Annex D

Department for Energy Security and Net Zero

Reference: DESNZ-ARP-REP-0003

Issue 05 | 22 May 2025

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

Job number 298791-00

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Acronyms and abbreviations

ASHP	Air Source Heat Pumps
BSI	British Standards Institution
DEFRA	Department of Environment, Food and Rural Affairs
DESNZ	Department of Energy Security and Net Zero
EPD	Environmental Product Declaration
GHG	Greenhouse gas
GSHP	Ground Source Heat Pump
GWP	Global Warming potential
ICE	Inventory of Carbon and Energy
IPCC	Intergovernmental Panel on Climate Change
SPF	Seasonal Performance Factor
WLC	Whole Life Carbon
WSHP	Water Source Heat Pump

Definitions

Carbon	Referring to carbon dioxide and carbon dioxide equivalent emissions. Often used as shorthand for greenhouse gas emissions. Carbon dioxide equivalent (CO_2e) is the universal unit of measurement to indicate the global warming potential (GWP) of all greenhouse gases (GHG), expressed in terms of the global warming potential (GWP) of one unit of carbon dioxide. [1]
Study period	Period over which the time-dependent characteristics of the object of assessment are analysed. In some cases, the reference study period may differ significantly from the design life of the building. [2]
Emission factor	An emission factor is a measure of the mass of emissions relative to a unit of activity. Often referred to as a carbon factor. For example, a kilogram of materials specified on site has an associated emissions factor such as kg/kgCO_2e.
Embodied Carbon	The carbon emissions associated with the extraction of materials, manufacturing, and transportation of products (A1-3), transportation of the product to site (A4), project construction (A5), repair, maintenance, and replacement emissions (B2-5) and end-of-life phases (C1-4).
Operational Carbon	The sum of the energy requirements (and therefore carbon) associated, directly or indirectly, within an operation. Operational carbon is that which comes under the control of the infrastructure's operations. It is associated with the lifecycle modules Use (B1), Operational energy consumption (B6), Operational water consumption (B7), and User Utilisation (B8).
PAS2080:2023	Publicly available specification on carbon management in buildings and infrastructure. PAS 2080 is a global standard for managing carbon in infrastructure. The framework looks at the whole value chain and aims to reduce carbon and cost through intelligent design, construction, and use. The standard is focused on managing whole-life carbon in infrastructure.

D.1 Whole Life Carbon Assessment

D.1.1 Introduction

This appendix represents the initial step in addressing DESNZ's Research Question Nr. 10:

Compare LCOH and carbon footprint of geothermal with comparable dispatchable heat sources (e.g. CHP, waste heat from industrial site, WSHP).

Additionally, this appendix addresses Research Question Nr. 11:

What are the total emissions for the different geothermal systems considered and include an assumption of costs based on a variable carbon price.

A Whole Life Carbon (WLC) assessment has been completed on the identified geothermal technologies. The WLC assessment has been undertaken in accordance with the Royal Institute of Chartered Surveyors (RICS) Whole Life Carbon Assessment for the Built Environment guidance (RICS, 2023)[3] in line with British Standards Institute's (BSI) PAS2080:2023 principles (BSI, 2023)[4].

The following technologies were assessed:

- Closed loop ground source heat pumps (GSHP): 1 borehole, 20 borehole, and 100 boreholes;
- Open loop GSHP: 20 litres per second (l/s);
- Deep geothermal doublet systems: 1km, 2km, 3km, 4km, 5km, 5km through hard rock.

Full assessment data inputs and carbon results are available in D.3, D.4 and D.5.

This assessment excludes the carbon costs associated with construction of back-up heat sources. It only captures the whole life carbon of the geothermal technologies themselves.

D.1.2 Methodology

The assessment methodology involved calculating the sum of greenhouse gas emissions (GHG) and removals over a 30-year period (2024-2054), encompassing all lifecycle stages, from preliminary studies and consultation through to decommissioned material disposal.

The carbon assessment included the following calculations:

- Calculating thermal capacities for each system to compare WLC emissions per thermal capacity of the system, which includes total heating capacity only. Geothermal systems have the capability to provide cooling and could increase the carbon saving. Thermal capacities were calculated based on the following assumed operations:
  - Closed loop system: heating only (5256hrs, 60% annual capacity)
  - Open loop system: heating only (5256hrs, 60%)
  - Deep geothermal (1km- 3km doublet): heating only (6000hrs, 68% annual capacity)
  - Deep geothermal (4km & 5km doublet): combined heat and power (7884hrs, 90% annual capacity)
- Calculating heat pump annual electrical demand by estimating the heating capacity then inversely applying the Seasonal Performance Factor (SPF).
- Calculating carbon emissions for each lifecycle activity (based on business-as-usual scenarios) using published emissions conversion factors [5][6][7].

The WLC assessment scope encompasses all work stages of the identified technologies, spanning a 30-year study period. This is a quantitative assessment, providing the sum of greenhouse gas emissions (GHG) and removals, referred to throughout as carbon. The emissions have been calculated by converting activity data for each technology's construction, use, operation, and decommissioning into carbon emissions through the application of referenced emissions conversion factors such as:

- Inventory of Carbon and Energy version 3.0, 2019 (ICE, 2019)[5];
- Various third part verified environmental product declarations (EPD) for relevant products;
- Department of Energy Security and Net Zero (DESNZ) and Department of Environment, Food and Rural Affairs (DEFRA) GHG conversion factors (DESNZ & DEFRA, 2023)[6];
- The Green Book (HM Treasury & DESNZ, 2023)[7].

The WLC data is based on business-as-usual scenarios for each identified technology. This relies on standard practice assumptions. Hence, the calculated carbon emissions are not based on actual project data. Further detail on the inclusions and exclusions of the assessment are detailed in Table 1 and a summary of assumptions is included in D.3, D.4 and D.5.

Table 1: WLC assessment scope inclusion justifications and data sources

PAS2080 ref [4]	Contributing components of Emissions	Inclusion / Exclusion	Justification	Data Source
A0	Preliminary studies, consultation	Excluded	Assumed minimal emissions due to majority of preliminary studies being desk based. Emissions associated with potential preliminary ground investigation works have been excluded as they vary on a site-by-site basis.	
A1-3	Raw materials extraction, supply, and manufacturing	Included	Emissions associated with typical construction materials are considered significant, usually making up the majority of the WLC assessment and therefore key to the WLC assessment.	Material and product types and quantities provided by technical professional, quantified from typical design details.
A4	Transport to Site	Included	Transport emissions associated with material transport to site, including return journeys. Can be significant when international journeys are required.	Assumed vehicle types and delivery distances (RICS, 2023)[3].
A5	Construction activities	Included	Construction emissions, associated with on-site construction activities such as fuel consumption and disposal of construction waste. Can have significant impacts on the WLC assessment depending on the construction activities and employed construction practices.	Detailed information not available. Benchmark applied based on project value (RICS, 2017)[8].
B1	Use	Excluded	Assumed minimal emissions associated with non-energy-related impacts during the life of the built asset, arising from its components.	
B2	Maintenance	Included	Emissions associated with annual inspections and regular maintenance during each technology's operation during the study period can be significant depending on the asset type. Maintenance emissions should be included in the assessment due to the nature of the geothermal technologies.	Detailed information not available. Benchmark applied based on Product Stage (A1-3) calculated emissions (RICS, 2023)[3].
B3	Repair	Included	Emissions associated with routine repairs during each technology's operation during the study period can be significant depending on	Detailed information not available. Benchmark applied based on Maintenance (B2)

PAS2080 ref [4]	Contributing components of Emissions	Inclusion / Exclusion	Justification	Data Source
			the asset type. Allowance for repair emissions should be included in the assessment due to the nature of the geothermal technologies.	calculated emissions (RICS, 2023)[3].
B4	Replacement	Included	Replacement emissions associated with material and product replacement during each technology's operation during the study period can be a significant proportion of the WLC assessment and should be included to demonstrate the whole life impact of the geothermal technology.	Repeat of associated Product Stage (A1-3) emissions for relevant elements that have a shorter design life than the study period.
B5	Refurbishment	Excluded	Assumed no planned refurbishment within the 30-year study period.	
B6	Operational energy use	Included	Operational emissions associated with electricity consumption to supply pumps during operation can be a significant proportion of the WLC assessment and should be included to understand the extent of their impact.	Energy consumption from National Grid and its associated decarbonised trajectory to 2050. Provided by technical professional, quantified based on power demand and system output.
B7	Operational water use	Excluded	Assuming no water use during operation.	
B8	User activities	Excluded	Assuming no user emissions.	Module D includes avoided emissions associated power generated by the geothermal technology of each scenario.
C1	Decommission / Deconstruction	Included	Emissions associated with the decommissions, deconstruction activities at the technology's end of life are not known at this stage and an allowance should be included to avoid underestimating the WLC emissions.	Detailed information not available. Benchmark applied based on construction stage (A5) calculated emissions (RICS, 2023)[3].
C2	Decommissioned material transport	Included	Emissions associated with the transport of decommissioned materials are not known at this stage and an allowance should be included to avoid underestimating the WLC emissions.	Assumed repeat of Transport (A4) calculated emissions.
C3	Decommissioned material processing	Included	Emissions associated with the waste processing and recovery of decommissioned materials are not known at this stage and an allowance should be included to avoid underestimating the WLC emissions.	Detailed information not available. Default end-of-life routes applied to relevant materials (RICS, 2023)[3].
C4	Decommissioned material disposal	Included	Emissions associated with the disposal of decommissioned materials are not known at this stage and an allowance should be included to avoid underestimating the WLC emissions.	Detailed information not available. Default end-of-life routes applied to relevant materials (RICS, 2023)[3].
D	Beyond the scope boundary	Included	The avoided emissions associated with geothermal heat output, from renewable technologies, replacing non-renewable heat generation should be included to demonstrate the benefit of these technologies.	Avoided emissions quantified based on comparable gas boiler output.

In accordance with the scope set out in Table 1, carbon emitting activities were identified, and relevant carbon factors were applied to quantify the assumed emissions. Table 2 details how the emissions have been calculated to cover the included scope.

Table 2: WLC assessment scope and calculation approach

PAS2080 ref [4]	Contributing components of Emissions	Approach	Carbon factor Source
A1-3	Raw materials extraction, supply, and manufacturing	Materials and products associated with geothermal infrastructure, including but not limited to: pipework, borehole casing, thermal grout, surface distribution, plant building, heat pumps, circulation pumps, buffer tank, heat exchanger.	(ICE, 2019)[5] and EPDs where appropriate
A4	Transport to Site	Assumed vehicle movements associated with delivery of materials, products, and plant equipment. Transport distances based on (RICS, 2023)[3] benchmark information.	(DESNZ & DEFRA, 2023)[6]
A5	Construction activities	Allowance for construction emissions included based on estimated project value (£) for each technology. Assumed allowance for construction activities including construction plant fuel consumption, water consumption during construction, on-site waste.	(RICS, 2017)[8]
B2	Maintenance	Allowance for emissions associated with infrastructure maintenance during the study period included. Emissions based on the calculated Product stage (A1-3) emissions, using industry benchmark.	(RICS, 2023)[3]
B3	Repair	Allowance for emissions associated with unplanned infrastructure repair during the study period included. Emissions based on the calculated Product stage (A1-3) emissions, using industry benchmark.	(RICS, 2023)[3]
B4	Replacement	Repeat of embodied emissions for elements that are replaced during the study period such as: heat pumps, circulation pumps, heat exchangers, buffer tank etc.	(ICE, 2019)[5] and EPDs where appropriate
B6	Operational energy use	Technology operational energy consumption throughout the study period applied to grid trajectory emission factors.	(HM Treasury & DESNZ, 2023)[7]
C1	Decommission / Deconstruction	Allowance for deconstruction emissions at the infrastructures end of life. Based on industry benchmark, dependent on calculated construction (A5) emissions.	(RICS, 2023)[3]
C2	Decommissioned material transport	Allowance for transport of deconstructed materials at the infrastructure end of life included as a repeat of calculated transport (A4) emissions.	(DESNZ & DEFRA, 2023)[6]
C3	Decommissioned material processing	Allowance for waste processing of decommissioned materials at the infrastructure end of life. Based on industry benchmark information, assuming material end of life waste processing rates (RICS, 2023)[3].	(DESNZ & DEFRA, 2023)[6]
C4	Decommissioned material disposal	Allowance for disposal of decommissioned materials at the infrastructure end of life. Based on industry benchmark information, assuming material end of life disposal rates (RICS, 2023)[3].	(DESNZ & DEFRA, 2023)[6]
D	Beyond the scope boundary	Accounting for the estimated "avoided" emissions from grid electricity. This assumes a carbon benefit as a result of avoiding national grid, fossil fuel emissions, by generating renewable energy. Based on each technologies power output and equivalent gas boiler heat output.	(HM Treasury & DESNZ, 2023)[7]

D.1.2.1 Technologies

The WLC assessment includes the following technologies:

- Closed loop boreholes (1 borehole, 20 boreholes, 100 boreholes)

- Open loop systems (single doublet, 20 l/s flow rate)
- Deep geothermal doublets (single doublet, 1km, 2km, 3km, 4km, 5km, 5km – hard rock)

These technologies were selected as they are considered representative of shallow and deep systems; as well as closed and open systems. A WLC assessment for all technologies exceeded the scope of works. However, the findings from these three technologies are likely applicable to comparative technologies (for example, similarities between mine water and open loop systems). A comparison with air-source-heat-pumps, and gas boilers has been undertaken for operational carbon only.

The carbon assessment includes a comparison of WLC emissions per thermal output. As part of this, the following thermal capacities for each system have been calculated, see Table 3. This is consistent with the LCOH assessment (Appendix B).

Thermal capacity was calculated by applying the outlined assumptions to closed loop and open loop systems; and via DoubletCalc for the deep geothermal systems. Heat pump annual electrical demand was calculated by estimating the heating and cooling capacity then inversely applying inferred Seasonal Performance Factor (SPF). The SPF was informed from stakeholder data. Additional electrical loads were applied for pumps and parasitic loads.

