heat capacity rock matrix at 20°C	1,000			$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix	2,500			kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix	2.5			$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix	0.0000011			m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation	-			-	

Parameter	Value			Units	Comment
	Min	Ave	Max		
Doublet and pump properties					
Exit temperature heat exchanger	40.0			°C	
Output temperature from wells	74.6			°C	
Delta T across doublet	34.6			°C	
Distance wells at aquifer level	2,000			m	
Pump system efficiency	0.6			-	
Production pump depth	300			m	
Pump pressure difference	30			bar	
Cooling as fraction of initial	0.1			ΔT	
Yearly full operational hours	6,000			Hours	
Well properties					
Calculation length subdivision	50			m	
Producer					
Outer diameter producer	7			Inch	
Skin producer	2			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
Injector					
Outer diameter producer	7			Inch	
Skin producer	0.5			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
General					
Segment	1			-	
Pipe segment sections	2,000 (Prod), 1,700 (Reinj)			mAH	
Pipe segment depth	2,000 (Prod), 1,700 (Reinj)			m TVD	
Pipe inner diameter	6			Inch	
Pipe roughness	1.38			milli-inch	

Table 24: Inputs for the Knox Pulpit Formation

Parameter	Value			Units	Comment / Reference
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	0.01	40	100	mDarcey	Permeability data has been inferred from and published literature [3]
Aquifer porosity	0.05	0.15	0.25	-	Porosity inferred from published literature [34]
Aquifer net to gross	0.5	0.6	0.8	-	Entire aquifer inferred to have geothermally contributing layers. Insufficient data to suggest otherwise
Aquifer gross thickness	120	150	180	m	Inferred from local O&G well data [4] and BGS datasets [6], and publications [7]. Applied +/- 20% error margin for min/max
Aquifer top at producer	1,935	2,150	2,365	m TVD	Inferred from local O&G well data [4] and BGS datasets [6], and publications [7] [28][29][30][31][32]. Located at 10m from base of aquifer. Applied +/- 10% error margin for min/max
Aquifer top at injector	1,800	2,000	2,200	m TVD	Inferred from local O&G well data [4] and BGS datasets [6], and publications [7] [28][29][30][31][32]. Located at 10m from top of aquifer. Applied +/- 10% error margin for min/max
Aquifer water salinity	50,000	80,000	150,000	ppm	Generic range
Aquifer net transmissivity	-			Dm	
Aquifer kh/kv ratio	0.5			-	Inferred to be 50% anisotropic.
Surface temperature	9			°C	Based on published data for the UK [8]
Geothermal gradient	0.0305			°C/m	Inferred from publications [9]
Mid Aquifer temperature producer	-			°C	
Initial aquifer pressure at producer	-			Bar	
Initial aquifer pressure at injector	-			Bar	
Heat capacity rock matrix at 20°C	1,000			$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix	2,500			kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix	2.5			$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix	0.0000011			m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation	-			-	
Doublet and pump properties					
Exit temperature heat exchanger	45			°C	

Parameter	Value			Units	Comment / Reference
	Min	Ave	Max		
Output temperature (ºC)	76.9			°C	
Delta T (ºC)	31.9				
Distance wells at aquifer level	2,000			m	
Pump system efficiency	0.6			-	Generic assumption
Production pump depth	300			m	Generic assumption
Pump pressure difference	30			bar	Generic assumption
Cooling as fraction of initial	0.1			dT	
Yearly full operational hours	6,000			Hours	
Well properties					
Calculation length subdivision	50			m	
Producer					
Outer diameter producer	7			Inch	
Skin producer	2			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
Injector					
Outer diameter producer	7			Inch	
Skin producer	0.5			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
General					
Segment	1			-	
Pipe segment sections	2,150 (Prod), 2,000 (Reinj)			mAH	
Pipe segment depth	2,150 (Prod), 2,000 (Reinj)			m TVD	
Pipe inner diameter	6			Inch	
Pipe roughness	1.38			milli-inch	Default

A.6.2 Doublet Calc Outputs

Kinnesswood Fm.

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	1	50	100
aquifer porosity (-)	0.03	0.15	0.25
aquifer net to gross (-)	0.5	0.6	0.8
aquifer gross thickness (m)	240	300	360
aquifer top at producer (m TVD)	1800	2000	2200
aquifer top at injector (m TVD)	1530	1700	1870
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

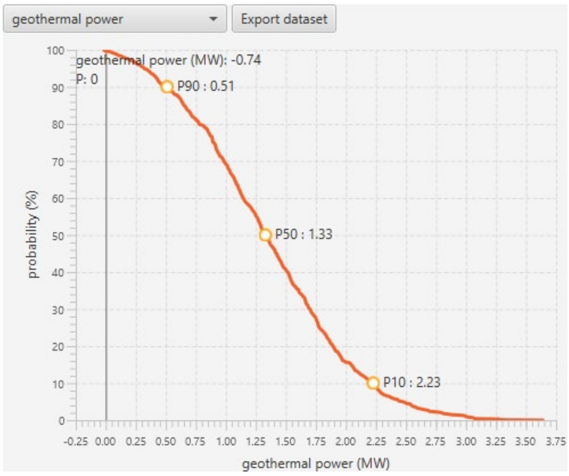
Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	9
geothermal gradient (°C/m)	0.0305
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	1000
density rock matrix (kg/m³)	2500
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	40
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	2000
pipe segment depth (m TVD)	2000
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	1700
pipe segment depth (m TVD)	1700
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	4.16	9.2	14.32
mass flow (kg/s)	5.52	11.96	18.35
pump volume flow (m³/h)	18.9	41.5	63.4
required pump power (kW)	26.2	57.6	88.1
geothermal power (MW)	0.51	1.33	2.23
COP (kW/kW)	18.5	23	26.1
doublet life time (years)	2581.2	3899.6	8394.2
doublet power over life time (PJ)	124.08	162.88	197.38
heat capacity rock matrix (J/Kg/K)	1087.4	1098.2	1105.7
aquifer pressure at producer (bar)	190.34	201.73	213.67
aquifer pressure at injector (bar)	161.78	171.34	181.05
pressure difference at producer (bar)	13.3	13.73	14.08
pressure difference at injector (bar)	17.23	17.87	18.44
aquifer temperature at producer * (°C)	71.18	74.5	78.04
temperature at heat exchanger (°C)	63.54	69.15	73.11
pressure at heat exchanger (bar)	11.06	13.81	15.15

base case (median value input)	value
aquifer kH net (Dm)	9
mass flow (kg/s)	11.9
pump volume flow (m³/h)	41.3
required pump power (kW)	57.4
geothermal power (MW)	1.35
COP (kW/kW)	23.4
doublet life time (years)	3945.9
doublet power over life time (PJ)	167.58
heat capacity rock matrix (J/Kg/K)	1099.1
aquifer pressure at producer (bar)	201.58
aquifer pressure at injector (bar)	170.97
pressure difference at producer (bar)	13.77
pressure difference at injector (bar)	17.91
aquifer temperature at producer * (°C)	74.57
temperature at heat exchanger (°C)	69.62
pressure at heat exchanger (bar)	13.91

* @ mid aquifer depth



Knox Pulpit Fm.

