



FINAL REPORT: APPENDICES

Analysis of a Strategic Hydrogen Refuelling Infrastructure (ATHENA)

Contents

Appendix A: Modelling assumptions	2
Appendix B: Demand data	3
Appendix C: Optimisation analysis	6

Appendix A: Modelling assumptions

The assumptions are derived from the “Hydrogen production costs 2021”¹ report and informed by subject matter experts and project partners.

Primary assumptions

- Focus on Northern England (NP11 region)
- Rollout phase estimated by 2027
- Mature phase estimated by 2040
- Maximum coverage distance is 20km at rollout phase and 2km at mature phase
- HGV demand converted to hydrogen in rollout phase is estimated as 0.1% and 50% in mature phase

Hydrogen refuelling stations (HRSs)

- Maximum HRS capacity is 28,955 kg/day (production output by 50MW on-site production)
- The HRS setup and storage cost are included in Table 1

Table 1: The HRS setup and storage cost factors.

	Rollout	Mature
Fixed setup cost (£)	2,033,834	1,217,731
Additional unit cost for storage (£/kg)	1.66	0.99

Localised (on-site) production

- 1MW production facility daily output of 579 kg (assume 95% efficiency)
- Minimum capacity is 2.9 kg/day/MW
- Localised production cost is 6.51 £/kg in the rollout phase and 4 £/kg in the mature phase
- The capital costs for the different localised production options are included in Table 2

Table 2: The localised production capital costs.

	Rollout	Mature
1MW capital cost (£)	384,654	262,043
5MW capital cost (£)	585,490	440,779
10MW capital cost (£)	836,534	664,199
30MW capital cost (£)	1,840,712	1,557,877
50MW capital cost (£)	2,844,889	2,451,556

Centralised (off-site) production

- Five centralised production facilities are included located at Teesside, Hornsea, Leeds, Merseyside and Humber
- A very large maximum capacity is assumed at all centralised facilities such that it does not impose limits within the model
- Green hydrogen production is assumed at all centralised facilities
- Production cost (across all centralised facilities) is 5.11 £/kg at rollout phase and 2 £/kg at mature phase
- Assume all centralised facilities can only supply to an HRS by tube trailer if HRS is within a 100km radius from facility

Dispense by tube trailers

- Hydrogen is assumed to be distributed in gaseous form in tube trailers
- Tube trailer capacity is 1,000 kg per delivery
- Transportation cost is 1 £/km in the rollout phase and 0.7 £/km in the rollout phase
- Maximum number of deliveries per day per HRS is 3

¹ Available at <https://www.gov.uk/government/publications/hydrogen-production-costs-2021>

Appendix B: Demand data

The demand data analysis allowed for the spatial analysis of hydrogen demand within the NP11 region. Information on the set of demand sites with the accompanying daily demand (in hydrogen kg) for the roll-out and mature phases are shown in Table 3 and Table 4.

Table 3: The set of demand sites as refined in the demand data analysis for the roll-out phase.

INDEX	LATITUDE	LONGITUDE	DAILY DEMAND (KG)
15	53.50075	-2.63373	179.50
31	54.90927	-1.48685	56.03
38	53.34962	-2.52877	109.77
39	53.41495	-2.61182	154.88
40	53.43175	-2.5098	56.01
52	53.53766	-1.03936	70.61
86	53.73621	-1.58034	151.04
91	53.70626	-1.39496	85.12
107	53.53941	-1.51045	126.88
112	52.98826	-2.17608	135.50
129	53.35894	-1.39067	185.85
135	53.53451	-2.16105	164.06
166	53.53964	-2.28314	210.79
210	53.69684	-0.44434	86.25

Table 4: The set of demand sites as refined in the demand data analysis for the mature phase.

INDEX	LATITUDE	LONGITUDE	DAILY DEMAND (KG)
1	53.47392	-1.49019	3034.37
2	53.47377	-1.48847	3002.40
3	53.47179	-2.86133	2820.45
4	53.47881	-2.84835	3980.95
5	53.36737	-1.48475	3317.36
6	53.78933	-2.64687	1411.58
7	53.48736	-2.84665	4359.55