For instance, an open loop system with a flow rate of 20 litres per second can provide 4670 MWh of heating and 1950 MWh of cooling annually. With a heating Seasonal Performance Factor (SPF) of 4 and a cooling SPF of 5, the system would need (4670 ÷ 4) + (1950 ÷ 5) = 1170 + 390 = 1560 MWh of electricity to run the heat pumps each year. Additionally, if a 15 kW electrical submersible pump is used to supply water continuously throughout the year (8760 hours), it would consume (15 kW × 8760) ÷ 1000 = 130 MWh of electricity. Combining these, the total annual electrical demand would be 1690 MWh.

For shallow systems, the normalised to energy carbon cost is quantified against total thermal capacity of the system, which comprises total heating and cooling capacity. A balanced heating and cooling system is typically more optimised and efficient, using less electricity to generate the same capacity relative to an imbalanced system. Relative to a heating only system; heating and cooling systems use more electricity annually, as they are assumed to operate for more hours annually. However, heating, and cooling systems would deliver lower normalised to energy carbon emissions for the same capacity relative to a heating only system owing to the improved efficiencies. Balanced systems are less common than heating only systems in the UK.

Table 3: Summary of geothermal capacities used to inform the WLC assessment

Technology	System	Operation	Annual Thermal capacity		Power		Electrical demand	Rational
			kW	MWh	kW	MWh	MWh	
Closed loop	1 borehole	Heating (5256hrs, 60% annual capacity)	8 (heating)	42	-	-	23	Closed loop capacity estimated from borehole depth (150m), thermal capacity (40W/m) and SPF (4 heating, 5 cooling) Electrical demand comprises heat pump and circulation pump demand.
	20 boreholes		160 (heating)	840	-	-	307	
	100 boreholes		800 (heating)	4205	-	-	1530	
Open loop system	20 l/s flow rate	Heating (5256hrs, 60%)	890 (heating)	4675	-	-	1690	Open loop capacity estimated from flow rate, heat difference across the heat exchanger (ΔT), specific heat capacity and density of water. Electrical demand comprises heat pump and electrical submersible pump demand.
Deep geothermal	1km doublet	Heating only (6000hrs, 68% annual capacity)	1,700	12,750	-	-	5,550	Deep geothermal capacity estimated from DoubletCalc tool. The medium case was selected as a representative value. Site specific geological conditions vary; this is high level and used to inform the carbon assessment only. Electrical demand comprises heat pump demand (for 1km, and 2km systems only), circulation, and abstraction pump demands.
	2km doublet		2,800	20,160	-	-	6,660	
	3km doublet		6,800	40,800	-	-	3,600	
	4km doublet	Combined heat and power (7884, 90% annual capacity)	12,200	96,185	1,200	9,460	6,701	
	5km doublet		16,400	129,300	2,700	21,290	8,672	
	5km doublet – hard rock		16,400	129,300	2,700	21,290	8,672	

D.1.3 Results

D.1.3.1 Closed loop

Closed loop borehole systems comprise an underground heat exchanger and piping network, heat pump/heat exchanger, and building distribution system. Manifolds are used to connect the borehole arrays.

The closed loop geothermal technologies covered in this carbon assessment include single borehole, 20 borehole, and 100 borehole scenarios. Each of these scenarios assumes a 150m deep, 140mm diameter borehole, and 40W/m capacity.

Table 4: Closed loop WLC results (tCO_2e)

System	Heating capacity (MWh)	Product Stage (A1-3)	Transport (A4)	Construction (A5)	In-use (B)	End of Life (C)	WLC Total (tCO2e)	Total per MWh thermal* ($kgCO_2e$/MWh)
Closed loop, single borehole	42	24	4	0.4	32	4	**64**	**51.0**
Closed loop, 20 boreholes	840	56	32	1	397	37	**529**	**21.0**
Closed loop, 100 boreholes	4,205	850	154	49	1,983	187	**2,470**	**25.6**
*WLC value divided by whole life thermal generation (heating), calculated as 30-year production.								

Counterintuitively, the normalised to energy carbon emissions (WLC per MWh) output drops from single to 20-borehole systems, then increases again to the 100-borehole system. This is principally driven by Product Stage and the requirement for an energy centre (with an assumed floor area of 1,800m^2) to be constructed for the 100-borehole system; relative to a small (assumed floor area of 25m^2) energy building for the 20-borehole system.

D.1.3.2 Open loop

Open-loop geothermal wells require at least two water wells (boreholes): one for abstraction and at least one for discharge of groundwater to and from the same aquifer.

The water is pumped from the abstraction borehole, usually using an electrical submersible pump (other pumps may be possible) and piped to the heat exchanger where heat is transferred to the heat pump prior to discharge.

The open loop geothermal technology included in this carbon assessment covers two wells with a well depth of 150m and borehole diameter of 305mm. The assessed open loop technology allows for a flow rate of 20l/s.

Table 5: Open loop WLC results (tCO_2e)

System	Heating capacity (MWh)	Product Stage (A1-3)	Transport (A4)	Construction (A5)	In-use (B)	End of Life (C)	WLC Total (tCO2e)	Total per MWh thermal* ($kgCO_2e$/MWh)
Open loop, 2 well	4,675	263	14	6	2,170	17	**2,470**	**17.6**
*WLC value divided by whole life thermal generation (heating), calculated as 30-year production.								

Open loop systems derive thermal energy from convection rather than conduction of closed loop systems. This is more efficient and as a result a single doublet pair can have a comparable thermal capacity to the 100-borehole system (which inherently has greater capital carbon cost owing to more boreholes). As a result, the normalised to energy carbon emissions are lower for open loop systems than closed loop systems. This assessment was only undertaken at 20 l/s. Greater flow rates would reduce the normalised to energy carbon emissions further; with greater thermal capacities.

D.1.3.3 Deep geothermal

Deep geothermal systems comprise hydrothermal and Enhanced Geothermal Systems (EGS) systems at depths of >500m. Both systems work in a similar way to an open-loop system, utilising a well doublet (i.e., abstraction and discharge borehole). Abstraction requires a pump (typically an electrical submersible pump), and a second pump may be required to discharge water back into the aquifer.

This carbon assessment has quantified whole life carbon emissions associated with deep geothermal technologies with scenarios from 1km to 5km borehole depths.

Table 6: Deep geothermal WLC results (tCO_2e)

System	Energy capacity (MWh)	Product Stage (A1-3)	Transport (A4)	Construction (A5)	In-use (B)	End of Life (C)	WLC Total (tCO2e)	Total per MWh Thermal* ($kgCO_2e$/ MWh)
Deep 1km	12,750 (heating)	1,942	239	112	9,326	339	**11,957**	**31.3**
Deep 2km	20,160 (heating)	2,046	335	196	11,175	503	**14,255**	**23.6**
Deep 3km	40,800 (heating)	2,098	339	245	6,090	572	**9,344**	**7.6**
Deep 4km	96,185 (heating) 9460 (power)	2,279	370	329	11,241	686	**14,906**	**4.7**
Deep 5km	129,300 (heating) 21,280 (power)	2,354	376	462	14,516	799	**18,506**	**4.1**
Deep 5km -hard rock	129,300 (heating) 21,280 (power)	2,266	369	560	14,516	841	**18,551**	**4.1**
*WLC value divided by whole life thermal generation (heating), and power generation, calculated as 30-year production.								

Owing to the high thermal capacities of deep geothermal systems they have relatively low normalised to energy carbon emission values. Notably the 1km and 2km systems are distinctly greater than the 3km, 4km, and 5km system (and open loop system). Deep geothermal systems can high operational energy demands owing to potentially large hydraulic heads and pumping requirements. The 1km and 2km system also need supplementary Water Source Heat Pump (WSHP) operation to boost the production fluid temperature (estimated at <75°C) to temperatures suitable for use in District Heating Networks or Commercial buildings (typically >85°C). Whilst these WSHPs are relatively efficient, they do require additional power. Conversely, the 3km, 4km, and 5km systems are likely to provide sufficient temperatures for direct use, (without the need for a WSHP). The combination of greater thermal capacity with deeper systems, and ability for direct heating means that they have the lowest normalised to energy carbon emission values.

D.1.3.4 Summary

Across all systems, the primary contributor to carbon emissions is the In-Use (B) phase. These emissions stem from electricity consumption. As the national grid continues to decarbonise, both GSHP and deep geothermal systems will follow suit. For example from 2050, the target for net zero carbon grid; all operational carbon costs (derived from electricity) will fall to zero. Further details are provided in the subsequent sections.

Deep geothermal systems and open loop systems presented the lowest normalised to energy carbon emissions; however, all systems were broadly comparable, generally within an order of magnitude of each other.

D.1.4 Technology comparators

D.1.4.1 Introduction

The below table includes the geothermal technology scenario outputs identified in this report as well as comparable alternative technologies. As outlined, operational (In-Use) emissions dominate the WLC values; and therefore, this is further explored within this section.

Table 7 presents power demand and projected operational carbon emissions for both gas boilers and air source heat pumps (ASHP) being higher than the majority of the geothermal technology scenarios. All renewable technologies included in the table show an operational carbon saving when compared to a scaled gas boiler system.

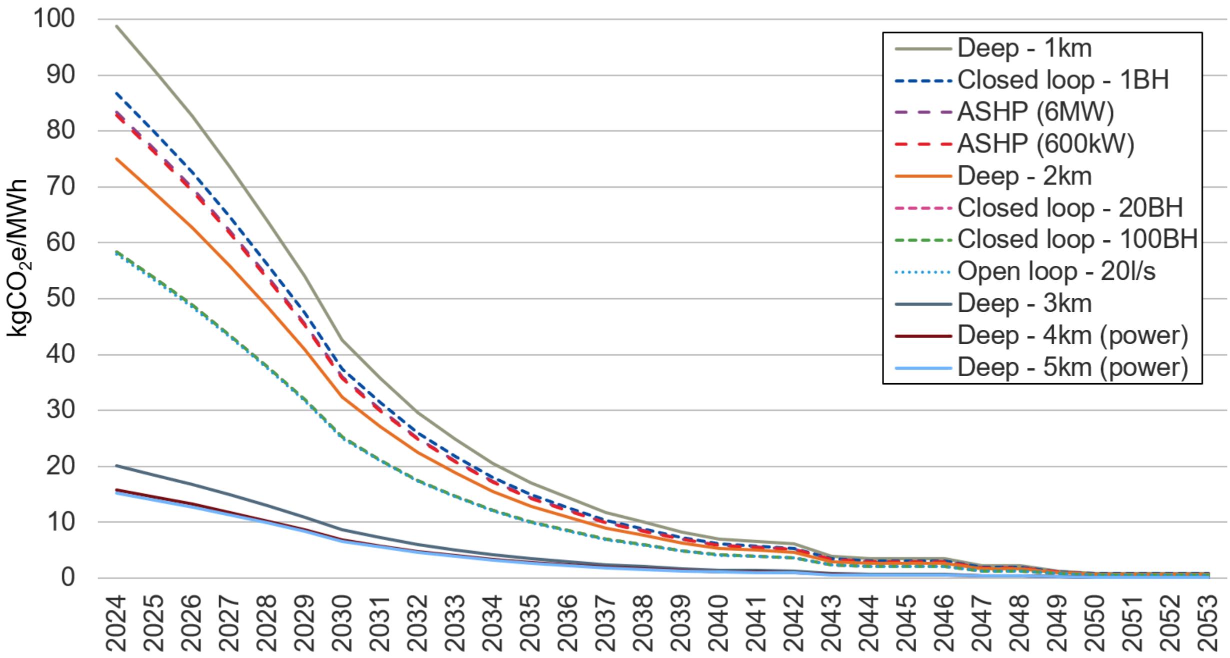
Table 7: All technologies comparable operational energy WLC demand and emissions

System	Energy Capacity (MWh)	Annual power demand – gas (MWh)	Annual power demand – electricity (MWh)	Electricity power demand per heat output (MWh/MW)	Operational carbon emissions, 30-year (tCO_2e)	Operational carbon emissions, 30-year ($kgCO_2e/MWh$)†	Avoided emissions against comparable gas system, 30-year (tCO_2e)*
Gas Boiler	3,155 (heating)	3,710	-		20,386	215	-
Gas Boiler	36,000 (heating)	42,353	-		232,721	215	-
ASHP	5,255 (heating)	-	2,111	2,111	3,500	27	29,780
ASHP	36,000 (heating)	-	24,029	2,403	39,839	27	341,057
Closed loop - 1BH	42 (heating)	-	19	2,409	32	51	234
Closed loop - 20BH	840 (heating)	-	237	1,478	392	21	4,928
Closed loop - 100BH	4,205 (heating)	-	1,183	1,478	1,961	35.6	24,640
Open loop - 20l/s	4,675 (heating)	-	1,300	1,462	2,155	17.6	27,407
Deep - 1km#	12,750 (heating)	-	5,550	2,612	9,202	31.3	73,220
Deep - 2km#	20,160 (heating)	-	6,660	1,982	11,042	23.6	119,281
Deep - 3km	40,800 (heating)	-	3,600	529	5,969	7.6	257,782
Deep - 4km	96,185 (heating) 9460 (power)	-	6,701	549	11,111	4.7	610,673
Deep - 5km	129,300 (heating) 21,280 (power)	-	8,672	529	14,379	4.1	821,462

* Based on GOV Green Book Natural gas value of 0.18316 tCO2e/MWh value [12], and gas boiler heat conversion efficiency of 0.85.

Deep geothermal 1km and 2km systems include use of a WSHP, required to boost fluid temperatures to meet DHN needs. Deeper, 3km, 4km, and 5km systems have sufficiently high fluid temperatures to provide direct heating without use of a WSHP. Where WSHPs are required, electrical demands (and operational carbon) are greater.

† Values are calculated by the dividing the 30-year operational carbon emission by total thermal (heating), ad power generation output over 30 years.



* Gas boilers have a consistent (flat line) carbon value of 215 $kgCO_2e/MWh$ which does not decrease over time.