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	0	40	100
aquifer porosity (-)	0.05	0.15	0.25
aquifer net to gross (-)	0.5	0.6	0.8
aquifer gross thickness (m)	120	150	180
aquifer top at producer (m TVD)	1935	2150	2365
aquifer top at injector (m TVD)	1800	2000	2200
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

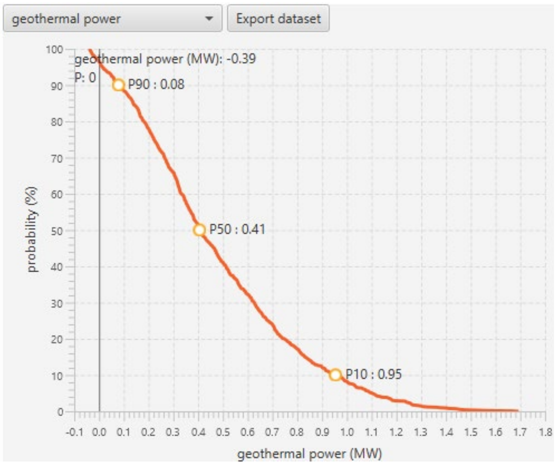
Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	9
geothermal gradient (°C/m)	0.0305
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	1000
density rock matrix (kg/m³)	2500
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	45
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	2150
pipe segment depth (m TVD)	2150
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	2000
pipe segment depth (m TVD)	2000
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	1.63	3.73	6.83
mass flow (kg/s)	2.31	5.31	9.64
pump volume flow (m³/h)	7.9	18.4	33.5
required pump power (kW)	11	25.6	46.5
geothermal power (MW)	0.08	0.41	0.95
COP (kW/kW)	7.2	16.2	20.8
doublet life time (years)	2410.2	4431.3	10169.3
doublet power over life time (PJ)	24.22	57.19	77.34
heat capacity rock matrix (J/Kg/K)	1068.8	1091.2	1102.3
aquifer pressure at producer (bar)	204.6	216.76	229.51
aquifer pressure at injector (bar)	190.44	201.65	213.19
pressure difference at producer (bar)	13.98	14.23	14.53
pressure difference at injector (bar)	17.75	18.24	18.72
aquifer temperature at producer * (°C)	73.2	76.85	80.48
temperature at heat exchanger (°C)	54.1	65.5	71.32
pressure at heat exchanger (bar)	10.28	13.23	14.74

base case (median value input)	value
aquifer kH net (Dm)	3.6
mass flow (kg/s)	5.19
pump volume flow (m³/h)	18
required pump power (kW)	25
geothermal power (MW)	0.41
COP (kW/kW)	16.2
doublet life time (years)	4481.4
doublet power over life time (PJ)	57.42
heat capacity rock matrix (J/Kg/K)	1091.1
aquifer pressure at producer (bar)	216.49
aquifer pressure at injector (bar)	201.19
pressure difference at producer (bar)	14.26
pressure difference at injector (bar)	18.32
aquifer temperature at producer * (°C)	76.86
temperature at heat exchanger (°C)	65.48
pressure at heat exchanger (bar)	13.4

* @ mid aquifer depth



A.7 Northern Ireland Sedimentary Basin (Lough Neagh Basin, Antrim)

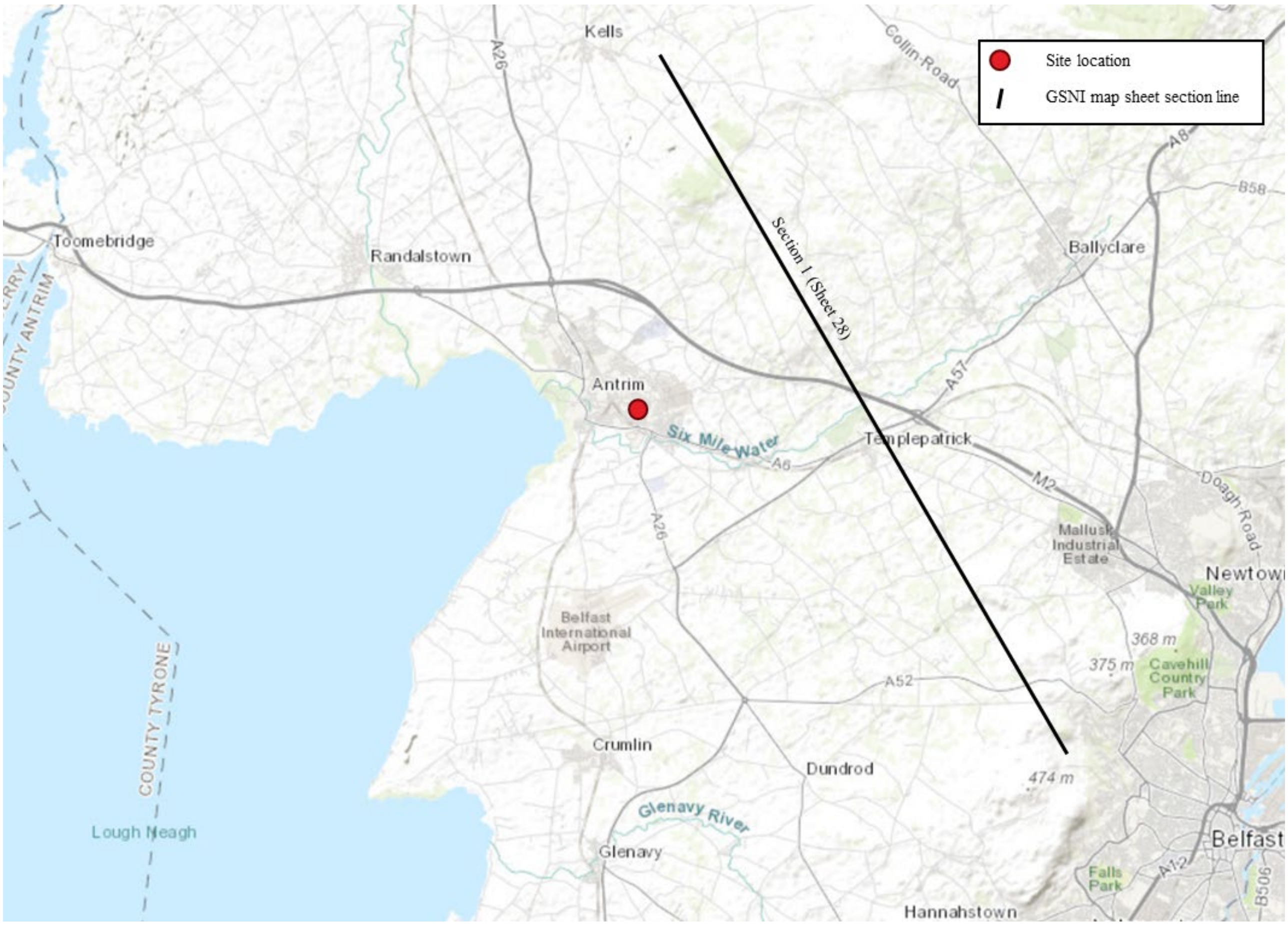


Figure 15: Site location and local data

Table 25: Geological summary

Parameter	Value
Geothermal gradient	Between 30 to 34 °C/km
Potential deep geothermal reservoirs	Sherwood Sandstone Group – Principal – 2000 to 2650m depth
	Lower Permian Sandstones – Principal – 2900 to 3200m depth

