ARUP

Annex C

Department for Energy Security and Net Zero

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

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C.1 Levelised Cost of Electricity (LCOE) – Data Tables

This appendix contains the input and output tables from the LCOE model. Discussion of the data inputs is provided in Table 1. This table should be reviewed in conjunction with the Main Report. The LCOE assessment considers Deep Geothermal (General), Sedimentary, and Granite assessments. Discussions for assumptions for each assessment are included within Table 1.

Table 1: Summary of data inputs and rational for use in LCOE model

Description	Data Source and rational
Technical	
Timescales	All timescales are consistent across the assessments. Published data and stakeholder data used to identify low, medium, high ranges: 1. Pre-development period: US 2023 (current): Pre-development (Surface exploration): 4 - 8 months; Exploration drilling (permit): 6 - 12 months; Exploration drilling: 1 - 1.5 years US (2035): Permitting: 2 - 4 months; Exploration (surface and drilling): 6 - 12 months; Environmental assessment (permits): 1 - 1.5 years UK Stakeholders: Feasibility & exploration planning: 8 months; Planning and permitting: 12 months; Well design and procurement: 15 months 2. Construction period: US 2023 (current): Production drilling and testing: 1 - 1.5 years; Plant (permit): 1 - 1.5 years; Plant and transmission line construction: 1 - 1.5 years US (2035): Production drilling: 1 - 1.5 years; Plant and transmission line construction: 1 - 1.5 years UK Stakeholders: Drilling and testing (variable): 3 months to 1 year; Plant design: 6 months; Plant construction: 20 months; New grid connection: up to 10 years 3. Decommissioning: UK Stakeholders: Single well decommissioning: 3 – 6 months.
Plant Operating Period	1 stakeholder, 1 data point; and 2 reports, 3 data points; used to inform assessment (including US Department of Energy and European Geothermal Energy Council). Data sets were combined, ranged, and split into low, medium, high estimates. Range from 20 to 40 years, generally 30 years.
Power output	FOAK power assessment based on Arup UK assessment, see Appendix A. NOAK power assessment values are based on US Department of Energy assumptions for system outputs. Assumed at 10MWe, 15MWe, and 20MWe (low, medium, and high respectively), for 4 to 8 production wells.
Heat output	Heat output based on ratios between power and heat for operational combined heat and power plants across Europe. A benchmarking exercise was undertaken using 4 reports, 20 data points. The min and max were excluded and an average value taken. This was calculated at a value of 4, however the full range is from 1 to 10. Datasets predominantly made us of Bavarian datasets, see Appendix A (Power Assessment, Benchmarking).
Net Efficiency	Values of 8 to 14% were used based on experience and stakeholder information. This is also consistent with the values of 13% used in the 2016 DESNZ LCOE model.
Availability	Load factor profile includes the availability profile. Publication data was used to inform this assessment. Published data for plant availability ranged from 77-89% (IRENA), 80-90%, and 90 - 95% (for 'modern plants'). As a result, FOAK plants assumed at low (80%), medium (85%) and high (90%). NOAK assumed at low (90%), medium (92.5%), and high (95%).