Figure 1: All technologies operational energy carbon emissions per thermal output, 30-year ($kgCO_2e/MWh$)

Figure 1 highlights operational energy carbon emissions across all assessed technologies. Gas boilers, due to their unchanging calorific value, do not decarbonise. In contrast, ASHPs and geothermal systems gradually decarbonise over time. Their operational emissions are closely linked to the carbon content of the National Grid. As the National Grid moves toward net-zero emissions by 2050 [12], the carbon impact of energy systems follows suit. Gas systems are not shown on this figure. They have a consistent yearly value of 215 $kgCO_2e/MWh$, calculated as 183.16$kgCO_2e/MWh$ (gas value) divided by 85% (efficiency of gas boiler, 1 unit of gas delivers 0.85 units of heat).

Notably, while geothermal systems are more efficient than ASHPs, resulting in lower electricity usage and fewer emissions for equivalent thermal capacities, this difference diminishes as we approach the 2050 net-zero target. Ultimately, achieving net-zero will render all electrical energy system operations emission-free.

D.1.5 Benchmarking

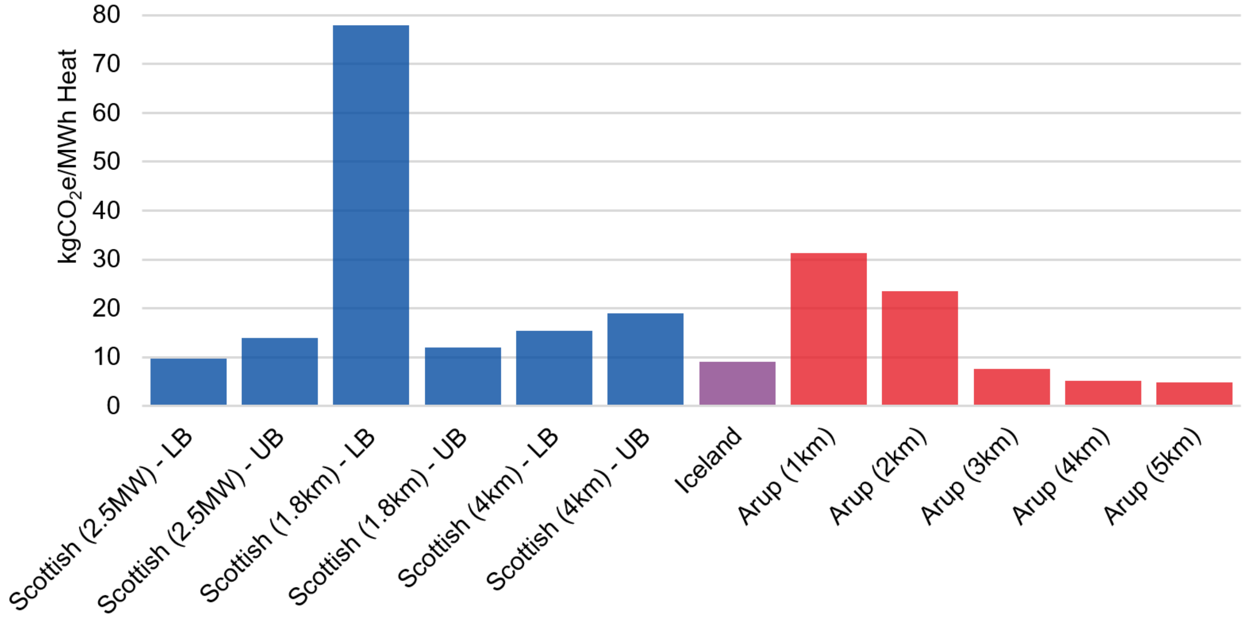
A benchmarking exercise was undertaken to see how Arup's assessment compares to similar Whole Life Carbon studies. Generally, it was found that there are limited geothermal WLC studies available, and those that do exist often rely on hidden or generalised assumptions. The following presents our findings:

- Scottish Deep Geothermal Scenario study [9]
  - A case study in Scotland examined the carbon intensity of proposed renewable energies, specifically focusing on a 2.5 MW low-enthalpy deep geothermal scenario [9]. In this study, the identified carbon intensity of the heat generated ranged from 9.7 to 14 $kgCO_2e/MWh$. Notably, this scenario had an annual heat output of 13,140 MWh, from a 2.5MWth source.
  - The study included a favourable drilling scenario and a more complex drilling scenario. Each assessment spanned a 30-year study period and found that the carbon intensity of the favourable drilling scenario (1.8 km deep well) had a range of 7.8 to 12 $kgCO_2e/MWh$, whereas the challenging conditions scenario (4 km deep well) showed a range of 15.4 to 19 $kgCO_2e/MWh$.
  - The system in this study had a 2.5MWth and 13,140MWh annual capacity. This is comparable to Arup's assessment of a 1km deep geothermal doublet, assumed to have 2.1MWth and 12,750MWh annual capacity. For Arup's assessment the normalised carbon value was 31.3 $kgCO_2e/MWh$; around 2.5 to 3 times the published values. However, Arup's range in normalised values for 1km to 5km systems, fall with the range of this study.

- This study references other assessments that have identified carbon intensities including heat only scenarios, estimating a carbon intensity of 9 $kgCO_2e/MWh$ and electrical power scenarios of 34 $kgCO_2e/MWh$ in an Icelandic power plant and 1800 $kgCO_2e/MWh$ in a deep geothermal power plant in Türkiye. This high Turkish value is likely the result of CO_2 off-gassing at surface. High CO_2 levels can derive from carbonate geothermal systems, however the CO_2 can be captured, reducing carbon intensities.
- McCay et al. (2019) did not cover all aspects of the whole life carbon assessment. Maintenance (B2), Repair (B3), and decommissioning (C1-4) stages were excluded. However, they did include emissions associated with the pre-construction, exploratory stage. Additionally, minimal materials were considered which included pipe work, borehole linings, cement, and associated drilling time.
- Therefore, this study is less inclusive of all associated activities to construct a functioning geothermal well and the assessment demonstrated in this report is more extensive. Nevertheless, this study and the findings of the assessment included in this report both demonstrate the significance of the operational stage and the carbon emissions associated making up the majority of the WLC.
- Arup's WLC assessment of power systems had normalised carbon values of 29 to 52 $kgCO_2e/MWh$ for 4km and 5km systems, respectively. These values are comparable to the 34 $kgCO_2e/MWh$ Iceland values, but far less than the Türkiye value; which appears to be far greater than other published values.

- French Caribbean Geothermal Scenario [10]
  - Another study explored the carbon intensity of geothermal power generation in the French Caribbean, examining three different geothermal plant scenarios. The carbon emission values in this context ranged from 38.5 to 47 $kgCO_2e/MWh$. [10].
  - Arup's WLC assessment of power systems had normalised carbon values of 29 to 52 $kgCO_2e/MWh$ for 4km and 5km systems, respectively. The Arup assessment is consistent with the published values.
  - It is important to recognise that the French Caribbean climate differs significantly from the scenarios covered in our report. Additionally, the Marchand et al. study considered factors such as land use change and the release of non-condensable gases during operation, which were not accounted for in the scenarios included in this appendix.
- Hellisheiði Geothermal Project (Iceland) [11]
  - A separate study quantified the carbon intensity of Hellisheiði, an Icelandic geothermal project [11]. Hellisheiði is a combined heat and power, double flash geothermal plant, with an installed capacity of 303.3 MWe of electricity and 133 MWth of hot water. This plant is the largest in Iceland and the sixth largest globally by electric capacity and has a combined heat and power carbon intensity ranging between 15 to 24 $kgCO_2e/MWh$.
  - The study compares the calculated carbon intensity to similar binary cycle geothermal plants, solar (photovoltaic) and hydropower, as well as to other dissimilar geothermal technologies and fossil-based technologies, nuclear and onshore wind.
  - This study did not cover all aspects of the whole life carbon assessment. Maintenance (B2), Repair (B3), and emissions associated with the pre-construction, exploratory stage were excluded. However, emissions associated with End of Life decommissioning were included, that were excluded in the McCay et al. (2019) Scotland case study.
  - Paulillo et al. conducted hotspot analysis of factors contributing to climate change, including carbon emissions. Notably, the operational phase accounted for a significant proportion of emissions, aligning with findings in this appendix where operational phases contribute 55-90% of the total WLC assessment emissions.

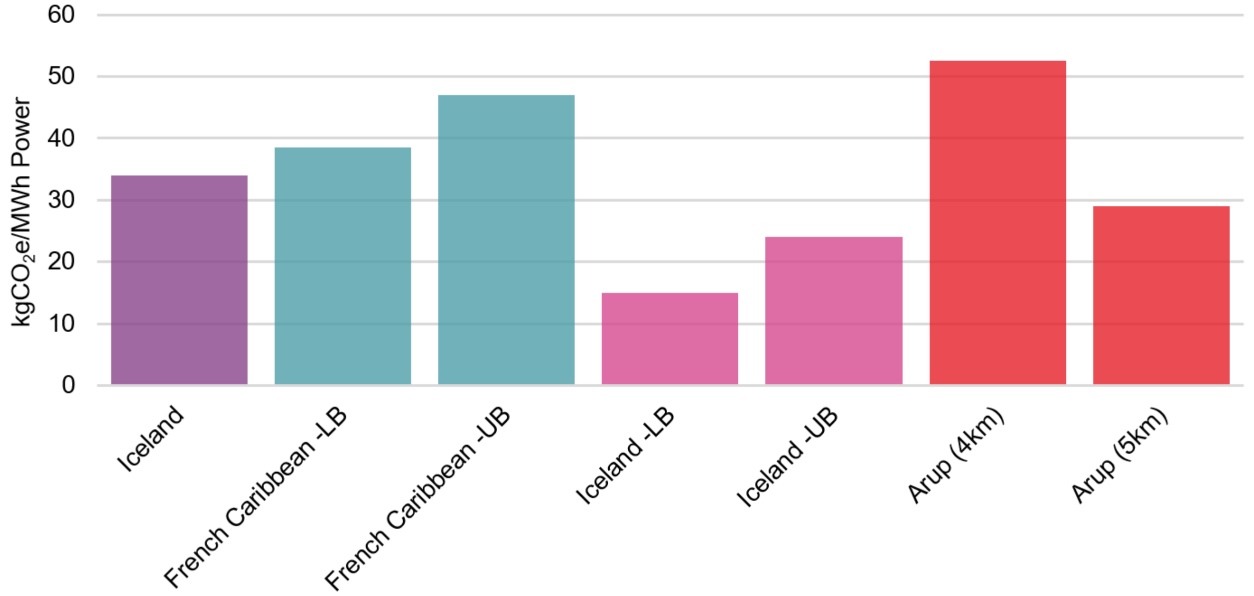
Reviewing geothermal WLC studies identifies some similarities and differences to the geothermal technology assessment included in this report. The selected scopes and methodologies differ greatly to quantify the estimated embodied carbon emissions associated with each technology. The majority of the studies identified have included a limited scope of embodied elements, namely focusing on piping and casing components. The majority of the studies also exclude elements from the operational phase such as Maintenance (B2), Repair (B3), and Replacement (B4). The WLC assessment covered in this report attempts to capture all PAS2080 lifecycle modules (A-C), excluding only certain aspects of operational carbon emissions such as In-Use and User activities. The assumptions made in the WLC modelling has ensured that allowances for each aspect of the geothermal technologies embodied and operational emissions are included. Regardless of the methodology variations, the Arup assessment is broadly comparable with the assessed published values, see Figure 2 and Figure 3.



* The different colours refer to different sources of information

* LB and UB refer to lower and upper bound respectively

Figure 2: Summary of published normalised whole life carbon emissions per thermal output compared to Arup results



* The different colours refer to different sources of information

* LB and UB refer to lower and upper bound respectively

* A published value of 1,800 kgCO_2e/MWh for Turkey is excluded as it exceeds the axis of the graph. The high value is the result of surface CO_2 off-gassing at the assessed facility. CO_2 production can be a byproduct of carbonate reservoir geothermal systems. However, it can be captured at surface (reducing carbon intensity).

Figure 3: Summary of published normalised whole life carbon emissions per power output compared to Arup results

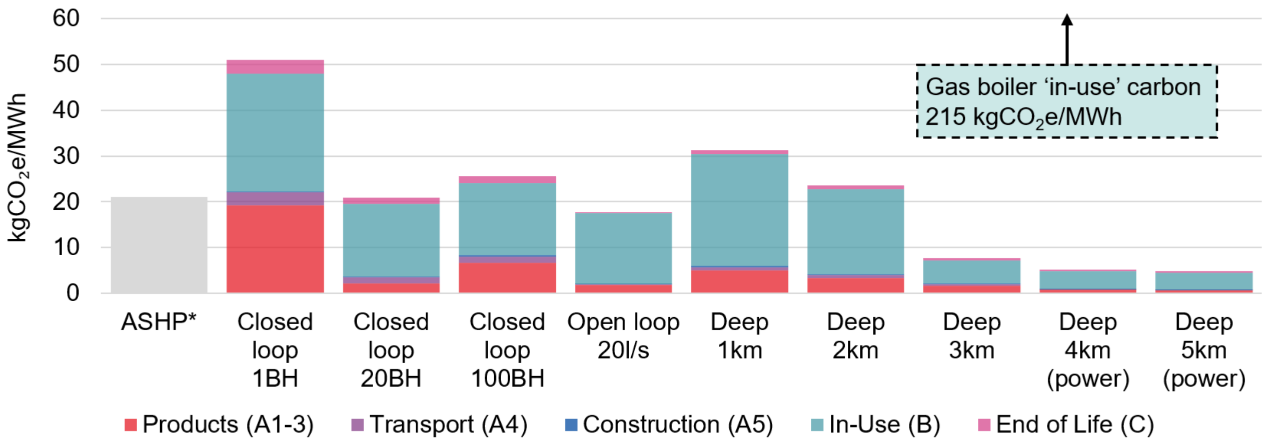
The carbon intensities calculated from the deep geothermal technologies included in this report range from 31.3 to 4.8 $kgCO_2e$/MWh for heat, and 29.1 to 52.5 $kgCO_2e$/MWh for power. These values are consistent with published values. The Türkiye value, at 1,800 $kgCO_2e$/MWh Power is two orders of magnitude greater than other published values. This value is excluded from Figure 3. The Arup assessment did not include greenhouse gas emissions released from the well as it depressurises. Different climatic regions, plant operational parameters, and operational emissions (associated with the local electrical grid) vary with region. These variables will have contributed to observed differences between the Arup and published studies.