INDEX	LATITUDE	LONGITUDE	DAILY DEMAND (KG)	INDEX	LATITUDE	LONGITUDE	DAILY DEMAND (KG)
8	53.5114	-1.12551	2484.09	17	53.55311	-2.66833	3113.98
9	53.48098	-2.86303	4158.14	18	53.55638	-2.66633	5433.80
10	53.78223	-1.04664	978.72	19	53.51744	-2.65534	3586.86
11	53.78403	-1.04981	4409.75	20	53.50518	-1.11937	2275.28
12	53.40389	-2.81153	4690.47	21	53.49976	-1.12642	2063.39
13	54.34513	-2.73851	1078.69	22	53.57088	-1.20998	1349.12
14	53.46312	-2.39487	3021.12	23	53.61461	-0.9803	9352.11
15	53.50075	-2.63373	9181.37	24	53.50911	-1.04329	2580.83
16	53.48884	-2.61185	8760.40	25	53.08544	-2.26891	3668.61

INDEX	LATITUDE	LONGITUDE	DAILY DEMAND (KG)
26	52.8597	-1.78096	1068.00
27	53.53862	-1.12007	2080.54
28	54.58892	-1.57714	1415.81
29	54.54988	-1.57115	706.29
30	53.6013	-1.26622	2205.50
31	54.90927	-1.48685	5332.77
32	53.60514	-1.2749	2365.83
33	53.59263	-2.31021	7828.04
34	53.57355	-2.30235	4070.30
35	53.56941	-2.30316	6948.69
36	53.35513	-2.52744	8413.19
37	53.72395	-0.40985	4412.64
38	53.34962	-2.52877	8724.35
39	53.41495	-2.61182	10332.72
40	53.43175	-2.5098	13756.79
41	53.36658	-1.49715	2607.96
42	53.6842	-2.66748	1838.53
43	53.19175	-1.35876	3779.02
44	53.41849	-2.60252	13548.26
45	53.40864	-2.53406	11224.61
46	53.20486	-1.38151	3583.13
47	53.02988	-1.41257	2973.29
48	54.05671	-2.84223	4062.09
49	53.67237	-2.64614	3801.41
50	53.67183	-2.63966	1195.64
51	54.92213	-2.95854	2948.93
52	53.53766	-1.03936	6747.88
53	53.78937	-2.34238	3071.09
54	53.79111	-2.34276	3092.73
55	53.57657	-1.17276	6793.16
56	53.53713	-1.03741	4324.13
57	53.39981	-1.37882	6909.68
58	53.42546	-1.36034	2286.33

INDEX	LATITUDE	LONGITUDE	DAILY DEMAND (KG)
59	53.45967	-2.30377	3640.43
60	53.67984	-1.73489	4453.03
61	53.45847	-2.32579	4020.40
62	54.87262	-1.58342	3550.43
63	54.5485	-1.5741	1503.33
64	53.46752	-2.30712	4073.70
65	53.4657	-2.33918	2984.77
66	53.45704	-2.16615	3913.15
67	53.42605	-2.23316	2185.86
68	53.42333	-2.20993	3201.11
69	53.43076	-2.23182	4832.35
70	53.43326	-2.23117	2326.82
71	53.4714	-2.33971	3475.92
72	53.55597	-2.53366	2053.83
73	53.23776	-3.03106	6425.96
74	53.23185	-3.01028	5367.70
75	53.23	-3.01447	5381.32
76	53.42284	-1.22693	2292.82
77	53.38672	-1.51215	2674.79
78	53.78398	-1.48964	5879.64
79	53.78319	-1.50289	4974.22
80	53.50043	-2.20283	6346.45
81	53.56893	-2.16769	4147.60
82	53.53975	-2.77797	3480.60
83	53.55604	-2.80254	2153.75
84	53.55867	-2.7955	2110.03
85	53.07204	-2.26382	3919.89
86	53.73621	-1.58034	11135.70
87	53.67137	-1.52464	4531.92
88	53.64359	-1.51193	3117.15
89	53.06348	-2.2297	4642.65
90	53.71989	-1.41814	6441.30
91	53.70626	-1.39496	9506.06