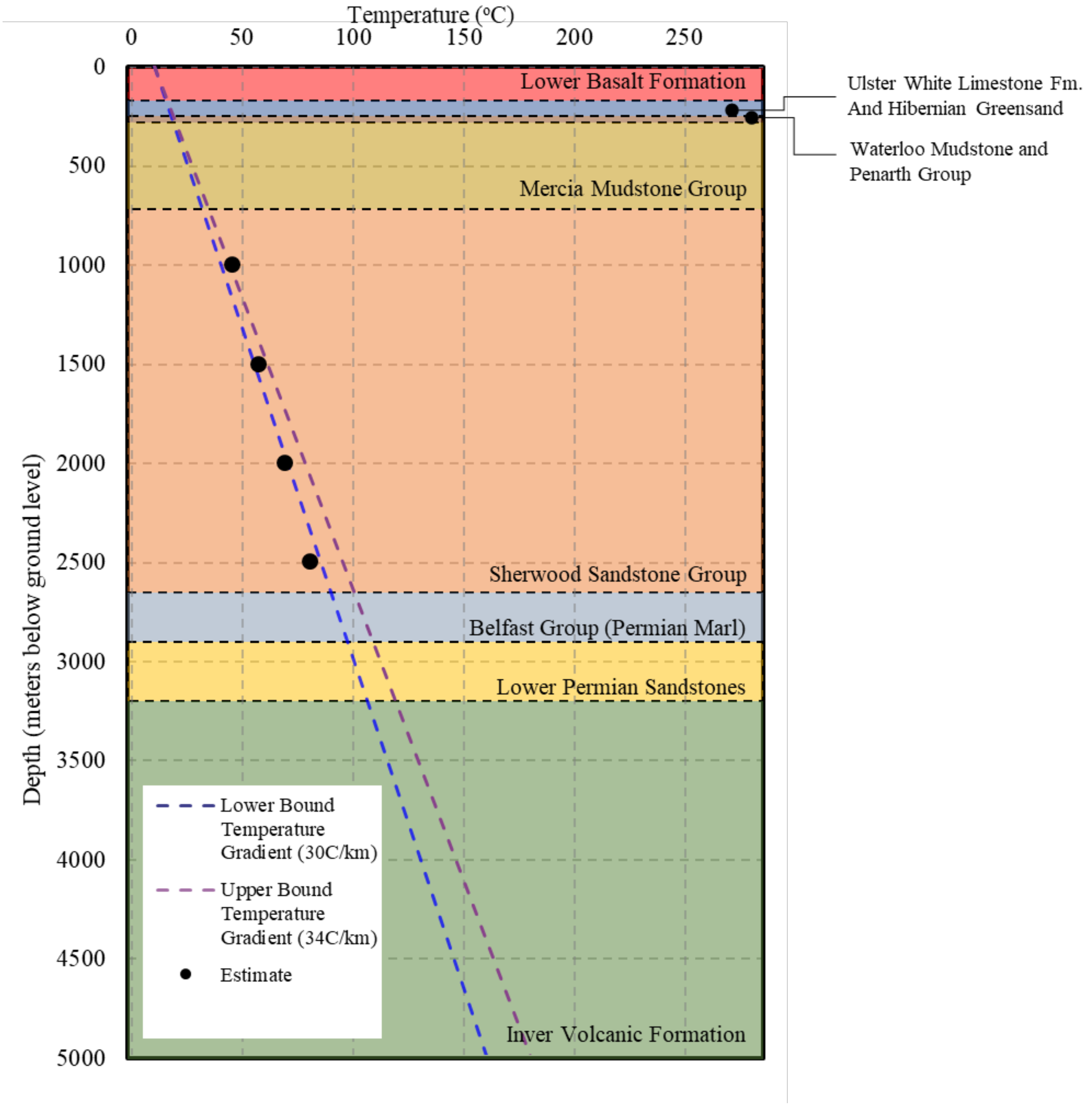


Figure 16: Inferred ground model and geothermal gradient

Table 26: Inferred ground model

Aquifer	Formation	Period	Lithology	Depth to top (mbgl)	Depth to base (mbgl)	Thickness (m)	Temperature Range (base) (°C)	Aquifer condition	Estimated hydraulic conductivity*	
									m/s	mD
Unclassified	Glacial Till	Tertiary	Clays, sands, and conglomerates	0	5	5	10.1	-		
Unclassified	Lower Basalt Formation	Tertiary	Volcanics, pyroclastics and terrestrial sediments	5	170	165	15.1 to 15.8	Predominantly fracture-moderately productive		
Unclassified	Ulster White Limestone Fm. And Hibernian Greensand	Cretaceous	Chalks and glauconitic sandstones	170	250	80	17.5 to 18.5	-		
Secondary U	Waterloo Mudstone and Penarth Group	Jurassic	Calcareous mudstone and thin limestones	250	280	30	18.4 to 19.5	Essentially no groundwater		
Secondary B	Mercia Mudstone Group	Triassic	Mudstones and thick evaporites	280	720	440	31.6 to 34.5	Predominantly fracture-low productivity		
Principal	Sherwood Sandstone Group	Triassic	Fluvial and aeolian sandstones	2200**	2650	450	89.5 to 100.1	Significant intergranular-highly productive		
Unclassified	Belfast Group (Permean Marl)	Permian	Mudstone, evaporites, Magnesian Limestone	2650	2900	250	97 to 108.6	-		
Principal	Lower Permian Sandstones	Permian	Sandstone	2900	3200	300	106 to 118.8	Significant intergranular-highly productive		
Unclassified	Inver Volcanic Formation	Permian	Basaltic to trachytic volcanics and tuffaceous siltstones. Sandstone/conglomerate unit at base	3200	Unknown	Unknown	N/A	-		

* Estimated permeabilities based on published data sources
**There remains significant uncertainty with the depth to the target reservoirs [18][36]

Highlighted	Key aquifers beneath the Site which have potential for GSHP or geothermal

A.7.1 Doublet Calc Inputs

Table 27: Inputs for the Sherwood Sandstone Group

Parameter	Value			Units	Comment
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	1	150	400	mDarcey	Permeability data has been inferred from and published literature [18][35][37][38]
Aquifer porosity	0.05	0.25	0.3	-	Porosity inferred from published literature [18][35][37][38]
Aquifer net to gross	0.99	1	1.01	-	Entire aquifer inferred to have geothermally contributing layers. Insufficient data to suggest otherwise
Aquifer gross thickness	360	450	540	m	Inferred from published data [18][35][37][38] Applied +/- 20% error margin for min/max
Aquifer top at producer	2,385	2,650	2,915	m TVD	Inferred from published data [18][35][37][38]. Located at 10m from base of aquifer. Applied +/- 10% error margin for min/max
Aquifer top at injector	1,980	2,200	2,420	m TVD	Inferred from published data [18][35][37][38]. Located at 10m from top of aquifer. Applied +/- 10% error margin for min/max
Aquifer water salinity	50,000	80,000	150,000	ppm	
Aquifer net transmissivity	-			Dm	
Aquifer kh/kv ratio	0.5			-	Inferred to be 50% anisotropic.
Surface temperature	10			°C	Based on published data for the UK [8]
Geothermal gradient	0.032			°C/m	Inferred from publications [9]
Mid Aquifer temperature producer	-			°C	
Initial aquifer pressure at producer	-			Bar	
Initial aquifer pressure at injector	-			Bar	
Heat capacity rock matrix at 20°C	930			$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix	2,500			kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix	2.5			$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix	0.0000013			m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation	-			-	
Doublet and pump properties					

Parameter	Value			Units	Comment
	Min	Ave	Max		
Exit temperature heat exchanger	60.0			°C	
Output temperature from wells	102.0			°C	
Delta T across doublet	42.0			°C	
Distance wells at aquifer level	2,000			m	
Pump system efficiency	0.6			-	
Production pump depth	300			m	
Pump pressure difference	30			bar	
Cooling as fraction of initial	0.1			ΔT	
Yearly full operational hours	6,000			Hours	
Well properties					
Calculation length subdivision	50			m	
Producer					
Outer diameter producer	8			Inch	
Skin producer	0			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
Injector					
Outer diameter producer	8			Inch	
Skin producer	0			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
General					
Segment	1			-	
Pipe segment sections	2,650 (Prod), 2,200 (Reinj)			mAH	
Pipe segment depth	2,650 (Prod), 2,200 (Reinj)			m TVD	
Pipe inner diameter	7			Inch	
Pipe roughness	1.2			milli-inch	