The Scottish Deep Geothermal Scenario found the largest source of emissions, over the 30-year lifetime of the geothermal system, to be a result of powering the injection/production pumps. Similarly, the Hellisheiði case study finds that the operational phase emissions contribute by 55-90% of the WLC total. The findings of WLC assessments included in this report support this trend. The operational energy emissions account for 55-90% of the geothermal technologies WLC totals.

Operation carbon is the biggest emissions contributor, and therefore as it decarbonises, the carbon benefits of renewable technologies reduce. Hence, the carbon benefits that accrue from the generation of renewable energy are challenging to quantify. The UK grid is set to decarbonise over time, and as average grid intensity decreases then the marginal carbon benefit of each unit of renewable energy similarly decreases. A simple arithmetic evaluation of carbon benefits, therefore, shows decreasing benefit over time. However, the national benefit is wholly reliant on renewable projects, such as geothermal, wind, and solar technologies, coming on line to provide this decarbonisation trend. Geothermal technologies, by design, reduce GHG emissions and, through the export of power, reduce the UK's reliance on fossil fuels within the national energy grid.

D.1.6 Discussion

The whole life carbon assessment results demonstrate that the deep geothermal technology scenarios have a larger carbon footprint in comparison to shallower geothermal systems; however, have a lower normalised to energy carbon intensity (owing to their greater capacities).



* ASHP embodied carbon from CIBSE TM65.1 Embodied carbon in building services: residential heating (2021) [115]. Arup converted the reported 55.2 $kgCO_2e$/kW to 21 $kgCO_2e$/MWh, assuming the system is used for heating for 60% of the year (5256hrs), to be comparable with the shallow geothermal systems. The full reported range is from 34.5 to 71.3 $kgCO_2e$/kW (c. 13.1 to 27.1 $kgCO_2e$/MWh). This is a residential value and therefore may not be suitable for direct comparison.

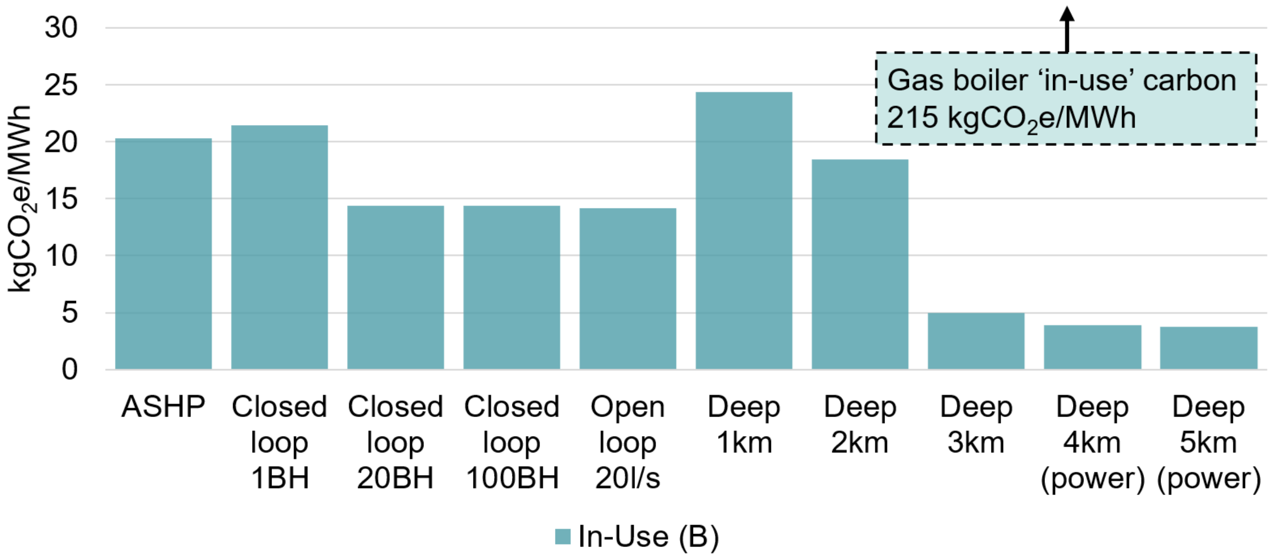
* Gas boilers excluded from graph. Gas boilers have an 'in-use' carbon value of 215 $kgCO_2e$/MWh, exceeding the axis of this graph.

* Carbon costs: A1-3, Products (piping, pumps, cement); A4, Transport (haulage); A5, Construction (enabling works, water disposal); B, In-Use (maintenance, equipment replacement, operational energy consumption); C, End of Life (demolition, transport, recycling).

Figure 4: Geothermal technologies whole life carbon emissions per 30-year thermal output ($kgCO_2e$/MWh)

The majority of the whole life carbon emissions are associated with the In-use stage, specifically the operational energy emissions. The operational energy emissions are based on the national grid trajectories ($kgCO_2e$/kWh), projected for the next 30 years, and represent the majority of the calculated emissions. The In-use stage (B) accounts for an average of 77% of each technology's whole life carbon emissions (ranging from 55-90%).

The operational emissions calculated for the closed and open loop scenarios are dwarfed by the deep geothermal operational emissions. However, the normalised to energy carbon emissions associated with the deep geothermal technologies are relatively lower than the shallower closed and open loop systems, and ASHPs owing to higher capacities outputs. This is demonstrated in Figure 5.



* Gas boilers excluded from graph. Gas boilers have an 'in-use' carbon value of 215 $kgCO_2e/MWh$, exceeding the axis of this graph.

Figure 5: Geothermal technologies and ASHP In-Use carbon emissions per 30-year thermal output (kgCO2e/MWh)

In-Use carbon is the biggest carbon component for the assessed renewable technologies. Figure 5, presents a comparison of the geothermal technologies with ASHPs. All operational emissions are relatively comparable, other than deep geothermal for direct heating which is lower.

In conclusion, deep geothermal has the greatest embodied carbon, but lowest normalised carbon owing to their high capacities. The shallow geothermal systems are relatively comparable, and also produce low normalised to energy carbon results. Operational emissions dominate the WLC assessment; and ASHPs have comparable emissions relative to similarly sized geothermal systems owing to lower efficiencies. However, owing to the National grid decarbonisation, this difference is forecast to reduce.

D.2 References

[1] Intergovernmental Panel on Climate Change (IPCC) (2018) Annex I: Glossary. Available at: https://www.ipcc.ch/sr15/chapter/glossary/ [Accessed: 11.06.24]

[2] BS EN 15978:2011, Sustainability of construction works - assessment of environmental performance of buildings - calculation method (incorporating corrigendum November 2011), British Standards Institution

[3] RICS (2023) Whole life carbon assessment for the built environment, 2nd Edition. Available at: https://www.rics.org/content/dam/ricsglobal/documents/standards/Whole_life_carbon_assessment_PS_Sept23.pdf . [Accessed: 11.06.24]

[4] BSI (2023) Carbon Management in Infrastructure and Built Environment - PAS 2080. Available at: https://www.bsigroup.com/en-GB/insights-and-media/insights/brochures/pas-2080-carbon-management-in-infrastructure-and-built-environment/. [Accessed: 11.06.24]

[5] ICE (2023) Embodied Carbon - The ICE Database, Version 3.0. Available at: https://circularecology.com/embodied-carbon-footprint-database.html. [Accessed: 11.06.24]

[6] DESNZ & DEFRA (2023) Greenhouse gas reporting: conversion factors 2023. Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023. [Accessed: 11.06.24]

[7] HM Treasury & DESNZ (2023) The Green Book. Available at: https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fassets.publishing.service.gov.uk%2Fmedia%2F6567994fcc1ec5000d8eef17%2Fdata-tables-1-19.xlsx&wdOrigin=BROWSELINK. [Accessed: 11.06.24]

[8] RICS (2017) Whole life carbon assessment for the built environment, 1st Edition.

[9] Alistair T. McCay, Michael E.J. Feliks, Jennifer J. Roberts (2019) Life cycle assessment of the carbon intensity of deep geothermal heat systems: A case study from Scotland. Science of The Total Environment, Volume 685, Pages 208-219. Available at: https://www.sciencedirect.com/science/article/pii/S0048969719323587. [Accessed: 11.06.24]

[10] Mathilde Marchand, Isabelle Blanc, Aline Marquand, Antoine Beylot, Sophie Bezelgues-Courtade, et al..(2015) Life Cycle Assessment of High Temperature Geothermal Energy Systems. World Geothermal Congress. International Geothermal Association, Apr 2015, Melbourne, Australia. pp.11 – Article 02028. Available at: https://minesparis-psl.hal.science/hal-01146355v1/document. [Accessed: 11.06.24]

[11] Andrea Paulillo, Aberto Striolo, Paola Lettieri (2019) The environmental impacts and the carbon intensity of geothermal energy: A case study on the Hellisheiði plant. Environment International, Volume 133, Part B, 105226. Available at: https://www.sciencedirect.com/science/article/pii/S0160412019318689 [Accessed: 11.06.24]

[12] UK Government, Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal, Tables 1, 2, and 4, web link: https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

D.3 Geothermal Carbon Costs (Closed Loop)

Closed loop ground source heat pumps (GSHP): 1 borehole, 20 boreholes and 100 boreholes

	Closed Loop					Single Well			20 Well			100 Well			Carbon Totals		
	Description	**Assumptions**	**Carbon Factor Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Single Well**	**20 Well**	**100 Well**
	Pre-Construction (non-physical)														**0**	**0**	**0**
A0	Pre-construction	Assuming NA															
	Materials														**24,218**	**55,821**	**849,885**
A1-3	Piping SDR11 PE1000, 300m, 40mm dia	Assumed DWV non-pressure pipe product specific carbon factor. Assuming 120kg of pipe per 300m	3.608kgCO2e/kg EPD of 40mm DWV pipe, 0.4kg/m	3.608	kgCO2e/kg	120	kg	433	120	kg	433	120	kg	433			
	Steel casing to top of borehole	Assuming 120m of steel pipe	Highways England CT, Steel Pipework 300mm conversion, 42.28kgCO2e/m	42.28	kgCO2e/m	120	m	5,074	120	m	5,074	120	m	5,074			
	Plastic casing to top of borehole	Assuming 20m of plastic pipe casing, 450mm dia	Highways England CT, ICE 3.0: Plastic, HDPE Pipe, 450mm dia HDPE density 0.97 t/m3	28.15	kgCO2e/m	20	m	563	20	m	563	20	m	563			
	Thermal grout, borehole infill	Assuming CEM I portland cement as product specific carbon factor not available.	ICE 3.0, Cement - CEM I - Portland Cement 0.912 kgCO2e/kg Density Cement screed - 2,100 kg/m3	1915.2	kgCO2e/m3	8.85	m3	16,950	8.85	m3	16,950	8.85	m3	16,950			
	Sacrificial weights - steel	Assuming engineering steel	Engineering Steel, ICE 3.0, 1.27 kgCO2e/kg	1.27	kgCO2e/kg	50	kg	64	50	kg	64	50	kg	64			
	Distribution - manifold	Assuming an allowance of plastic pipe, assuming 0.5m	Highways England CT, ICE 3.0: Plastic, HDPE Pipe, 150mm dia pipe, HDPE density 0.97 t/m3	2.975	kgCO2e/0.5m	NA	NA	0	1	nr	3	5	nr	15			
	Distribution - surface piping	Assuming 150mm dia pipe	Highways England CT, ICE 3.0: Plastic, HDPE Pipe, 150mm dia pipe, HDPE density 0.97 t/m3	5.95	kgCO2e/m	80	m	476	1600	m	9,520	8000	m	47,600			

	Closed Loop					Single Well			20 Well			100 Well			Carbon Totals		
	Description	**Assumptions**	**Carbon Factor Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Single Well**	**20 Well**	**100 Well**
	Distribution - surface piping, aggregate fill (0.6m x 0.6m)	Assuming imported backfill to pipe surround	ICE 3.0, Aggregates and Sand - Typical UK Mix, 0.00747 kgCO2e/kg (2,240 kg/m3)	17.928	kgCO2e/m3	28.8	m3	516	576	m3	10,327	2880	m3	51,633			
	Plant building (20 well (L) 5m x (W) 5m x (H) 3m, 100 well (L) 60m x (W) 30m x (H) 3m)		OneClick 400kgCO2e/m2 (A1-3 for "industrial" European building)	400	kgCO2e/m2	NA		0	25	m2	10,000	1800	m2	720,000			
	Heat pumps	Single BH, 6kW, use Shoebox System (113kg) 20 boreholes, 120kW, use 2x Kensa Q systems (665kg each, 1330kg total) 100 boreholes, 600kW, use 7x Kensa Q systems (665kg each, 4655kg total)	ICE 3.0 Steel - Engineering, 1.27 kgCO2e/kg	1.27	kgCO2e/kg	113	kg	144	1330	kg	1,689	4655	kg	5,912			
	Submersible circulation pump	Excluded from closed loop															
	Buffer tank	Assumed hot water tank product, 270L. Assuming stainless steel.	aroSTOR 270 litre, 68kg empty weight, ICE 3.0 Stainless Steel 6.52 kgCO2e/kg	6.52	kgCO2e/kg	NA		0	1	nr	443	2	nr	887			
	Plate heat exchanger	Assuming 80kW heat transfer plate, 58kg empty weight. Assuming stainless steel.	Weight of steel: Plate Heat Exchanger Strebel 80kW, 58kg. ICE 3.0 Stainless Steel 6.52 kgCO2e/kg	6.52	kgCO2e/kg	NA		0	2	nr	756	2	nr	756			
	Transport														**3350**	**32,450**	**154,366**