Description	Data Source and rational
Learning Rates	US DOE values present low, medium, and high scenarios from 0.5%, 13%, 30%; from 2035 – 2050[1]. Fervo presented a learning rate of c. 3.3% over the last 6 years. Arup assessment used high, med, low of 3.3%, 0.5%, and 0.1% to 2035, then 0.5% across all cases thereafter. Within the models, learning rates were applied to all capital costs; rather than to drilling only or plant only.
Hurdle Rate	10.1%. Consistent with 2026 DESNZ commissioned research Hurdle rate estimates for electricity sector technologies, to be published. (https://www.gov.uk/government/collections/energy-generation-cost-projections)
Costs	
Pre-development	Stakeholder data generally ranged from £200k to £1.2M (from 7 stakeholders). Each stakeholder outlined that the range is dependent on the level of investigation required; for example, the lower bound represents quick assessment of readily available data; whereas the upper bound >£1M represents acquisition and reinterpretation of new 2D seismic data. One stakeholder outlined the cost for 3D seismics at £4M. This was excluded from the upper bound as this would only typically be considered within large NOAK geothermal basin systems. The UK is not at this stage currently.
Construction & Infrastructure	1. Drilling costs • Inferred from stakeholder data (general values rather than project data), and published literature. The drilling costs plot within the report clearly presents the FOAK and NOAK estimates for the UK. The FOAK estimates are based on the stakeholder data ranges, the high costs are notably higher than published data, the medium costs fall within typical costs presented globally, and the low costs fall within the lower ranges of global costs. The NOAK costs are broadly based on the US Earthshot estimates, and represent low, linear cost estimates; which require substantial advancements in drilling rates and price savings (evidenced at FORGE and Fervo in Texas, US). • High drilling costs have been used for the High LCOE model run, and Low drilling costs paired with the Low LCOE model run. As presented, the drilling costs can vary significantly. • Costs for 4000m and 5000m targets have been used to inform the model. For FOAK, Low costs for a 4000m well is £5.5M (1.4M/km), medium cost for a 4500m well is £10.05M (£2.2M/km), and high costs for a 5000m well is £21.5M (£4.3M/km). For NOAK, low cost for a 4000m well is £2.63M (0.65M/km), medium costs for 4500m well is £3.83M (£0.85M), and high cost for a 5000m well is £4.98M (1M/km). These values are multiplied by 2 (as a doublet is assumed, (1 abstraction, 1 reinjection well). The total cost is then divided by the power outputs (assumed at 0.5MWe, 1.5MWe, 3MWe) to derive the cost per kW. 2. Plant: Plant costs derive from literature, namely IRENA and US DOE. The literature values outlined current costs and anticipated 2035 costs. These ranged from around £4,800 to £8,200/kW. Current estimates were used for the FOAK data (from £6,600 to £8,200/kW) and predicted values used for NOAK data (from £4,800 to £5,900/kW).
Decommission	Decommissioning cost for wells informed from 6 stakeholders, between £200k to £1.2M per well (depending on the regulatory requirements, complexity of the well, etc.). Plant decommissioning costs informed from single Belgium stakeholder data (actual data, put aside for decommissioning budget)

[1] National Renewable Energy Laboratory (NREL), 2023, Annual Technology Baseline, web link: https://atb.nrel.gov/electricity/2023/geothermal#capital_expenditures_(CAPEX)

Description	Data Source and rational
Fixed O&M	Literature data (IRENA) and one stakeholder data point has been used to inform data. This was then divided by the low, medium, high power output value.
Variable O&M	Literature data (IRENA, and US DOE) used to inform data. This was then divided by the low, medium, high power output value.
Insurance & UoS	Excluded.

C.1.1 LCOE – Inputs

	–	Deep Geothermal, NOAK			Deep Geothermal, FOAK			Deep Geothermal, Granite, FOAK			Deep Geothermal, Sedimentary, FOAK			Deep Geothermal, Granite, NOAK			Deep Geothermal, Sedimentary, NOAK		
Description		**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Project start	Yr.	1.0	1.5	2.0	1.0	2.0	3.0	1.0	2.0	3.0	1.0	2.0	3.0	1.0	1.5	2.0	1.0	1.5	2.0
Construction start	Yr.	3.3	4.5	6.0	4.0	5.3	6.5	4.0	5.3	6.5	4.0	5.3	6.5	3.3	4.5	4.5	3.3	4.5	6.0
Operation start	Yr.	25.0	30.0	40.0	20.0	25.0	30.0	20.0	25.0	30.0	20.0	25.0	30.0	25.0	30.0	40.0	25.0	30.0	40.0
Heat revenue period	Yr.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Decommission period	Yr.	0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5
Power revenue ends	Yr.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pre-development	£/kW	20	62	130	130	619	2,600	139	422	1,083	433	2,320	13,000	20	62	130	59	186	390
Construction	£/kW	5,858	7,911	12,885	10,332	20,796	94,137	8,425	11,055	22,248	12,092	27,237	136,332	3,783	5,497	6,997	5,004	7,456	10,801
Infrastructure	£'000s	1,000	5,500	10,000	1,000	5,500	10,000	1,000	5,500	10,000	1,000	5,500	10,000	1,000	5,500	10,000	1,000	5,500	10,000
Decommission	£/kW	176	180	183	287	293	299	381	721	2,588	1,153	3,216	20,255	143	306	1,031	550	1,017	2,852
Total fixed O&M	£/MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fixed O&M	£/MW	73,600	101,200	120,800	81,600	241,200	408,800	81,600	241,200	408,800	81,600	241,200	408,800	73,600	101,200	120,800	73,600	101,200	120,800
Variable O&M	£/MWh	20	25	30	20	25	30	20	25	30	20	25	30	20	25	30	20	25	30
BSUoS	£/MWh	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Insurance	£/MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UoS	£/MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Net Electrical output	MWe	10.0	15.0	20.0	0.5	1.5	3.0	1.2	2.2	2.8	0.1	0.4	0.9	10.0	15.0	20.0	3.3	5.0	6.7
Net Efficiency (LHV)	%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%
Hours per year	No/hrs	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760
Fuel calorific value (gross)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Load Factor	%	95%	93%	90%	90%	85%	80%	90%	85%	80%	90%	85%	80%	95%	93%	90%	95%	93%	90%
Availability	%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Baseload heating - capacity	MWth	40.0	60.0	80.0	2.0	6.0	12.0	4.8	8.8	11.2	0.4	1.6	3.6	40.0	60.0	80.0	13.3	20.0	26.7
Baseload heating - output	MWh	332,880	486,180	630,720	15,768	44,676	84,096	37,843	65,525	78,490	3,154	11,914	25,229	332,880	486,180	630,720	110,960	162,060	210,240