Table 28: Inputs for the Lower Permian Sandstones

Parameter	Value			Units	Comment
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	1	100	400	mDarcey	Permeability data has been inferred from and published literature Inferred from published data from published data [18][35][37][38].
Aquifer porosity	0.06	0.25	0.27	-	Porosity inferred from published literature [18][35][37][38]
Aquifer net to gross	0.99	1	1.01	-	Entire aquifer inferred to have geothermally contributing layers. Insufficient data to suggest otherwise
Aquifer gross thickness	240	300	360	m	Inferred from published data from published data [35][37][38]. Applied +/- 20% error margin for min/max
Aquifer top at producer	2,880	3,200	3,520	m TVD	Inferred from Inferred from published data from published data [35][37][38]. Located at 10m from base of aquifer. Applied +/- 10% error margin for min/max
Aquifer top at injector	2,610	2,900	3,190	m TVD	Inferred from Inferred from published data from published data [35][37][38]. Located at 10m from top of aquifer. Applied +/- 10% error margin for min/max
Aquifer water salinity	50,000	80,000	150,000	ppm	General assumption
Aquifer net transmissivity	-			Dm	
Aquifer kh/kv ratio	0.5			-	Inferred to be 50% anisotropic.
Surface temperature	10.1			°C	Based on published data for the UK [8]
Geothermal gradient	0.0325			°C/m	Inferred from publications [9]
Mid Aquifer temperature producer	-			°C	
Initial aquifer pressure at producer	-			Bar	
Initial aquifer pressure at injector	-			Bar	
Heat capacity rock matrix at 20°C	930			$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix	2,500			kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix	2.5			$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix	0.0000013			m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation	-			-	
Doublet and pump properties					
Exit temperature heat exchanger	70.0			°C	

Parameter	Value			Units	Comment
	Min	Ave	Max		
Output temperature from wells	117.2			°C	
Delta T across doublet	47.2			°C	
Distance wells at aquifer level	2,000			m	
Pump system efficiency	0.6			-	
Production pump depth	300			m	
Pump pressure difference	30			bar	
Cooling as fraction of initial	0.1			ΔT	
Yearly full operational hours	6,000			Hours	
Well properties					
Calculation length subdivision	50			m	
Producer					
Outer diameter producer	8			Inch	
Skin producer	0			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
Injector					
Outer diameter producer	8			Inch	
Skin producer	0			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
General					
Segment	1			-	
Pipe segment sections	3,200 (Prod), 2,900 (Reinj)			mAH	
Pipe segment depth	3,200 (Prod), 2,900 (Reinj)			m TVD	
Pipe inner diameter	7			Inch	
Pipe roughness	1.2			milli-inch	

A.7.2 Doublet Calc Outputs

Sherwood Sandstone

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	1	100	300
aquifer porosity (-)	0.06	0.25	0.27
aquifer net to gross (-)	0.5	0.6	0.8
aquifer gross thickness (m)	240	300	360
aquifer top at producer (m TVD)	2880	3200	3520
aquifer top at injector (m TVD)	2610	2900	3190
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	10
geothermal gradient (°C/m)	0.032
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	1000
density rock matrix (kg/m^3)	2500
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	70
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	3200
pipe segment depth (m TVD)	3200
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	2900
pipe segment depth (m TVD)	2900
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

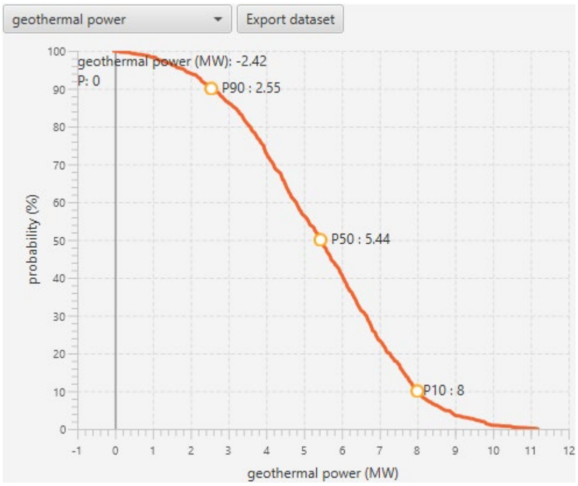
Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	8.16	18.85	38.86
mass flow (kg/s)	17.77	33.33	46.79
pump volume flow (m^3/h)	62.6	118.3	166.5
required pump power (kW)	86.9	164.3	231.2
geothermal power (MW)	2.55	5.44	8
COP (kW/kW)	27.7	32.8	37.2
doublet life time (years)	1091.5	1529.7	2875.2
doublet power over life time (PJ)	207.62	259.04	309.96
heat capacity rock matrix (J/Kg/K)	1164.7	1175.9	1185.9

aquifer pressure at producer (bar)	301.73	319.87	339.05
aquifer pressure at injector (bar)	273.75	290.37	306.3
pressure difference at producer (bar)	8.22	12.15	14.94
pressure difference at injector (bar)	11	16.5	20.43
aquifer temperature at producer * (°C)	111.56	117.2	122.98
temperature at heat exchanger (°C)	105.63	112.2	118.12
pressure at heat exchanger (bar)	9.83	14.01	16.25

base case (median value input)	value
aquifer kH net (Dm)	18
mass flow (kg/s)	32.54
pump volume flow (m^3/h)	116
required pump power (kW)	161.1
geothermal power (MW)	5.34
COP (kW/kW)	33.1
doublet life time (years)	1573.6
doublet power over life time (PJ)	265.2
heat capacity rock matrix (J/Kg/K)	1176.6

aquifer pressure at producer (bar)	319.45
aquifer pressure at injector (bar)	289.41
pressure difference at producer (bar)	12.29
pressure difference at injector (bar)	16.61
aquifer temperature at producer * (°C)	117.2
temperature at heat exchanger (°C)	112.62
pressure at heat exchanger (bar)	14.37

* @ mid aquifer depth



Lower Permian

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	1	150	400
aquifer porosity (-)	0.05	0.25	0.3
aquifer net to gross (-)	0.5	0.6	0.8
aquifer gross thickness (m)	360	450	540
aquifer top at producer (m TVD)	2385	2650	2915
aquifer top at injector (m TVD)	1980	2200	2420
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	10
geothermal gradient (°C/m)	0.032
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	1000
density rock matrix (kg/m^3)	2500
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	60
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	2650
pipe segment depth (m TVD)	2650
pipe inner diameter (inch)	66
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	2200
pipe segment depth (m TVD)	2200
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

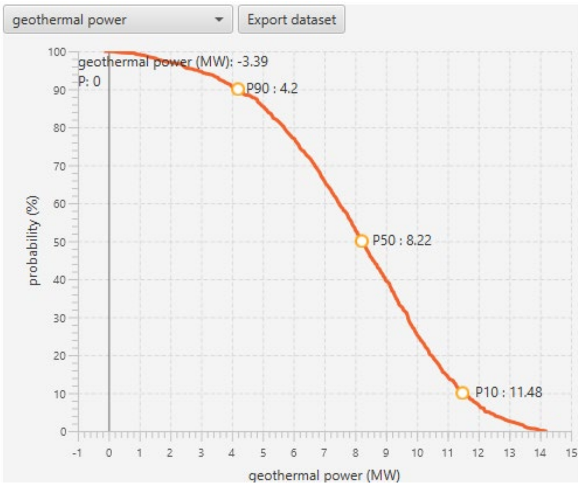
Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	18.44	41.91	79.2
mass flow (kg/s)	31.86	56.96	75.99
pump volume flow (m^3/h)	111.4	200	267.4
required pump power (kW)	154.8	277.8	371.4
geothermal power (MW)	4.2	8.22	11.48
COP (kW/kW)	25.3	29.4	33.2
doublet life time (years)	987	1337.7	2341.8
doublet power over life time (PJ)	275.02	340.84	406.51
heat capacity rock matrix (J/Kg/K)	1141.3	1150.7	1159.4

aquifer pressure at producer (bar)	250.99	266.21	281.57
aquifer pressure at injector (bar)	208.63	220.48	233.21
pressure difference at producer (bar)	7.64	10.92	13.82
pressure difference at injector (bar)	9.84	14.18	17.99
aquifer temperature at producer * (°C)	97.34	101.94	106.7
temperature at heat exchanger (°C)	92.4	97.67	102.6
pressure at heat exchanger (bar)	14.32	18.64	22.78

base case (median value input)	value
aquifer kH net (Dm)	40.5
mass flow (kg/s)	55.93
pump volume flow (m^3/h)	197.4
required pump power (kW)	274.2
geothermal power (MW)	8.17
COP (kW/kW)	29.8
doublet life time (years)	1353.6
doublet power over life time (PJ)	349.14
heat capacity rock matrix (J/Kg/K)	1151.5

aquifer pressure at producer (bar)	265.63
aquifer pressure at injector (bar)	220.19
pressure difference at producer (bar)	11.03
pressure difference at injector (bar)	14.27
aquifer temperature at producer * (°C)	102
temperature at heat exchanger (°C)	98.09
pressure at heat exchanger (bar)	18.98