	Closed Loop					Single Well			20 Well			100 Well			Carbon Totals		
	Description	Assumptions	Carbon Factor Source	Carbon factor	Carbon factor unit	Quantity	Unit	Carbon (kgCO2e)	Quantity	Unit	Carbon (kgCO2e)	Quantity	Unit	Carbon (kgCO2e)	Single Well	20 Well	100 Well
A4	x1 truck movement with drilling rig	Assuming 100km each way	DEFRA Average HGV, Average Laden 0.872048477852349kgCO2e/km	174.4096956	kgCO2e/vehicle	1	nr	174	1	nr	174	1	nr	174			
	x1 truck movements with equipment (bailers, generator, mini-forklift, pipes)	Assuming regional 80km each way (RICS, 2023)	DEFRA Average HGV, Average Laden 0.872048477852349kgCO2e/km	139.5277565	kgCO2e/vehicle	1	nr	140	1	nr	140	1	nr	140			
	x1 Van movements for thermal testing rig	Assuming local, 50km each way (RICS, 2023)	DEFRA average Van, 0.230369656375839kgCO2e/km	23.03696564	kgCO2e/vehicle	1	nr	23	1	nr	23	1	nr	23			
	3x Truck for site cabins	Assuming local, 50km each way (RICS, 2023)	DEFRA Average HGV, Average Laden 0.872048477852349kgCO2e/km	87.20484779	kgCO2e/vehicle	3	nr	262	3	nr	262	3	nr	262			
	x1 truck for excavator	Assuming local, 50km each way (RICS, 2023)	DEFRA Average HGV, Average Laden 0.872048477852349kgCO2e/km	87.20484779	kgCO2e/vehicle	1	nr	87	1	nr	87	1	nr	87			
	single well - x1 truck for piping, 20 wells - x5 truck for piping, 100 wells - x25 trucks for piping	Assuming local, 50km each way (RICS, 2023)	DEFRA Average HGV, Average Laden 0.872048477852349kgCO2e/km	87.20484779	kgCO2e/vehicle	1	nr	87	5	nr	436	25	nr	2,180			
	x 4 truck for plant equipment	Assuming national 120km each way (RICS, 2023)	DEFRA Average HGV, Average Laden 0.872048477852349kgCO2e/km	209.2916347	kgCO2e/vehicle	4	nr	837	4	nr	837	4	nr	837			
	Vehicles for other material deliveries (e.g. grout, sacrificial weight plant building, GSHPs, pumps, buffer tanks, plate heat exchanger)	Assuming national 120km each way (RICS, 2023)	DEFRA Average HGV, average laden 0.09695746711kgCO2e/t/km	23.26979211	kgCO2e/t	83380	approx. kg	1,940	1310325	approx. kg	30,491	6474610	approx. kg	150, 663			

	Closed Loop					Single Well			20 Well			100 Well			Carbon Totals		
	Description	**Assumptions**	**Carbon Factor Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Single Well**	**20 Well**	**100 Well**
	Construction														**350**	**6,300**	**49,000**
A5.1	**Demolition**	Assuming NA															
A5.2	Construction activities benchmark	1BH - 18k, plus HP (£5k). Assume £25k 20BHs - £17k each (£340k), plus HPs (£80k) - assume £450k 100BHs - £14k each (1.4M) + HPs (£1M) - assume 3.5M	RICS WLC 1st Edition 1400kgCO2e/£100k of project value	0.014	kgCO2e/£ of project value	25,000	£k Project value	350	450000	£k Project value	6,300	3500000	£k Project Value	49,000			
	Enabling works	Assumed allowance included with cost benchmark															
	Construction activities - Drilling fuel, 2x days drilling, drilling rig - per well)	Assumed allowance included with cost benchmark															
	Construction activities - Water supply during drilling	Assumed allowance included with cost benchmark															
	Construction activities - Excavator fuel	Assumed allowance included with cost benchmark															

	Closed Loop					Single Well			20 Well			100 Well			Carbon Totals		
	Description	**Assumptions**	**Carbon Factor Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Single Well**	**20 Well**	**100 Well**
	Construction activities - On site electricity consumption	Assumed allowance included with cost benchmark															
	Construction activities - On site water consumption	Assumed allowance included with cost benchmark															
A5.3	On site waste	Assumed allowance included with cost benchmark															
	On Site waste disposal	Assumed allowance included with cost benchmark															
A5.4	Optional – site staff commute	excluded															
	In-Use														**32,462**	**397,222**	**1,982,896**
B1.1	**In-use material emissions and**																
B1.2	**In-use fugitive emissions**																
B2	Maintenance	Assuming no complications or unexpected requirements, routine maintenance	RICS WLC Guidance 2023, 1% of A1-5 kgCO2e total	0.01	Maintenance allowance of A1- 5	28118.8	A1-5kgCO2e total	281	94570.8	A1-5kgCO2e total	946	1053251	A1-5kgCO2e total	10,533			

	Description	Assumptions	Carbon Factor Source	Carbon factor	Carbon factor unit	Single Well			20 Well			100 Well			Carbon Totals		
	Repair Impacts																
	Closed Loop					**Single Well**			**20 Well**			**100 Well**			**Carbon Totals**		
	Description	**Assumptions**	**Carbon Factor Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Single Well**	**20 Well**	**100 Well**
B3	Repair	Benchmark increased in proportion to each scenario.	RICS WLC Guidance 2023, 25% of B2 kgCO2e total	0.25	Repairs allowance of B2	281.188	B2 kgCO2e total	70	945.708	B2 kgCO2e total	236	10532.5	B2 kgCO2e total	2,633			
			RICS WLC Guidance 2023, 10% of M&E elements of A1-3 kgCO2e total	0.1	Repairs allowance of M&E	143.51	A1-3 associated with Mechanical and electrical products/materials	14	2448.4	A1-3 associated with Mechanical and electrical products/materials	245	6683.05	A1-3 associated with Mechanical and electrical products/materials	668			
	Replacement																
B4	Replacement of construction products, components and systems																
	Replacement of industrial systems (if applicable for infrastructure):																
	Heat pumps	Assuming 20 year replacement rate		1	replacements per 30 years	143.51	A1-3 kgCO2e	144	1689.1	A1-3 kgCO2e	1,689	5911.85	A1-3 kgCO2e	5,912			
	Plant heat exchangers	Assuming 10 year replacement rate		2	replacements per 30 years	N/A	N/A		75.32	A1-3 kgCO2e	1,513	756.32	A1-3 kgCO2e	1,513			
	Buffer tank	Assuming 20 year replacement rate		1	replacements per 30 years	N/A	N/A		443.36	A1-3 kgCO2e	443	886.72	A1-3 kgCO2e	887			
	Refurbishment planned																
B5	Refurbishment	Assuming NA															

	Use																
	Closed Loop					**Single Well**			**20 Well**			**100 Well**			**Carbon Totals**		
	Description	**Assumptions**	**Carbon Factor Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Single Well**	**20 Well**	**100 Well**
B6	Operational energy consumption - annual electricity for 30 year system life		See operational energy emissions tab	30	Year study period	19.272	MWh	31,953	236.52	MWh	392,150	1182.6	MWh	1,960,751			
	Operational energy – annual electricity outputs 30 years output		See operational energy emissions tab				MWh			MWh			MWh				
B7	Operational water consumption	Assuming NA															
B8	User activities	Assuming NA															
	End of Life																
C1	Deconstruction/Demolition	Assuming best practice deconstruction to maximise reuse of materials	50% of A5, RICS WLC Guidance V2, 2023	0.5		350	A5 kgCO2e	175	6300	A5 kgCO2e	3,150	49000	A5 kgCO2e	24,500			
C2	Transport	Assuming repeat of A4 emissions						3,550			32,450			154,366			
C3	Waste processing for reuse, recycling or other recovery		RICS, 2023: Steel 7% reuse, 93% recycle DEFRA & DESNZ, 2023: Metal recycling 0.985kgCo2e/t	0.00091605	93% recycled Metal kgCO2e/kg	50	kg	0.05	50	kg	0.05	50	kg	0.05			
			RICS, 2023: aggregate 97.5% recycle DEFRA & DESNZ, 2023: Aggregate recycling 0.985kgCo2e/t	0.000960375	97.5% Aggregate kgCO2e/kg	64512	kg	62	1290240	kg	1,239	6451200	kg	6,196			

	Closed Loop					**Single Well**			**20 Well**			**100 Well**			**Carbon Totals**		
	Description	**Assumptions**	**Carbon Factor Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**Single Well**	**20 Well**	**100 Well**
			RICS, 2023: MEP 70% recycle, 30% disposal DEFRA & DESNZ, 2023: WEEE Large recycling 21.281kgCo2e/t	0.0148967	70% recycled MEP kgCO2e/kg	113	kg	2	1330	kg	20	4655	kg	69			
			RICS, 2023: Pipes 90% recycle, 10% disposal DEFRA & DESNZ, 2023: WEEE recycling 21.281kgCo2e/t	0.0191529	Pipes kgCO2e/kg	120	kg	2	120	kg	2	120	kg	2			
C4	Disposal impacts	No emissions associated with reuse	Steel no disposal														
			RICS, 2023: Aggregate 2.5% disposal DEFRA & DESNZ, 2023: Aggregate disposal 1.234kgCO2e/t	0.0003085	2.5% Aggregate kgCO2e/kg	64512	kg	20	1290240	kg	398	6451200	kg	1,990			
			RICS, 2023: MEP 30% disposal DEFRA & DESNZ, 2023: WEEE Large disposal 8.884kgCO2e/t	0.0026652	30% recycled MEP kgCO2e/kg	113	kg	0.3	1330	kg	4	4655	kg	12			
			RICS, 2023: Pipes 90% recycle, 10% disposal DEFRA & DESNZ, 2023: WEEE disposal 8.884kgCO2e/t	0.0008884	Pipes kgCO2e/kg	120	kg	0.1	120	kg	0.1	120	kg	0.1			
	Total														**64,393**	**529,056**	**3,223,283**

D.4 Geothermal Carbon Costs (Open Loop)

Open loop GSHP: 20 litres per second (l/s)

	Open Loop					2 Wells			Carbon Totals
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Pre-Construction (non-physical)								**0**
A0	Pre-construction	Assuming NA							
	Materials								**263,172**
A1-3	Steel casing to top of borehole	Assuming 120m of steel pipe	Highways England CT, Steel Pipework 300mm conversion, 42.28kgCO2e/m	42.28	kgCO2e/m	120.00	m	5,073.60	
	Plastic casing to top of borehole	Assuming 30m of HDPE pipe, 600mm dia	Highways England CT, ICE 3.0: Plastic, HDPE Pipe, 600mm dia HDPE density 0.97 t/m3	51.6	kgCO2e/m	30.00	m	1,548.00	
	Cement to casing and pipe	Assuming CEM I portland cement	ICE 3.0, Cement - CEM I - Portland Cement 0.912 kgCO2e/kg Density Cement screed - 2,100 kg/m3	1915.2	kgCO2e/m3	34.94	m3	66,914.73	
	Abandonment carbon plugging wells with cement	Assuming CEM I portland cement.	ICE 3.0, Cement - CEM I - Portland Cement 0.912 kgCO2e/kg Density Cement screed - 2,100 kg/m3	1915.2	kgCO2e/m3	87.63	m3	167,828.11	
	Distribution - manifold	Assuming an allowance of plastic pipe, assuming 0.5m. Inclusion to be reviewed.	Highways England CT, ICE 3.0: Plastic, HDPE Pipe, 150mm dia pipe, HDPE density 0.97 t/m3	2.975	kgCO2e/0.5m	1.00	nr distribution manifold	2.98	
	Distribution - surface piping	Assuming 150mm dia pipe, 145mm internal dia. 300m length	Highways England CT, ICE 3.0: Plastic, HDPE Pipe, 150mm dia pipe, HDPE density 0.97 t/m3	5.95	kgCO2e/m	300.00	m	1,785.00	
	Distribution - surface piping, aggregate fill (0.6m x 0.6m)	Assuming imported backfill to pipe surround	ICE 3.0,	17.928	kgCO2e/m3	108.00	m3	1,936.22	

			Aggregates and Sand - Typical UK Mix, 0.00747 kgCO2e/kg (2,240 kg/m3)						
	Open Loop					**2 Wells**			**Carbon Totals**
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Plant building (2 well (L) 5m x (W) 5m x (H) 3m		OneClick 400kgCO2e/m2 (A1-3 for "industrial" European building)	400	kgCO2e/m2	25.00	m2	10,000.00	
	GSHP - heat pumps)	Assumed flow rate of 20 l/s; equivalent to 670kW. Use 8x Kensa Q systems (665kg each, 5320kg total)	ICE 3.0 Steel - Engineering, 1.27 kgCO2e/kg	1.27	kgco2e/kg	5320.00	kg	6,756.40	
	Submersible circulation Pumps	Assumed electrical submersible pump is 100kg of steel total weight	ICE 3.0 Steel - Engineering, 1.27 kgCO2e/kg	1.27	kgco2e/kg	100.00	kg	127.00	
	Buffer tank	Assumed hot water tank product, 270L. Assuming stainless steel.	aroSTOR 270 litre, 68kg empty weight, ICE 3.0 Stainless Steel 6.52 kgCO2e/kg	443.36	kgCO2e/assumed tank	1.00	nr	443.36	
	Plate heat exchanger	Assuming 80kW heat transfer plate, 58kg empty weight. Assuming stainless steel.	Weight of steel: Plate Heat Exchanger Strebel 80kW, 58kg. ICE 3.0 Stainless Steel 6.52 kgCO2e/kg	378.16	kgCO2e/assumed exchanger	2.00	nr	756.32	
	Transport								**14,041**
A4	x2 truck movement with drilling rig	Assuming 100km each way	DEFRA Average HGV, Average Laden 0.872048477852349kgCO2e/km	174.4096956	kgCO2e/vehicle	2.00	nr	348.82	

	x2 truck movements with equipment (bailers, generator, mini-forklift, pipes)	Assuming regional 80km each way	DEFRA Average HGV, Average Laden 0.872048477852349kgCO2e/km	139.5277565	kgCO2e/vehicle	2.00	nr	279.06	