Key

Standard - per technology
Varies per case study
No data available

C.1.2 LCOE – Outputs

Table 1: Total Capital Costs (£/kW) and Operating Costs (£/kW), 2023 Real Prices

Deep Geothermal, NOAK

Scenario	Total Capital Costs, £/kW	Total Operating Costs, £/kW
Low	6,878	73,766
Medium	13,473	101,403
High	23,015	121,037

Deep Geothermal, FOAK

Scenario	Total Capital Costs, £/kW	Total Operating Costs, £/kW
Low	11,462	81,758
Medium	26,915	241,386
High	106,737	409,010

Deep Geothermal, Granite, FOAK

Scenario	Total Capital Costs, £/kW	Total Operating Costs, £/kW
Low	9,564	81,758
Medium	16,977	241,386
High	33,331	409,010

Deep Geothermal, Sedimentary, FOAK

Scenario	Total Capital Costs, £/kW	Total Operating Costs, £/kW
Low	13,525	81,758
Medium	35,057	241,386
High	159,332	409,010

Deep Geothermal, Granite, NOAK

Scenario	Total Capital Costs, £/kW	Total Operating Costs, £/kW
Low	4,803	73,766
Medium	11,059	101,403
High	17,127	121,037

Deep Geothermal, Sedimentary, NOAK

Scenario	Total Capital Costs, £/kW	Total Operating Costs, £/kW
Low	6,063	73,766
Medium	13,142	101,403
High	21,191	121,037

Table 2: Total Capital Costs, 2023 Real Prices £/kW

Deep Geothermal, NOAK

Scenario	2024	2030	2035	2040	2050
Low	191	179	152	129	93
Medium	294	293	286	279	266
High	523	523	520	518	513

Deep Geothermal, FOAK

Scenario	2024	2030	2035	2040	2050
Low	421	399	347	311	299
Medium	976	972	952	932	893
High	4,418	4,418	4,397	4,376	4,186

Deep Geothermal, Granite, FOAK

Scenario	2024	2030	2035	2040	2050
Low	318	291	250	227	217
Medium	546	542	531	520	499
High	1,203	1,202	1,197	1,192	1,141

Deep Geothermal, Sedimentary, FOAK

Scenario	2024	2030	2035	2040	2050
Low	765	737	676	631	617
Medium	1,722	1,717	1,688	1,659	1,604
High	7,431	7,431	7,399	7,364	7,062

Deep Geothermal, Granite, NOAK

Scenario	2024	2030	2035	2040	2050
Low	125	117	99	84	61
Medium	210	209	204	199	190
High	297	297	296	294	291

Deep Geothermal, Sedimentary, NOAK

Scenario	2024	2030	2035	2040	2050
Low	172	161	138	118	87
Medium	312	310	304	297	285
High	500	500	498	496	491

Table 3: Total Operating Costs, 2023 Real Prices £/kW

Deep Geothermal, NOAK

Scenario	2024	2030	2035	2040	2050
Low	175	175	175	175	175
Medium	215	215	215	215	215
High	252	252	252	252	252

Deep Geothermal, FOAK

Scenario	2024	2030	2035	2040	2050
Low	168	168	168	168	168
Medium	219	219	219	219	219
High	269	269	269	269	269

Deep Geothermal, Granite, FOAK

Scenario	2024	2030	2035	2040	2050
Low	168	168	168	168	168
Medium	219	219	219	219	219
High	269	269	269	269	269