* @ mid aquifer depth



A.8 Cornish Granites

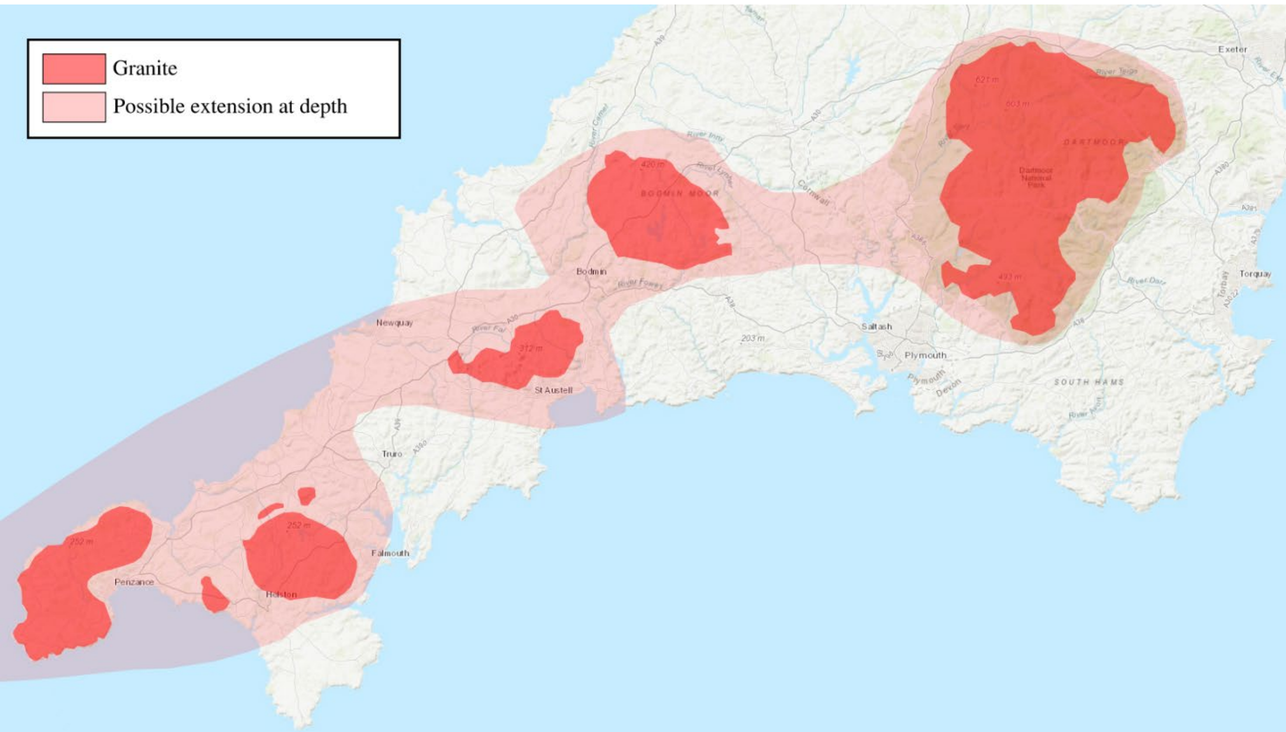


Figure 17: Inferred extent of Cornish granites [19]

Table 29: Geological summary

Parameter	Value
Geothermal gradient	Between 33 to 35 °C/km
Potential deep geothermal reservoirs	Cornwall granite – Unclassified – 4000m depth
	Cornwall granite – Unclassified – 5000m depth

A.8.1 Doublet Calc Inputs

Table 30: Inputs for the Granite 4km

Parameter	Value			Units	Comment
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	1	150	5,000	mDarcey	Permeability data has been inferred – professional judgement
Aquifer porosity	0	0.005	0.01	-	Porosity inferred – professional judgement
Aquifer net to gross	0.1	0.4	0.8	-	Entire aquifer inferred to have geothermally contributing layers. Insufficient data to suggest otherwise
Aquifer gross thickness	400	500	600	m	Inferred. Applied +/- 20% error margin for min/max
Aquifer top at producer	3,600	4,000	4,400	m TVD	Inferred. Applied +/- 10% error margin for min/max
Aquifer top at injector	3,600	4,000	4,400	m TVD	Inferred. Applied +/- 10% error margin for min/max
Aquifer water salinity	50,000	80,000	150,000	ppm	
Aquifer net transmissivity	-			Dm	
Aquifer kh/kv ratio	0.5			-	Inferred to be 50% anisotropic.
Surface temperature	9			°C	Based on published data for the UK [8]
Geothermal gradient	0.0305			°C/m	Inferred from publications [9]
Mid Aquifer temperature producer	-			°C	
Initial aquifer pressure at producer	-			Bar	
Initial aquifer pressure at injector	-			Bar	
Heat capacity rock matrix at 20°C	900			$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix	2,400			kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix	2.8			$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix	0.0000012			m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation	-			-	
Doublet and pump properties					
Exit temperature heat exchanger	80.0			°C	
Output temperature from wells	145.0			°C	
Delta T across doublet	65.0			°C	

Parameter	Value			Units	Comment
	Min	Ave	Max		
Distance wells at aquifer level	2,000			m	
Pump system efficiency	0.6			-	
Production pump depth	300			m	
Pump pressure difference	30			bar	
Cooling as fraction of initial	0.1			ΔT	
Yearly full operational hours	6,000			Hours	
Well properties					
Calculation length subdivision	50			m	
Producer					
Outer diameter producer	7			Inch	
Skin producer	2			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
Injector					
Outer diameter producer	7			Inch	
Skin producer	0.5			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
General					
Segment	1			-	
Pipe segment sections	4,000 (Prod), 4,000 (Reinj)			mAH	
Pipe segment depth	4,000 (Prod), 4,000 (Reinj)			m TVD	
Pipe inner diameter	6			Inch	
Pipe roughness	1.38			milli-inch	

Table 31: Inputs for the Granite 5km

Parameter	Value			Units	Comment / Reference
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	1	150	5,000	mDarcey	Permeability data has been inferred – professional judgement
Aquifer porosity	0	0.005	0.01	-	Porosity inferred – professional judgement
Aquifer net to gross	0.1	0.4	0.8	-	Entire aquifer inferred to have geothermally contributing layers. Insufficient data to suggest otherwise
Aquifer gross thickness	320	400	480	m	Inferred. Applied +/- 20% error margin for min/max
Aquifer top at producer	4,500	5,000	5,500	m TVD	Inferred. Applied +/- 10% error margin for min/max
Aquifer top at injector	4,500	5,000	5,500	m TVD	Inferred. Applied +/- 10% error margin for min/max
Aquifer water salinity	50,000	80,000	150,000	ppm	Generic range
Aquifer net transmissivity	-			Dm	
Aquifer kh/kv ratio	0.5			-	Inferred to be 50% anisotropic.
Surface temperature	9			°C	Based on published data for the UK [8]
Geothermal gradient	0.034			°C/m	Inferred from publications [9]
Mid Aquifer temperature producer	-			°C	
Initial aquifer pressure at producer	-			Bar	
Initial aquifer pressure at injector	-			Bar	
Heat capacity rock matrix at 20°C	900			$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix	2,600			kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix	2.8			$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix	0.0000012			m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation	-			-	
Doublet and pump properties					
Exit temperature heat exchanger	100.0			°C	
Output temperature (°C)	180			°C	Not a DoubletCalc input - but useful for reporting ((Geothermal grad * midpoint of aquifer) + surface temp)
Delta T (°C)	80				Not a DoubletCalc input - but useful for reporting (output - reinject temp)