	Open Loop					2 Wells			Carbon Totals
	Description	Assumptions	Carbon Source	Carbon factor	Carbon factor unit	Quantity	Unit	Carbon (kgCO2e)	2 Wells
	x2 Van movements for thermal testing rig	Assuming local, 50km each way	DEFRA average Van, 0.230369656375839kgCO2e/km	23.03696564	kgCO2e/vehicle	2.00	nr	46.07	
	6x Truck for site cabins	Assuming local, 50km each way	DEFRA Average HGV, Average Laden 0.872048477852349kgCO2e/km	87.20484779	kgCO2e/vehicle	6.00	nr	523.23	
	x2 truck for excavator	Assuming local, 50km each way	DEFRA Average HGV, Average Laden 0.872048477852349kgCO2e/km	87.20484779	kgCO2e/vehicle	2.00	nr	174.41	
	single well - x1 truck for piping, 20 wells - x10 truck for piping, 100 wells - x50 trucks for piping	Assuming local, 50km each way	DEFRA Average HGV, Average Laden 0.872048477852349kgCO2e/km	87.20484779	kgCO2e/vehicle	1.00	nr	87.20	
	x 4 truck for plant equipment	Assuming national 120km each way	DEFRA Average HGV, Average Laden 0.872048477852349kgCO2e/km	209.2916347	kgCO2e/vehicle	4.00	nr	837.17	
	Vehicles for other material deliveries (e.g. grout, sacrificial weight plant building, GSHPs, pumps, buffer tanks, plate heat exchanger)	Assuming national 120km each way	DEFRA Average HGV, average laden 0.09695746711kgCO2e/t/km	23.26979211	kgCO2e/t	504733.47	approx. kg	11,745.04	
	Construction								**5,600**
A5.1	Demolition	Assuming NA							

A5.2	Construction activities benchmark	each (£300k total), plus equipment £100k - assume £400k	RICS WLC 1st Edition 1400kgCO2e/£100k of project value	0.014	kgCO2e/£ of project value	400000.00	£	5,600.00	
	Enabling works	Assumed allowance included with cost benchmark							
	Open Loop					**2 Wells**			**Carbon Totals**
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Construction activities - Drilling fuel, 4x days drilling, drilling rig - per well)	Assumed allowance included with cost benchmark							
	Construction activities - Water supply during drilling	Assumed allowance included with cost benchmark							
	Construction activities - Excavator fuel	Assumed allowance included with cost benchmark							
	Construction activities - On site electricity consumption	Assumed allowance included with cost benchmark							
	Construction activities - On site water consumption	Assumed allowance included with cost benchmark							
A5.3	On site waste	Assumed allowance included with cost benchmark							
	On site waste disposal	Assumed allowance included with cost benchmark							
A5.4	Optional – Site staff commute	Excluded							
	In-Use								**2,170,087**
B1.1	**In-use material emissions and**								
B1.2	**In-use fugitive emissions**								
	Maintenance impacts								

B2	Maintenance	Assuming no complications or unexpected requirements, routine maintenance. RICS benchmark increased to allow for increased maintenance associated with each scenario.	RICS WLC Guidance 2023, 1% of A1-5 kgCO2e total. Increased in proportion to each scenario	1.50%	Maintenance allowance of A1-5	282812.72	A1-5kgCO2e total	4,242.19	
	Open Loop					**2 Wells**			**Carbon Totals**
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Repair Impacts								
B3	Repair	Benchmark increased in proportion to each scenario.	RICS WLC Guidance 2023, 25% of B2 kgCO2e total. Increased in proportion to each scenario	30.00%	Repairs allowance of B2	4242.19	B2 kgCO2e total	1,272.66	
			RICS WLC Guidance 2023, 10% of M&E elements of A1-3 kgCO2e total	10.00%	Repairs allowance of M&E	7639.72	A1-3 associated with Mechanical and electrical products/ materials	763.97	
	Replacement								
B4.1	Replacement of construction products, components and systems								
B4.2	Replacement of industrial systems (if applicable for infrastructure):								
	Heat pumps	Assuming 20 year replacement rate		1	Replacement per 30 years	6756.40	A1-3 kgCO2e	6756.40	
	Pumps	Assuming 5 year replacement rate		5	Replacement per 30 years	127.00	A1-3 kgCO2e	635.00	

	Plant heat exchanger	Assuming 10 year replacement rate		2	Replacement per 30 years	756.32	A1-3 kgCO2e	886.72	
	Buffer tank	Assuming 20 year replacement rate		1	Replacements per 30 years	443.36	A1-3 kgCO2e	756.32	
	Refurbishment/planned								
B5	Refurbishment	Assuming NA							
	Open Loop					**2 Wells**			**Carbon Totals**
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Use								
B6	Operational energy consumption - annual electricity for 40 year system life	Assuming 20l/s system, 2400 MWh(annual), 74,000 (30 years)	See operational energy emissions tab		30 year study period	131.40	MWh	2,154,773.92	
	Power outputs 40 year output						MWh		
B7	Operational water consumption	Assuming NA							
B8	User activities	Assuming NA							
	End of Life								**17,433**
	Deconstruction/Demolition	Assuming best practice deconstruction to maximise reuse of materials	50% of A5, RICS WLC Guidance V2, 2023	50.00%		5600.00	A5 kgCO2e total	2,800.00	
C2	Transport	Assuming same as A4				14041.00	A4 kgCO2e total	14,041.00	
C3	Waste processing for reuse, recycling or other recovery		RICS, 2023: Steel 7% reuse, 93% recycle DEFRA & DESNZ, 2023: Metal recycling 0.985kgCo2e/t	0.00091605	93% recycled Metal kgCO2e/kg	68.00	kg	0.06	

			RICS, 2023: concrete 97.5% recycle DEFRA & DESNZ, 2023: Concrete recycling 0.985kgCo2e/t	0.000960375	97.5% Concrete kgCO2e/kg	257393.47	kg	247.19	
			RICS, 2023: aggregate 97.5% recycle DEFRA & DESNZ, 2023: Aggregate recycling 0.985kgCo2e/t	0.000960375	97.5% Aggregate kgCO2e/kg	241920.00	kg	232.33	
	Open Loop					**2 Wells**			**Carbon Totals**
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
			RICS, 2023: MEP 70% recycle DEFRA & DESNZ, 2023: WEEE Large recycling 21.281kgCo2e/t	0.0148967	70% recycled MEP kgCO2e/kg	5536.00	kg	82.47	
C4	Disposal impacts	No emissions	Steel no disposal						
			RICS, 2023: Aggregate 2.5% disposal DEFRA & DESNZ, 2023: Aggregate disposal 1.234kgCO2e/t	0.00003085	2.5% Aggregate kgCO2e/kg	257393.47	kg	7.94	
			RICS, 2023: Concrete 2.5% disposal DEFRA & DESNZ, 2023: Concrete disposal 1.234kgCO2e/t	0.00003085	2.5% Concrete kgCO2e/kg	241920.00	kg	7.46	
			RICS, 2023: MEP 30% disposal DEFRA & DESNZ, 2023: WEEE Large disposal 8.884kgCO2e/t	0.0026652	30% disposal MEP kgCO2e/kg	5536.00	kg	14.75	
	Total								**2,470,333**

D.5 Geothermal Carbon Costs (Deep Geothermal)

Deep geothermal doublet systems: 1km, 2km, 3km, 4km, 5km, and 5km through hard rock

	System Overview					1km Doublet (2 wells, 1km each)			Carbon Totals	2km Doublet (2 wells, 2km each)			Carbon Totals
	System Description												
	Description	Assumptions	Carbon Source	Carbon factor	Carbon factor unit	Quantity	Unit	Carbon (kgCO2e)	2 Wells	Quantity	Unit	Carbon (kgCO2e)	2 Wells
	Pre-Construction (non-physical								0				0
A0	Pre-construction	Assuming NA											
	Materials								**1,941,524**				**2,046,448**
	Steel casing to top of borehole	Assuming steel material weight based on 10,000kg per 500m of tubing. This varies with well depth (e.g. 1km, 2km ,3km have 10, 20, 30 tonnes respectively)	ICE 3.0 Steel, Engineering steel - 1.27kgCO2e/kg	1.27	kgCO2e/kg	10,000	kg	12,700		20,000	kg	25,400	
	Cement Infill between drilled hole and casing	Assuming CEM I portland cement.	ICE 3.0, Cement - CEM I - Portland Cement 0.912 kgCO2e/kg Density Cement screed - 2,100 kg/m3	1915.2	kgCO2e/m3	34	m3	64,393		82	m3	156,617	
	Plant building	assume 2 storey building with c. 4000m2 footprint (includes substructure and superstructure)	OneClick 400kgCO2e/m2 (A1-3 for "industrial" European building)	400	kgCO2e/m2	4,000	m2	1,600,000		4,000	m2	1,600,000	
	GSHP heatpumps	Assumed 1 large heat pump required for 1km, 2km scenarios, 10,000kg for each. Assumed no heat pump required for 3km, 4km,	ICE 3.0 Steel, Engineering steel - 1.27kgCO2e/kg	1.27	kgCO2e/pump	10,000	kg	12,700		10,000	kg	12,700	

		5km scenarios (water is hot enough already)											
	System Overview					**1km Doublet (2 wells, 1km each)**			**Carbon Totals**	**2km Doublet (2 wells, 2km each)**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Surface piping - Each well 1km from the energy centre (2km total)	Assumed EPD	11.6kgCO2e/1m(3.98kg) insulated pipe product, steel and HDPE	11.6	kgCO2e/m	2,000	m	23,200		2,000	m	23,200	
	Electrical submersible pumps	Assuming 1,300kg per pump, 4" diameter, 5m long, 8,000kg/m3.	ICE 3.0 Steel, Engineering steel - 1.27kgCO2e/kg	1.27	kgCO2e/kg	1,300	kg	1,651		1,300	kg	1,651	
	Degasser	Assuming volume of galvanised steel as product specific carbon information not available	ICE 3.0 Steel, Hot dip galvanised steel - 2.76kgCO2e/kg	2.76	kg steel	14,500	kg	40,020		14,500	kg	40,020	
	Pressure Booster	Assuming volume of galvanised steel as product specific carbon information not available	ICE 3.0 Steel, Hot dip galvanised steel - 2.76kgCO2e/kg	2.76	kg steel	700	kg	1,932		700	kg	1,932	

	Filters	Assuming volume of galvanised steel as product specific carbon information not available	ICE 3.0 Steel, Hot dip galvanised steel - 2.76kgCO2e/kg	2.76	kg steel	600	kg	1,656		600	kg	1,656	
	System Overview					**1km Doublet (2 wells, 1km each)**			**Carbon Totals**	**2km Doublet (2 wells, 2km each)**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Plate Heat exchanger	Assuming volume of galvanised steel as product specific carbon information not available	ICE 3.0 Steel, Hot dip galvanised steel - 2.76kgCO2e/kg	2.76	kg steel	1,800	kg	4,968		1,800	kg	4,968	
	Plant pipework	Assuming HDPE 150mm dia pipe	Highways England CT, ICE 2.0: Plastic, HDPE Pipe 150mm diameter, 2.52 tCO2e/t. Conversion factor 0.002	5.04	kgCO2e/m	100	m	504.0		100	m	504.0	
	Allowance for other elements: Cooling fans Structural steel ORC plant Binary plant Pipework Building	Allowance for other elements lacking specific information.	ICE 3.0 Steel, Engineering steel - 1.27kgCO2e/kg	1.27	kgCO2e/kg	140,000	kg	177,800.0		140,000	kg	177,800.0	
	Transport								**239,098**				**334,511**
A4	Drilling rig truck movement	Assuming each truck travels 1,000km. In each direction	DEFRA Average HGV, Average Laden 0.872048477852349 kgCO2e/km	0.872048478	kgCO2e/km	100,000	km	87,205		200,000	km	174,410	
	Other transport emissions	Assumed emissions based on ratio of A1-						151,893				160,101	

		3kgCO2e of Closed loop and open loop to respective A4kgCO2e											
	Construction								**112,000**				**196,000**
A5.1	Demolition	Assuming NA											
	System Overview					**1km Doublet (2 wells, 1km each)**			**Carbon Totals**	**2km Doublet (2 wells, 2km each)**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Construction activities	Assumed project values: 1km system - £8M 2km - £14M 3km - £17.5M 4km - £23.5M 5km - £33M 5km (hard rock) - £40M	RICS WLC 1st Edition 1400kgCO2e/£100k of project value	0.014	KgCO2e/£ of project value	8,000,000	£	112,000		14,000,000	£	196,000	
	Enabling works activities												
	Construction activities - On site electricity consumption												
	Construction activities - On site water consumption												
A5.3	On site waste												
	On site waste disposal												
A5.4	Optional – Site staff commute												
	In-Use								**9,325,642**				**11,174,552**
B1.1	**In-use material emissions and**												
B1.2	**In-use fugitive emissions**												
	Maintenance impacts												
B2	Maintenance	Assuming no complications or unexpected	RICS WLC Guidance 2023, 1% of A1-5 kgCO2e total.	2.00%	Maintenance allowance of A1- 5	2,292,622	A1-5 kgCO2e total	45,852		2,576,959	A1-5 kgCO2e total	51,539	

		requirements, routine maintenance. RICS benchmark increased to allow for increased maintenance associated with each scenario.	Increased in proportion to each scenario.										
	Repair Impacts												
	System Overview					**1km Doublet (2 wells, 1km each)**			**Carbon Totals**	**2km Doublet (2 wells, 2km each)**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
B3	Repair	Benchmark increased in proportion to each scenario	RICS WLC Guidance 2023, 25% of B2 kgCO2e total	50.00%	Repairs allowance of B2	45,852	B2 kgCO2e total	22,926		51,539	B2 kgCO2e total	25,770	
			RICS WLC Guidance 2023, 10% of M&E elements of A1-3 kgCO2e total	10.00%	Repairs allowance of M&E A1-3	240,727	A1-3 associated with Mechanical and electrical products/ materials	24,073		240,727	A1-3 associated with Mechanical and electrical product/ materials	24,073	
	Replacement												
B4.1	Replacement of construction products, components and systems												
B4.2	Replacement of industrial systems (if applicable for infrastructure):												
	Heat pumps	Assuming 20 year replacement rate		1	Replacement per 30 years	12,700	A1-3 kgCO2e	12,700		12,700	A1-3 kgCO2e	12,700	
	Plant heat exchanger	Assuming 10 year replacement rate		2	Replacement per 40 years	4,968	A1-3 kgCO2e	9,936		4,968	A1-3 kgCO2e	9,936	
	Electrical submersible pumps	Assuming 5 year replacement rate		5	Replacements per 40 years	1,651	A1-3 kgCO2e	8,255		1,651	A1-3 kgCO2e	8,255	
	Refurbishment/planned												
B5	Refurbishment												