Deep Geothermal, Sedimentary, FOAK

Scenario	2024	2030	2035	2040	2050
Low	168	168	168	168	168
Medium	219	219	219	219	219
High	269	269	269	269	269

Deep Geothermal, Granite, NOAK

Scenario	2024	2030	2035	2040	2050
Low	175	175	175	175	175
Medium	215	215	215	215	215
High	252	252	252	252	252

Deep Geothermal, Sedimentary, NOAK

Scenario	2024	2030	2035	2040	2050
Low	175	175	175	175	175
Medium	215	215	215	215	215

High	252	252	252	252	252

Table 4: Cost Breakdown for a 'Medium' Project, £/kW

Deep Geothermal, NOAK

Assumption	Unit	2024	2030	2035	2040	2050
Development	£/kW	4	4	4	4	3
Construction	£/kW	290	289	282	276	263
Infrastructure	£'000's	5,500	5,500	5,500	5,500	5,500
Total Capex	**£/kW**	294	293	286	279	266
Fixed O&M	£/MW	12	12	12	12	12
Variable O&M	£/MWh	25	25	25	25	25
Total Opex	**£/MW**	37	37	37	37	37

Deep Geothermal, FOAK

Assumption	Unit	2024	2030	2035	2040	2050
Development	£/kW	42	42	41	40	38
Construction	£/kW	934	930	911	892	855
Infrastructure	£'000's	5,500	5,500	5,500	5,500	5,500
Total Capex	**£/kW**	976	972	952	932	893
Fixed O&M	£/MW	32	32	32	32	32
Variable O&M	£/MWh	25	25	25	25	25
Total Opex	**£/MW**	57	57	57	57	57

Deep Geothermal, Granite, FOAK

Assumption	Unit	2024	2030	2035	2040	2050
Development	£/kW	29	29	28	27	26
Construction	£/kW	518	513	503	493	474
Infrastructure	£'000's	5,500	5,500	5,500	5,500	5,500
Total Capex	**£/kW**	546	542	531	520	499
Fixed O&M	£/MW	32	32	32	32	32
Variable O&M	£/MWh	25	25	25	25	25
Total Opex	**£/MW**	57	57	57	57	57

Table 5: Levelised Cost, £/MWh

Deep Geothermal, NOAK

Scenario	2024	2030	2035	2040	2050
Heating Revenue					
Low	2	-16	-44	-63	-86
Medium	33	24	3	-12	-26
High	140	132	114	101	91
No Heating Revenue					
Low	125	119	105	94	76
Medium	175	175	172	168	162
High	274	274	273	272	270

Deep Geothermal, FOAK

Scenario	2024	2030	2035	2040	2050
Heating Revenue					
Low	119	95	55	30	19
Medium	370	359	332	310	284
High	1876	1868	1842	1821	1731
No Heating Revenue					
Low	242	230	205	186	180
Medium	512	510	500	491	473
High	2011	2011	2001	1992	1910

Deep Geothermal, Granite, FOAK

Scenario	2024	2030	2035	2040	2050
Heating Revenue					
Low	67	41	7	-12	-22
Medium	169	159	136	119	101
High	475	466	447	433	404
No Heating Revenue					
Low	190	176	156	144	139
Medium	311	309	304	299	290
High	609	609	606	604	583

Deep Geothermal, Sedimentary, FOAK

Scenario	2024	2030	2035	2040	2050
Heating Revenue					
Low	291	265	220	191	179
Medium	710	699	668	643	610
High	3117	3109	3078	3052	2915
No Heating Revenue					
Low	414	400	369	347	340
Medium	852	850	837	824	798
High	3251	3251	3237	3223	3094

Deep Geothermal, Granite, NOAK

Scenario	2024	2030	2035	2040	2050
Heating Revenue					
Low	-31	-47	-71	-85	-102
Medium	-6	-15	-36	-50	-62
High	41	33	15	3	-6
No Heating Revenue					
Low	92	88	79	71	60
Medium	136	135	133	131	127
High	175	175	175	174	173

Deep Geothermal, Sedimentary, NOAK

Scenario	2024	2030	2035	2040	2050
Heating Revenue					
Low	-7	-25	-51	-68	-88
Medium	41	32	11	-4	-18
High	129	121	103	90	81
No Heating Revenue					
Low	115	110	98	89	73
Medium	183	183	180	177	171
High	263	263	262	261	259