Parameter	Value			Units	Comment / Reference
	Min	Ave	Max		
Distance wells at aquifer level	2,000			m	
Pump system efficiency	0.6			-	Generic assumption
Production pump depth	300			m	Generic assumption
Pump pressure difference	30			bar	Generic assumption
Cooling as fraction of initial	0.1			dT	
Yearly full operational hours	6,000			Hours	
Well properties					
Calculation length subdivision	50			m	
Producer					
Outer diameter producer	7			Inch	
Skin producer	2			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
Injector					
Outer diameter producer	7			Inch	
Skin producer	0.5			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
General					
Segment	1			-	
Pipe segment sections	5,000 (Prod), 5,000 (Reinj)			mAH	
Pipe segment depth	5,000 (Prod), 5,000 (Reinj)			m TVD	
Pipe inner diameter	6			Inch	
Pipe roughness	1.38			milli-inch	Default

A.8.2 Doublet Calc Outputs

Cornish granite – 4km

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	1	200	5000
aquifer porosity (-)	0	0.01	0.01
aquifer net to gross (-)	0.1	0.4	0.8
aquifer gross thickness (m)	400	500	550
aquifer top at producer (m TVD)	3600	4000	4400
aquifer top at injector (m TVD)	3600	4000	4400
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

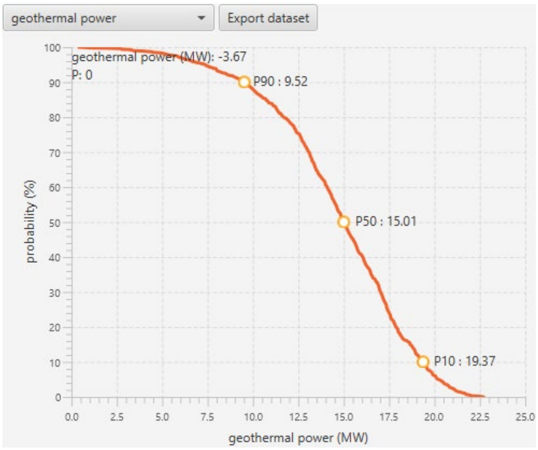
Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	10
geothermal gradient (°C/m)	0.034
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	900
density rock matrix (kg/m³)	2600
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	80
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	4000
pipe segment depth (m TVD)	4000
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	4000
pipe segment depth (m TVD)	4000
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	14.78	52.96	588.06
mass flow (kg/s)	37.36	56.55	66.2
pump volume flow (m³/h)	135.5	206.3	243.5
required pump power (kW)	188.2	286.5	338.2
geothermal power (MW)	9.52	15.01	19.37
COP (kW/kW)	46.9	52.9	58.8
doublet life time (years)	1141	1368.3	2083.9
doublet power over life time (PJ)	556.4	659.11	759.33
heat capacity rock matrix (J/Kg/K)	1101.1	1112	1122.3
aquifer pressure at producer (bar)	374.27	396.39	419.41
aquifer pressure at injector (bar)	374.31	396.39	418.33
pressure difference at producer (bar)	0.61	5.63	13.63
pressure difference at injector (bar)	0.93	8.51	21.21
aquifer temperature at producer * (°C)	147.03	154.31	161.94
temperature at heat exchanger (°C)	141.39	149.24	156.81
pressure at heat exchanger (bar)	9.71	14.98	18.34

base case (median value input)	value
aquifer kH net (Dm)	40
mass flow (kg/s)	53.43
pump volume flow (m³/h)	196.3
required pump power (kW)	272.6
geothermal power (MW)	14.55
COP (kW/kW)	53.4
doublet life time (years)	1468.9
doublet power over life time (PJ)	674.21
heat capacity rock matrix (J/Kg/K)	1112.5
aquifer pressure at producer (bar)	395.69
aquifer pressure at injector (bar)	395.69
pressure difference at producer (bar)	7.07
pressure difference at injector (bar)	10.83
aquifer temperature at producer * (°C)	154.5
temperature at heat exchanger (°C)	149.57
pressure at heat exchanger (bar)	15.78

* @ mid aquifer depth



Cornish granite – 5km

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	1	150	5000
aquifer porosity (-)	0	0.01	0.01
aquifer net to gross (-)	0.1	0.4	0.8
aquifer gross thickness (m)	320	400	480
aquifer top at producer (m TVD)	4500	5000	5500
aquifer top at injector (m TVD)	4500	5000	5500
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

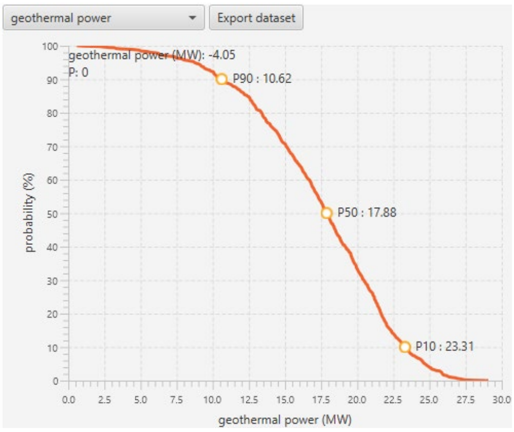
Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	10
geothermal gradient (°C/m)	0.034
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	900
density rock matrix (kg/m³)	2600
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	100
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	5000
pipe segment depth (m TVD)	5000
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	5000
pipe segment depth (m TVD)	5000
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	9.03	33.92	491.15
mass flow (kg/s)	36.37	56.79	67.22
pump volume flow (m³/h)	135	215.7	255.2
required pump power (kW)	187.5	299.6	354.5
geothermal power (MW)	10.62	17.88	23.31
COP (kW/kW)	53.3	60.9	68.3
doublet life time (years)	941.2	1147.7	1782.5
doublet power over life time (PJ)	534.97	649.48	783.95
heat capacity rock matrix (J/Kg/K)	1139.8	1152.1	1164.2
aquifer pressure at producer (bar)	462.7	490.58	518.02
aquifer pressure at injector (bar)	463.51	490.2	518.09
pressure difference at producer (bar)	0.6	7.43	17.93
pressure difference at injector (bar)	0.92	11.22	26.93
aquifer temperature at producer * (°C)	177.42	186.8	196.28
temperature at heat exchanger (°C)	170.19	179.87	189.69
pressure at heat exchanger (bar)	11.95	18.73	23.66

base case (median value input)	value
aquifer kH net (Dm)	24
mass flow (kg/s)	52.83
pump volume flow (m³/h)	200
required pump power (kW)	277.7
geothermal power (MW)	16.97
COP (kW/kW)	61.1
doublet life time (years)	1223.7
doublet power over life time (PJ)	655.24
heat capacity rock matrix (J/Kg/K)	1152.4
aquifer pressure at producer (bar)	489.47
aquifer pressure at injector (bar)	489.47
pressure difference at producer (bar)	9.66
pressure difference at injector (bar)	14.58
aquifer temperature at producer * (°C)	186.8
temperature at heat exchanger (°C)	180.11
pressure at heat exchanger (bar)	20.04

* @ mid aquifer depth



A.9 North Scotland Granites (Aberdeen)