	Use												
B6	Operational energy consumption - annual electricity	Assumed low scenario	See operational energy emissions tab			5,500	MWh	9,201,900		6,660	MWh	11,042,280	
	System Overview					**1km Doublet (2 wells, 1km each)**			**Carbon Totals**	**2km Doublet (2 wells, 2km each)**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Power outputs 30 year output	Assumed electrical output per scenario: 1km , 2km, 3km NO ELECTRICAL OUTPUT 4km - 1.5MWe output (c. 12,000MWhe) 5km - 3MWe output (c. 24,000MWhe)	See operational energy emissions tab			NA	MWh			NA	MWh		
B7	Operational water consumption	Assuming NA											
B8	User activities	Assuming NA											
	End of Life								**338,579**				**503,059**
C1	Deconstruction/ Demolition	Assuming best practice deconstruction to maximise reuse of materials	50% of A5, RICS WLC Guidance V2, 2023	50.00%		112,000	A5 total kgCO2e	56,000		196,000		98,000	
	Plugs	Assuming abandoned material to cap borehole at end of life	ICE 3.0, Cement - CEM I - Portland Cement 0.912 kgCO2e/kg Density Cement screed - 2,100 kg/m3	1915.2	kgCO2e/m3	21	m3	40,436		35	m3	67,393	
C2	Transport	Assuming same as A4	A4 total kgCO2e					239,098				334,511	
C3	Waste processing for reuse, recycling or other recovery		RICS, 2023: Steel 7% reuse, 93% recycle DEFRA & DESNZ, 2023:	0.00091605	93% recycled Metal kgCO2e/kg	10,000	kg	9		20,000	kg	18	

			Metal recycling 0.985kgCO2e/t										
			RICS, 2023: concrete 97.5% recycle DEFRA & DESNZ, 2023: Concrete recycling 0.985kgCO2e/t	0.000960375	97.5% Concrete kgCO2e/kg	70,607	kg	68		171,729	kg	165	
	System Overview					**1km Doublet (2 wells, 1km each)**			**Carbon Totals**	**2km Doublet (2 wells, 2km each)**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
			RICS, 2023: MEP 70% recycle DEFRA & DESNZ, 2023: WEEE Large recycling 21.281kgCO2e/t	0.0148967	70% recycled MEP kgCO2e/kg	168,900	kg	2,516		168,900	kg	2,516	
C4	Disposal impacts	No emissions	Steel no disposal										
			RICS, 2023: Concrete 2.5% disposal DEFRA & DESNZ, 2023: Concrete disposal 1.234kgCO2e/t	0.00003085	2.5% Concrete kgCO2e/kg	70,607	kg	2		171,729	kg	5	
			RICS, 2023: MEP 30% disposal DEFRA & DESNZ, 2023: WEEE Large disposal 8.884kgCO2e/t	0.0026652	30% disposal MEP kgCO2e/kg	168,900	kg	450		168,900	kg	450	
	Total								**11,956,843**				**14,254,570**

	System Overview					3km Doublet (2 wells, 3km each)			Carbon Totals	4km Doublet (2 wells, 4km each)			Carbon Totals
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Pre-Construction (non-physical								**0**				**0**
A0	Pre-construction	Assuming NA											
	Materials								**2,098,337**				**2,279,246**
	Steel casing to top of borehole	Assuming steel material weight based on 10,000kg per 500m of tubing. This varies with well depth (e.g. 1km, 2km ,3km have 10, 20, 30 tonnes respectively)	ICE 3.0 Steel, Engineering steel - 1.27kgCO2e/kg	1.27	kgCO2e/kg	30,000	kg	38,100		40,000	kg	50,800	
	Cement Infill between drilled hole and casing	Assuming CEM I portland cement.	ICE 3.0, Cement - CEM I - Portland Cement 0.912 kgCO2e/kg Density Cement screed - 2,100 kg/m3	1915.2	kgCO2e/m3	109	m3	208,506		197	m3	376,715	
	Plant building	assume 2 storey building with c. 4000m2 footprint (includes substructure and superstructure)	OneClick 400kgCO2e/m2 (A1-3 for "industrial" European building)	400	kgCO2e/m2	4,000	m2	1,600,000		4,000	m2	1,600,000	
	GSHP heat pumps	Assumed 1 large heat pump required for 1km, 2km scenarios, 10,000kg for each. Assumed no heat pump required for 3km, 4km,	ICE 3.0 Steel, Engineering steel - 1.27kgCO2e/kg	1.27	kgCO2e/pump			0				0	

		5km scenarios (water is hot enough already)											
	System Overview					**3km Doublet (2 wells, 3km each)**			**Carbon Totals**	**3km Doublet (2 wells, 4km each)**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Surface piping - Each well 1km from the energy centre (2km total)	Assumed EPD	11.6kgCO2e/1m(3.98kg) insulated pipe product, steel and HDPE	11.6	kgCO2e/m	2,000	m	23,200		2,000	m	23,200	
	Electrical submersible pumps	Assuming 1,300kg per pump, 4" diameter, 5m long, 8,000kg/m3.	ICE 3.0 Steel, Engineering steel - 1.27kgCO2e/kg	1.27	kgCO2e/kg	1,300	kg	1,651		1,300	kg	1,651	
	Degasser	Assuming volume of galvanised steel as product specific carbon information not available	ICE 3.0 Steel, Hot dip galvanised steel - 2.76kgCO2e/kg	2.76	kg steel	14,500	kg	40,020		14,500	kg	40,020	
	Pressure Booster	Assuming volume of galvanised steel as product specific carbon information not available	ICE 3.0 Steel, Hot dip galvanised steel - 2.76kgCO2e/kg	2.76	kg steel	700	kg	1,932		700	kg	1,932	

	Filters	Assuming volume of galvanised steel as product specific carbon information not available	ICE 3.0 Steel, Hot dip galvanised steel - 2.76kgCO2e/kg	2.76	kg steel	600	kg	1,656		600	kg	1,656	
	System Overview					**3km Doublet (2 wells, 3km each)**			**Carbon Totals**	**3km Doublet (2 wells, 4km each)**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Plate Heat exchanger	Assuming volume of galvanised steel as product specific carbon information not available	ICE 3.0 Steel, Hot dip galvanised steel - 2.76kgCO2e/kg	2.76	kg steel	1,800	kg	4,968		1,800	kg	4,968	
	Plant pipework	Assuming HDPE 150mm dia pipe	Highways England CT, ICE 2.0: Plastic, HDPE Pipe 150mm diameter, 2.52 tCO2e/t. Conversion factor 0.002	5.04	kgCO2e/m	100	m	504.0		100	m	504.0	
	Allowance for other elements: Cooling fans Structural steel ORC plant Binary plant Pipework Building	Allowance for other elements lacking specific information.	ICE 3.0 Steel, Engineering steel - 1.27kgCO2e/kg	1.27	kgCO2e/kg	140,000	kg	177,800.0		140,000	kg	177,800.0	
	Transport								**338,571**				**370,165**
A4	Drilling rig truck movement	Assuming each truck travels 1,000km. In each direction	DEFRA Average HGV, Average Laden 0.872048477852349 kgC O2e/km	0.87204847 8	kgCO2e/km	200,000	km	174,410		220,000	km	191,851	

	Other transport emissions	Assumed emissions based on ratio of A1-3kgCO2e of Closed loop and open loop to respective A4kgCO2e						164,161				178,314	
	System Overview					**3km Doublet (2 wells, 3km each)**			**Carbon Totals**	**4km Doublet (2 wells, 4km each)**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Construction								**245,000**				**329,000**
A5.1	Demolition	Assuming NA											
	Construction activities	Assumed project values: 1km system - £8M 2km - £14M 3km - £17.5M 4km - £23.5M 5km - £33M 5km (hard rock) - £40M	RICS WLC 1st Edition 1400kgCO2e/£100k of project value	0.014	KgCO2e/£ of project value	17,500,000	£	245,000		23,500,000	£	329,000	
	Enabling works activities												
	Construction activities - On site electricity consumption												
	Construction activities - On site water consumption												
A5.3	On site waste												
	On site waste disposal												
A5.4	Optional – Site staff commute	Excluded											
	In-Use								**6,090,251**				**11,241,267**
B1.1	**In-use material emissions and**												

B1.2	**In-use fugitive emissions**												
	Maintenance impacts												
	System Overview					**3km Doublet (2 wells, 3km each)**			**Carbon Totals**	**4km Doublet (2 wells, 4km each)**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
B2	Maintenance	Assuming no complications or unexpected requirements, routine maintenance. RICS benchmark increased to allow for increased maintenance associated with each scenario.	RICS WLC Guidance 2023, 1% of A1-5 kgCO2e total. Increased in proportion to each scenario.	2.00%	Maintenance allowance of A1- 5	2,681,907	A1-5 kgCO2e total	53,638		2,978,411	A1-5 kgCO2e total	59,568	
	Repair Impacts												
B3	Repair	Benchmark increased in proportion to each scenario	RICS WLC Guidance 2023, 25% of B2 kgCO2e total	50.00%	Repairs allowance of B2	53,638	B2 kgCO2e total	26,819		59,568	B2 kgCO2e total	29,784	
			RICS WLC Guidance 2023, 10% of M&E elements of A1-3 kgCO2e total	10.00%	Repairs allowance of M&E A1-3	228,027	A1-3 associated with Mechanical and electrical products/ materials	22,803		228,027	A1-3 associated with Mechanical and electrical product/ materials	22,803	
	Replacement												
B4.1	Replacement of construction products, components and systems												
B4.2	Replacement of industrial systems (if applicable for infrastructure):												
	Heat pumps	Assuming 20 year replacement rate		1	Replacement per 30 years	0	A1-3 kgCO2e	0		0	A1-3 kgCO2e	0	

	Plant heat exchanger	Assuming 10 year replacement rate		2	Replacement per 40 years	4,968	A1-3 kgCO2e	9,936		4,968	A1-3 kgCO2e	9,936	
	Electrical submersible pumps	Assuming 5 year replacement rate		5	Replacements per 40 years	1,651	A1-3 kgCO2e	8,255		1,651	A1-3 kgCO2e	8,255	
	Refurbishment/planned												
	System Overview					**3km Doublet (2 wells, 3km each)**			**Carbon Totals**	**4km Doublet (2 wells, 4km each)**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
B5	Refurbishment	Assumed NA											
	Use												
B6	Operational energy consumption - annual electricity	Assumed low scenario	See operational energy emissions tab			3600	MWh	5,968,800		6,701	MWh	11,110,921	
	Power outputs 30 year output	Assumed electrical output per scenario: 1km , 2km, 3km NO ELECTRICAL OUTPUT 4km - 1.5MWe output (c. 12,000MWhe) 5km - 3MWe output (c. 24,000MWhe)	See operational energy emissions tab			NA	MWh			NA	MWh		
B7	Operational water consumption	Assuming NA											
B8	User activities	Assuming NA											
	End of Life								**571,944**				**686,166**
C1	Deconstruction/ Demolition	Assuming best practice deconstruction to maximise reuse of materials	50% of A5, RICS WLC Guidance V2, 2023	50.00%		245,000		122,500		329,000		164,500	

	Plugs	Assuming abandoned material to cap borehole at end of life	ICE 3.0, Cement - CEM I - Portland Cement 0.912 kgCO2e/kg Density Cement screed - 2,100 kg/m3	1915.2	kgCO2e/m3	56	m3	107,829		77	m3	148,265	
C2	Transport	Assuming same as A4	A4 total kgCO2e					338,571				370,165	
	System Overview					**3km Doublet (2 wells, 3km each)**			**Carbon Totals**	**4km Doublet (2 wells, 4km each)**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Waste processing for reuse, recycling or other recovery		RICS, 2023: Steel 7% reuse, 93% recycle DEFRA & DESNZ, 2023: Metal recycling 0.985kgCO2e/t	0.00091605	93% recycled Metal kgCO2e/kg	30,000	kg	27		40,000	kg	37	
			RICS, 2023: concrete 97.5% recycle DEFRA & DESNZ, 2023: Concrete recycling 0.985kgCO2e/t	0.000960375	97.5% Concrete kgCO2e/kg	228,625	kg	220		413,065	kg	397	
			RICS, 2023: MEP 70% recycle DEFRA & DESNZ, 2023: WEEE Large recycling 21.281kgCO2e/t	0.0148967	70% recycled MEP kgCO2e/kg	158,900	kg	2,367		158,900	kg	2,367	
C4	Disposal impacts	No emissions	Steel no disposal										
			RICS, 2023: Concrete 2.5% disposal DEFRA & DESNZ, 2023: Concrete disposal 1.234kgCO2e/t	0.00003085	2.5% Concrete kgCO2e/kg	228,625	kg	7		413,065	kg	13	
			RICS, 2023:	0.0026652	30% disposal MEP kgCO2e/kg	158,900	kg	424		158,900	kg	424	

			MEP 30% disposal DEFRA & DESNZ, 2023: WEEE Large disposal 8.884kgCO2e/t										
	Total								**9,344,102**				**14,905,845**

	System Overview					5km Doublet (2 wells, 5km each)			Carbon Totals	5km Doublet (2 wells, 5km each) Hard rock			Carbon Totals
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Pre-Construction (non-physical								0				**0**
A0	Pre construction	Assuming NA											
	Materials								2,353,534				2,265,667
	Steel casing to top of borehole	Assuming steel material weight based on 10,000kg per 500m of tubing. This varies with well depth (e.g. 1km, 2km ,3km have 10, 20, 30 tonnes respectively)	ICE 3.0 Steel, Engineering steel - 1.27kgCO2e/kg	1.27	kgCO2e/kg	50,000	kg	63,500		50,000	kg	63,500	
	Cement Infill between drilled hole and casing	Assuming CEM I portland cement.	ICE 3.0, Cement - CEM I - Portland Cement 0.912 kgCO2e/kg Density Cement screed - 2,100 kg/m3	1915.2	kgCO2e/m3	229	m3	438,303		183	m3	350,436	
	Plant building	assume 2 storey building with c. 4000m2 footprint (includes substructure and superstructure)	OneClick 400kgCO2e/m2 (A1-3 for "industrial" European building)	400	kgCO2e/m2	4,000	m2	1,600,000		4,000	m2	1,600,000	
	GSHP heat pumps	Assumed 1 large heat pump required for 1km, 2km scenarios, 10,000kg for each. Assumed no heat pump required for 3km, 4km,	ICE 3.0 Steel, Engineering steel - 1.27kgCO2e/kg	1.27	kgCO2e/pump			0				0	

		5km scenarios (water is hot enough already)											
	System Overview					**5km Doublet (2 wells, 5km each)**			**Carbon Totals**	**5km Doublet (2 wells, 5km each) Hard rock**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Surface piping - Each well 1km from the energy centre (2km total)	Assumed EPD	11.6kgCO2e/1m(3.98kg) insulated pipe product, steel and HDPE	11.6	kgCO2e/m	2,000	m	23,200		2,000	m	23,200	
	Electrical submersible pumps	Assuming 1,300kg per pump, 4" diameter, 5m long, 8,000kg/m3.	ICE 3.0 Steel, Engineering steel - 1.27kgCO2e/kg	1.27	kgCO2e/kg	1,300	kg	1,651		1,300	kg	1,651	
	Degasser	Assuming volume of galvanised steel as product specific carbon information not available	ICE 3.0 Steel, Hot dip galvanised steel - 2.76kgCO2e/kg	2.76	kg steel	14,500	kg	40,020		14,500	kg	40,020	
	Pressure Booster	Assuming volume of galvanised steel as product specific carbon information not available	ICE 3.0 Steel, Hot dip galvanised steel - 2.76kgCO2e/kg	2.76	kg steel	700	kg	1,932		700	kg	1,932	

	Filters	Assuming volume of galvanised steel as product specific carbon information not available	ICE 3.0 Steel, Hot dip galvanised steel - 2.76kgCO2e/kg	2.76	kg steel	600	kg	1,656		600	kg	1,656	
	System Overview					**5km Doublet (2 wells, 5km each)**			**Carbon Totals**	**5km Doublet (2 wells, 5km each) Hard rock**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Plate Heat exchanger	Assuming volume of galvanised steel as product specific carbon information not available	ICE 3.0 Steel, Hot dip galvanised steel - 2.76kgCO2e/kg	2.76	kg steel	1,800	kg	4,968		1,800	kg	4,968	
	Plant pipework	Assuming HDPE 150mm dia pipe	Highways England CT, ICE 2.0: Plastic, HDPE Pipe 150mm diameter, 2.52 tCO2e/t. Conversion factor 0.002	5.04	kgCO2e/m	100	m	504.0		100	m	504.0	
	Allowance for other elements: Cooling fans Structural steel ORC plant Binary plant Pipework Building	Allowance for other elements lacking specific information.	ICE 3.0 Steel, Engineering steel - 1.27kgCO2e/kg	1.27	kgCO2e/kg	140,000	kg	177,800.0		140,000	kg	177,800.0	
	Transport								**375,976**				**369,102**
A4	Drilling rig truck movement	Assuming each truck travels 1,000km. In each direction	DEFRA Average HGV, Average Laden 0.872048477852349 kgCO2e/km	0.872048478	kgCO2e/km	220,000	km	191,851		220,000	km	191,851	

	Other transport emissions	Assumed emissions based on ratio of A1-3kgCO2e of Closed loop and open loop to respective A4kgCO2e						184,126				177,252	
	System Overview					**5km Doublet (2 wells, 5km each)**			**Carbon Totals**	**5km Doublet (2 wells, 5km each) Hard rock**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Construction								462,000				560,000
A5.1	Demolition	Assuming NA											
	Construction activities	Assumed project values: 1km system - £8M 2km - £14M 3km - £17.5M 4km - £23.5M 5km - £33M 5km (hard rock) - £40M	RICS WLC 1st Edition 1400kgCO2e/£100k of project value	0.014	KgCO2e/£ of project value	33,000,000	£	462,000		40,000,000	£	560,000	
	Enabling works activities												
	Construction activities - On site electricity consumption												
	Construction activities - On site water consumption												
A5.3	On site waste												
	On site waste disposal												
A5.4	Optional – Site staff commute	Excluded											
	In-Use								**14,515,578**				**14,515,676**
B1.1													

	In-use material emissions and												
B1.2	**In-use fugitive emissions**												
	Maintenance impacts												
	System Overview					**5km Doublet (2 wells, 5km each)**			**Carbon Totals**	**5km Doublet (2 wells, 5km each) Hard rock**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
B2	Maintenance	Assuming no complications or unexpected requirements, routine maintenance. RICS benchmark increased to allow for increased maintenance associated with each scenario.	RICS WLC Guidance 2023, 1% of A1-5 kgCO2e total. Increased in proportion to each scenario.	2.00%	Maintenance allowance of A1- 5	3,191,510	A1-5 kgCO2e total	63,830		3,194,770	A1-5 kgCO2e total	63,895	
	Repair Impacts												
B3	Repair	Benchmark increased in proportion to each scenario	RICS WLC Guidance 2023, 25% of B2 kgCO2e total	50.00%	Repairs allowance of B2	63,830	B2 kgCO2e total	31,915		63,895	B2 kgCO2e total	31,948	
			RICS WLC Guidance 2023, 10% of M&E elements of A1-3 kgCO2e total	10.00%	Repairs allowance of M&E A1-3	228,027	A1-3 associated with Mechanical and electrical products/ materials	22,803		228,027	A1-3 associated with Mechanical and electrical product/ materials	22,803	
	Replacement												
B4.1	Replacement of construction products, components and systems												
B4.2	Replacement of industrial systems (if applicable for infrastructure):												

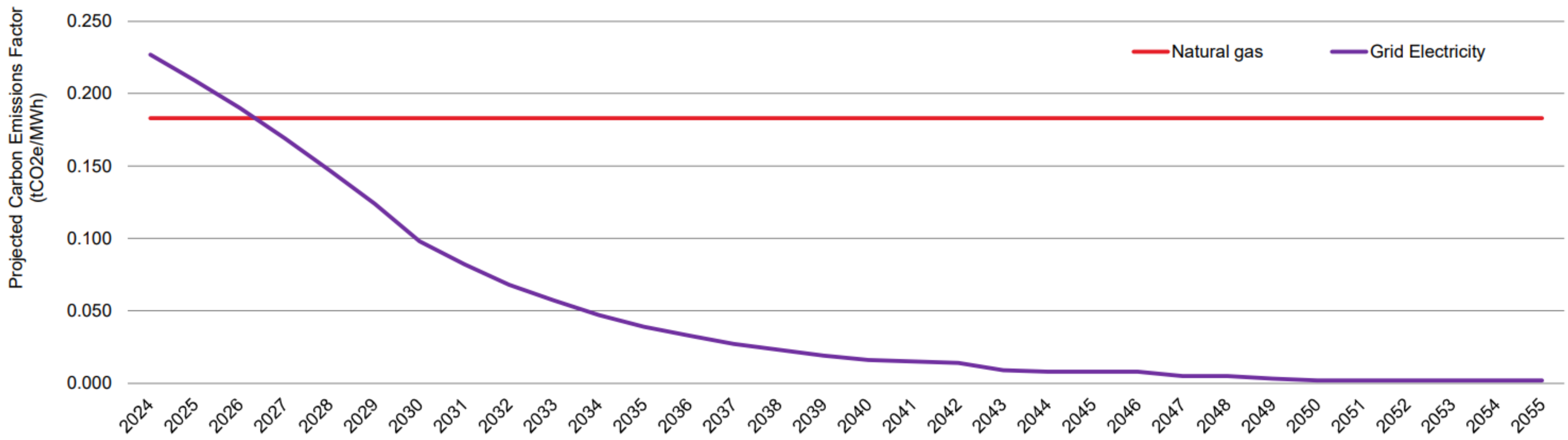
	Heat pumps	Assuming 20 year replacement rate		1	Replacement per 30 years	0	A1-3 kgCO2e	0		0	A1-3 kgCO2e	0	
	Plant heat exchanger	Assuming 10 year replacement rate		2	Replacement per 40 years	4,968	A1-3 kgCO2e	9,936		4,968	A1-3 kgCO2e	9,936	
	Electrical submersible pumps	Assuming 5 year replacement rate		5	Replacements per 40 years	1,651	A1-3 kgCO2e	8,255		1,651	A1-3 kgCO2e	8,255	
	System Overview					**5km Doublet (2 wells, 5km each)**			**Carbon Totals**	**5km Doublet (2 wells, 5km each) Hard rock**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
	Refurbishment/planned												
B5	Refurbishment	Assumed NA											
	Use												
B6	Operational energy consumption - annual electricity	Assumed low scenario	See operational energy emissions tab			8,672	MWh	14,378,839		8,672	MWh	14,378,839	
	Power outputs 30 year output	Assumed electrical output per scenario: 1km , 2km, 3km NO ELECTRICAL OUTPUT 4km - 1.5MWe output (c. 12,000MWhe) 5km - 3MWe output (c. 24,000MWhe)	See operational energy emissions tab				MWh				MWh		
B7	Operational water consumption	Assuming NA											
B8	User activities	Assuming NA											
	End of Life								**798,990**				**841,020**
C1	Deconstruction/ Demolition	Assuming best practice deconstruction to	50% of A5, RICS WLC Guidance V2, 2023	50.00%		462,000		231,000		560,000		280,000	

		maximise reuse of materials											
	Plugs	Assuming abandoned material to cap borehole at end of life	ICE 3.0, Cement - CEM I - Portland Cement 0.912 kgCO2e/kg Density Cement screed - 2,100 kg/m3	1915.2	kgCO2e/m3	99	m3	188,701		99	m3	188,701	
	System Overview					**5km Doublet (2 wells, 5km each)**			**Carbon Totals**	**5km Doublet (2 wells, 5km each) Hard rock**			**Carbon Totals**
	System Description												
	Description	**Assumptions**	**Carbon Source**	**Carbon factor**	**Carbon factor unit**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**	**Quantity**	**Unit**	**Carbon (kgCO2e)**	**2 Wells**
C2	Transport	Assuming same as A4	A4 total kgCO2e					375,976				369,102	
	Waste processing for reuse, recycling or other recovery		RICS, 2023: Steel 7% reuse, 93% recycle DEFRA & DESNZ, 2023: Metal recycling 0.985kgCO2e/t	0.00091605	93% recycled Metal kgCO2e/kg	50,000	kg	46		50,000	kg	46	
			RICS, 2023: concrete 97.5% recycle DEFRA & DESNZ, 2023: Concrete recycling 0.985kgCO2e/t	0.000960375	97.5% Concrete kgCO2e/kg	480,595	kg	462		384,250	kg	369	
			RICS, 2023: MEP 70% recycle DEFRA & DESNZ, 2023: WEEE Large recycling 21.281kgCO2e/t	0.0148967	70% recycled MEP kgCO2e/kg	158,900	kg	2,367		158,900	kg	2,367	
C4	Disposal impacts	No emissions	Steel no disposal										
			RICS, 2023: Concrete 2.5% disposal DEFRA & DESNZ, 2023: Concrete disposal 1.234kgCO2e/t	0.00003085	2.5% Concrete kgCO2e/kg	480,595	kg	15		384,250	kg	12	

			RICS, 2023: MEP 30% disposal DEFRA & DESNZ, 2023: WEEE Large disposal 8.884kgCO2e/t	0.0026652	30% disposal MEP kgCO2e/kg	158,900	kg	424		158,900	kg	424	
	Total								**18,506,078**				**18,551,466**

D.6 Geothermal Carbon Costs (Operational Carbon)

Parameter	Unit	Gas Boiler (600kW)	Gas Boiler (6MW)	ASHP (600kW)	ASHP (6MW)	Closed loop - 1BH	Closed loop - 20BH	Closed loop - 100BH	Open loop - 20l/s	Deep - 1km	Deep - 2km	Deep - 3km	Deep - 4km (power)	Deep - 5km (power)
no. wells	-					1	20	100	1 Pair	1 Pair	1 Pair	1 Pair	1 Pair	1 Pair
baseload	kW	600	6,000	600	6,000	10	120	600	670	1,700	2,800	6,800	12,200	16,400
SPF Heating	-	0.85	0.85	2.50	2.50	4	4	4	4	5	6			
Heating hours	hr	5,260	6,000	5,260	6,000	5,260	5,260	5,260	5,260	6,000	6,000	6,000	7,880	7,880
SPF Cooling	-			0	0	10	10	10	10					
Cooling hours	hr			3,500	3,500	3,500	3,500	3,500	3,500					
Power Generation	MW												1	3
Power Generation	MWh												9,460	21,290
Heat	kW			1,000	10,000	10	160	800	890	2,130	3,360	6,800	12,200	16,400
Annual heat	MWh	3,150	36,000	5,260	60,000	40	840	4,200	4,670	12,750	20,160	40,800	96,180	129,300
Heating - HP electricity	MWh			2,100	24,000	10	210	1,050	1,170	2,550	3,360			
Total annual thermal ouput	MWh	3,150	36,000	5,260	60,000	40	840	4,200	4,670	12,750	20,160	40,800	96,180	129,300
Total HP electricity	MWh			2,100	24,000	10	210	1,050	1,170	2,550	3,360			
Circulation pump power	kW							20		200	200	200	400	600
Abstraction pump power	kW								20	300	350	400	450	500
Circulation/abstraction pump electricity	MWh			10	30	10	30	130	130	3,000	3,300	3,600	6,700	8,670
Total Electricity per year	MWh			2,110	24,030	20	240	1,180	1,300	5,550	6,660	3,600	6,700	8,670
Total Operational carbon emissions (30 year life)	tCO2e	20,390	232,720	3,500	39,840	30	390	1,960	2,150	9,200	11,040	5,970	11,110	14,380
Total Operational carbon emissions per total thermal output	tCO2e/MWh	215	215	22	22	25	16	16	15	24	18	5	4	4



Natural gas	tCO2e/MWh	0.18316	Green Book Data Tables - Table 2a
Grid Electricity	tCO2e/year	**reducing**	Green Book Data Tables - Table 1 - Commercial long run