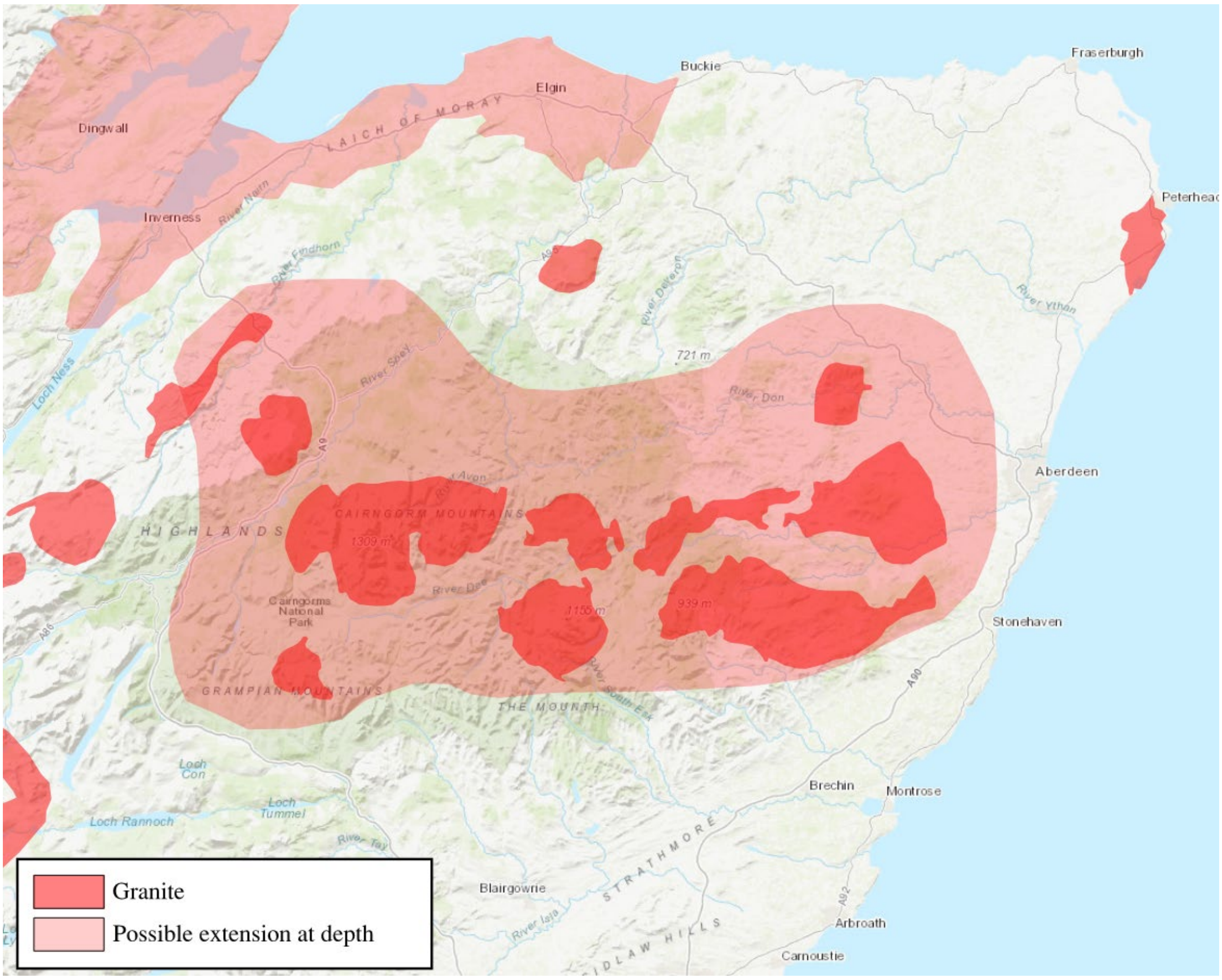


Figure 18: Inferred extent of Scottish granites [4][20]

Table 32: Geological summary

Parameter	Value
Geothermal gradient	Between 28 to 32 °C/km
Potential deep geothermal reservoirs	Scottish granite – Unclassified – 4000m depth
	Scottish granite – Unclassified – 5000m depth

A.9.1 Doublet Calc Inputs

Table 33: Inputs for the Granite 4km

Parameter	Value			Units	Comment
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	1	100	5,000	mDarcey	Permeability data has been inferred – professional judgement
Aquifer porosity	0	0.005	0.01	-	Porosity inferred – professional judgement
Aquifer net to gross	0.99	1	1.01	-	Entire aquifer inferred to have geothermally contributing layers. Insufficient data to suggest otherwise
Aquifer gross thickness	400	500	600	m	Inferred. Applied +/- 20% error margin for min/max
Aquifer top at producer	3,600	4,000	4,400	m TVD	Inferred. Applied +/- 10% error margin for min/max
Aquifer top at injector	3,600	4,000	4,400	m TVD	Inferred. Applied +/- 10% error margin for min/max
Aquifer water salinity	50,000	80,000	150,000	ppm	
Aquifer net transmissivity	-			Dm	
Aquifer kh/kv ratio	0.5			-	Inferred to be 50% anisotropic.
Surface temperature	9			°C	Based on published data for the UK [8]
Geothermal gradient	0.0305			°C/m	Inferred from publications [9]
Mid Aquifer temperature producer	-			°C	
Initial aquifer pressure at producer	-			Bar	
Initial aquifer pressure at injector	-			Bar	
Heat capacity rock matrix at 20°C	900			$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix	2,600			kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix	2.8			$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix	0.0000012			m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation	-			-	
Doublet and pump properties					
Exit temperature heat exchanger	80.0			°C	
Output temperature from wells	131.0			°C	
Delta T across doublet	51.0			°C	

Parameter	Value			Units	Comment
	Min	Ave	Max		
Distance wells at aquifer level	2,000			m	
Pump system efficiency	0.6			-	
Production pump depth	300			m	
Pump pressure difference	30			bar	
Cooling as fraction of initial	0.1			ΔT	
Yearly full operational hours	6,000			Hours	
Well properties					
Calculation length subdivision	50			m	
Producer					
Outer diameter producer	7			Inch	
Skin producer	2			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
Injector					
Outer diameter producer	7			Inch	
Skin producer	0.5			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
General					
Segment	1			-	
Pipe segment sections	4,000 (Prod), 4,000 (Reinj)			mAH	
Pipe segment depth	4,000 (Prod), 4,000 (Reinj)			m TVD	
Pipe inner diameter	6			Inch	
Pipe roughness	1.38			milli-inch	

Table 34: Inputs for the Granite 5km

Parameter	Value			Units	Comment / Reference
	Min	Ave	Max		
Aquifer properties					
Aquifer permeability	1	100	5,000	mDarcey	Permeability data has been inferred – professional judgement
Aquifer porosity	0	0.005	0.01	-	Porosity inferred – professional judgement
Aquifer net to gross	0.1	0.3	0.6	-	Entire aquifer inferred to have geothermally contributing layers. Insufficient data to suggest otherwise
Aquifer gross thickness	320	400	480	m	Inferred. Applied +/- 20% error margin for min/max
Aquifer top at producer	4,500	5,000	5,500	m TVD	Inferred. Applied +/- 10% error margin for min/max
Aquifer top at injector	4,500	5,000	5,500	m TVD	Inferred. Applied +/- 10% error margin for min/max
Aquifer water salinity	50,000	80,000	150,000	ppm	Generic range
Aquifer net transmissivity	-			Dm	
Aquifer kh/kv ratio	0.5			-	Inferred to be 50% anisotropic.
Surface temperature	9			°C	Based on published data for the UK [8]
Geothermal gradient	0.0305			°C/m	Inferred from publications [9]
Mid Aquifer temperature producer	-			°C	
Initial aquifer pressure at producer	-			Bar	
Initial aquifer pressure at injector	-			Bar	
Heat capacity rock matrix at 20°C	900			$Jkg^{-1}K^{-1}$	Based on published data [10]
Density rock matrix	2,600			Kgm^{-3}	Based on published data [11]
Thermal conductivity rock matrix	2.8			$Wm^{-1}K$	Based on published data [12]
Thermal diffusivity rock matrix	0.0000012			m^2s^{-1}	Based on published data [13]
Use Kestin Viscosity correlation	-			-	
Doublet and pump properties					
Exit temperature heat exchanger	90.0			°C	
Output temperature (°C)	161.5			°C	
Delta T (°C)	71.5			°C	
Distance wells at aquifer level	2,000			m	

Parameter	Value			Units	Comment / Reference
	Min	Ave	Max		
Pump system efficiency	0.6			-	Generic assumption
Production pump depth	300			m	Generic assumption
Pump pressure difference	30			bar	Generic assumption
Cooling as fraction of initial	0.1			dT	
Yearly full operational hours	6,000			Hours	
Well properties					
Calculation length subdivision	50			m	
Producer					
Outer diameter producer	7			Inch	
Skin producer	2			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
Injector					
Outer diameter producer	7			Inch	
Skin producer	0.5			-	
Penetration angle producer	-			° Degrees	
Skin due to penetration angle	0			-	
Total skin producer	0			-	
General					
Segment	1			-	
Pipe segment sections	5,000 (Prod), 5,000 (Reinj)			mAH	
Pipe segment depth	5,000 (Prod), 5,000 (Reinj)			m TVD	
Pipe inner diameter	6			Inch	
Pipe roughness	1.38			milli-inch	Default

A.9.2 Doublet Calc Outputs

North Scottish granite – 4km

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	1	100	5000
aquifer porosity (-)	0	0.01	0.01
aquifer net to gross (-)	0.1	0.3	0.6
aquifer gross thickness (m)	400	500	600
aquifer top at producer (m TVD)	3600	4000	4400
aquifer top at injector (m TVD)	3600	4000	4400
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	10
geothermal gradient (°C/m)	0.0305
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	900
density rock matrix (kg/m^3)	2600
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	70
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	4000
pipe segment depth (m TVD)	4000
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	4000
pipe segment depth (m TVD)	4000
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

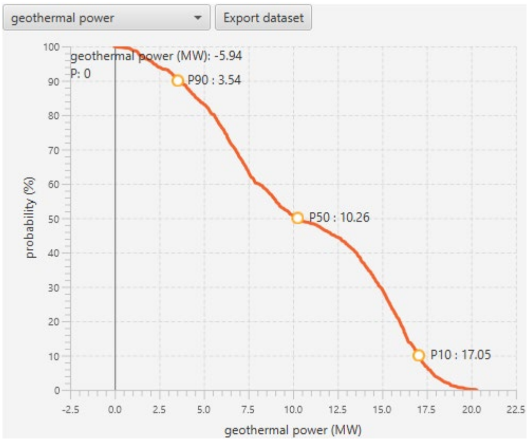
Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	5.88	21.87	448.71
mass flow (kg/s)	17.03	40.95	63.78
pump volume flow (m^3/h)	61.3	147.4	231.3
required pump power (kW)	85.1	204.7	321.3
geothermal power (MW)	3.54	10.26	17.05
COP (kW/kW)	40.6	48.4	54.3
doublet life time (years)	1172.4	1841.3	4239.1
doublet power over life time (PJ)	461.76	588.25	700.26
heat capacity rock matrix (J/Kg/K)	1074.4	1089	1100.3

aquifer pressure at producer (bar)	375.31	398.76	422.21
aquifer pressure at injector (bar)	375.82	398.29	420.13
pressure difference at producer (bar)	0.83	11.15	17.19
pressure difference at injector (bar)	1.27	16.98	26.33
aquifer temperature at producer * (°C)	132.93	139.64	146.56
temperature at heat exchanger (°C)	122.85	132.85	140.79
pressure at heat exchanger (bar)	8.68	13.79	18

base case (median value input)	value
aquifer kH net (Dm)	15
mass flow (kg/s)	34.44
pump volume flow (m^3/h)	124.7
required pump power (kW)	173.2
geothermal power (MW)	8.36
COP (kW/kW)	48.3
doublet life time (years)	2228.6
doublet power over life time (PJ)	587.99
heat capacity rock matrix (J/Kg/K)	1088.6

aquifer pressure at producer (bar)	397.42
aquifer pressure at injector (bar)	397.42
pressure difference at producer (bar)	13.35
pressure difference at injector (bar)	20.73
aquifer temperature at producer * (°C)	139.62
temperature at heat exchanger (°C)	132.59
pressure at heat exchanger (bar)	15.8

* @ mid aquifer depth



North Scottish granite – 5km

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	1	100	5000
aquifer porosity (-)	0	0.01	0.01
aquifer net to gross (-)	0.1	0.3	0.6
aquifer gross thickness (m)	320	400	480
aquifer top at producer (m TVD)	4500	5000	5500
aquifer top at injector (m TVD)	4500	5000	5500
aquifer water salinity (ppm)	50000	80000	150000
aquifer net transmissivity (Dm)	0	0	0

Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	0.5
surface temperature (°C)	10
geothermal gradient (°C/m)	0.0305
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	900
density rock matrix (kg/m^3)	2600
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	80
distance wells at aquifer level (m)	2000
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	7
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	5000
pipe segment depth (m TVD)	5000
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	7
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	5000
pipe segment depth (m TVD)	5000
pipe inner diameter (inch)	6
pipe roughness (milli-inch)	1.38

Geotechnical output

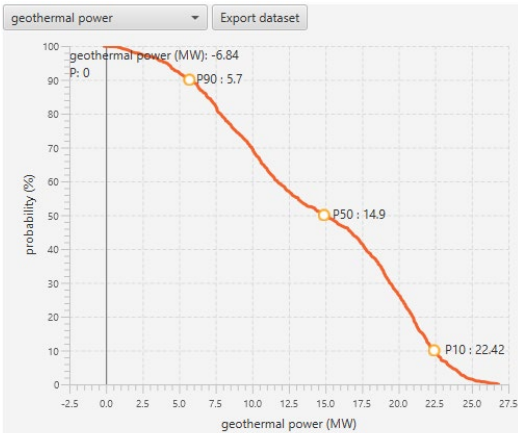
Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	4.73	18.41	343.17
mass flow (kg/s)	20.4	45.92	64.98
pump volume flow (m^3/h)	75.2	171.8	242.2
required pump power (kW)	104.5	238.7	336.4
geothermal power (MW)	5.7	14.9	22.42
COP (kW/kW)	52.7	60.9	68.1
doublet life time (years)	952.8	1393.6	3038.2
doublet power over life time (PJ)	507.96	627.39	753.56
heat capacity rock matrix (J/Kg/K)	1111.7	1126.3	1138.6

aquifer pressure at producer (bar)	465.6	493.41	522.77
aquifer pressure at injector (bar)	466.12	493.74	520.39
pressure difference at producer (bar)	0.92	11.8	20.69
pressure difference at injector (bar)	1.53	19.5	34.36
aquifer temperature at producer * (°C)	160.19	168.56	177.21
temperature at heat exchanger (°C)	148.97	159.86	169.21
pressure at heat exchanger (bar)	9.24	15.87	21.42

base case (median value input)	value
aquifer kH net (Dm)	12
mass flow (kg/s)	38.21
pump volume flow (m^3/h)	141.7
required pump power (kW)	196.9
geothermal power (MW)	12.01
COP (kW/kW)	61
doublet life time (years)	1667.8
doublet power over life time (PJ)	632.25
heat capacity rock matrix (J/Kg/K)	1126.3

aquifer pressure at producer (bar)	492.55
aquifer pressure at injector (bar)	492.55
pressure difference at producer (bar)	15.23
pressure difference at injector (bar)	25.44
aquifer temperature at producer * (°C)	168.6
temperature at heat exchanger (°C)	159.79
pressure at heat exchanger (bar)	18.67

* @ mid aquifer depth



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