INDEX	LATITUDE	LONGITUDE	DAILY DEMAND (KG)
92	53.69814	-1.39867	6553.21
93	53.70243	-1.39687	6204.36
94	53.70189	-1.39104	4623.76
95	53.42669	-2.70418	7404.71
96	53.71284	-1.52113	5394.78
97	53.7145	-1.52474	5554.68
98	53.57323	-2.19071	7770.58
99	53.46168	-2.31208	3631.88
100	53.01679	-2.19709	6589.54
101	53.58362	-1.53171	4877.74
102	53.52617	-1.32704	1239.96
103	53.5453	-1.5348	5587.91
104	53.50668	-1.45037	6312.35
105	53.55623	-1.35069	1910.81
106	53.55186	-1.37009	4971.91
107	53.53941	-1.51045	10827.73
108	53.49061	-1.49291	8522.65
109	53.69436	-1.82824	2372.02
110	53.6939	-1.82144	2346.06
111	53.35253	-2.74675	3112.18
112	52.98826	-2.17608	11409.85
113	52.97919	-2.17533	3627.31
114	53.26819	-2.77619	1044.41
115	53.20574	-2.49873	7803.20
116	53.20367	-2.49779	4377.25
117	53.19418	-2.4908	5045.45
118	53.19408	-2.48678	5513.17
119	53.28127	-1.28605	4008.74
120	52.98493	-2.17796	4196.65
121	53.35239	-2.65392	6494.60
122	53.42873	-1.23784	2840.82
123	53.51046	-1.38569	3150.82
124	53.57947	-1.45124	3117.13

INDEX	LATITUDE	LONGITUDE	DAILY DEMAND (KG)
125	52.97457	-2.09421	4158.48
126	53.63782	-1.66251	2791.52
127	53.76089	-1.74521	5838.08
128	52.9582	-1.06533	4210.51
129	53.35894	-1.39067	13016.06
130	53.29539	-1.06628	5481.98
131	53.29652	-1.09195	4583.27
132	53.29883	-1.07889	2856.10
133	53.31938	-1.13839	8956.48
134	53.32191	-1.14719	2528.19
135	53.53451	-2.16105	9347.78
136	53.53325	-2.16819	3435.64
137	53.5589	-2.11065	3651.53
138	53.53209	-2.16558	4596.22
139	53.48236	-2.11908	5598.43
140	53.72524	-2.45272	2922.02
141	53.44958	-2.13135	5444.91
142	53.47755	-1.47055	2440.74
143	53.44595	-1.46219	4443.86
144	53.40067	-1.38685	5393.45
145	53.40389	-1.40189	3708.83
146	53.41671	-2.23991	3466.56
147	54.17418	-1.48066	830.07
148	53.08802	-2.41765	2350.06
149	53.09061	-2.43244	3894.49
150	53.08614	-2.42769	2589.38
151	53.08813	-2.43036	3526.37
152	53.08037	-2.41893	3464.53
153	53.39011	-2.57927	8583.05
154	53.46617	-2.33623	3325.03
155	53.37869	-2.14146	4227.58
156	53.53601	-2.17006	4101.14
157	53.52419	-2.14211	3424.26

INDEX	LATITUDE	LONGITUDE	DAILY DEMAND (KG)
158	53.53218	-2.16884	3141.93
160	53.20538	-3.02265	8265.11
161	53.36102	-2.73944	2264.28
162	53.42243	-2.91501	2062.65
163	53.45703	-2.91604	2245.62
164	52.96693	-2.70545	1177.95
165	53.07374	-2.43557	1849.66
166	53.53964	-2.28314	12161.77
168	53.51825	-2.1455	4848.51
169	53.59272	-2.28374	2266.63
170	53.10156	-2.00968	736.52
171	53.764	-2.59748	1716.49
172	52.90817	-2.16237	1690.30
173	53.73068	-2.45258	2364.97
174	52.8732	-2.1612	577.90
175	52.8932	-2.13046	1153.00
177	53.79656	-2.98541	989.32
178	53.82067	-3.0331	782.25
179	53.77178	-1.73076	2817.85
180	54.13824	-2.75785	785.97
184	53.46717	-3.02038	2240.02
185	53.47228	-2.32873	2665.80
186	53.08012	-0.81314	1924.31
187	53.06898	-2.26513	2196.24
188	54.64886	-1.50269	989.49
189	53.71315	-2.47636	3102.14
190	53.7727	-1.47127	5008.87
191	53.13392	-1.332	1583.88
192	54.46504	-1.6651	4759.46
193	53.6976	-1.26667	3420.75
194	54.17916	-2.73371	785.97
195	53.76625	-2.33854	2212.24
196	53.3725	-1.4717	1406.34

INDEX	LATITUDE	LONGITUDE	DAILY DEMAND (KG)
198	53.45657	-2.3365	5163.21
199	53.36057	-2.50707	14537.59
200	53.46935	-2.77376	2794.53
201	53.87492	-1.90322	660.22
205	54.03461	-2.91449	7355.06
206	53.74366	-0.33824	19251.10
207	53.43541	-3.00444	5661.78
208	53.47201	-2.29857	9629.13
210	53.69684	-0.44434	19040.52
211	54.92256	-1.36457	6725.28

Appendix C: Optimisation analysis

The optimisation model output for Experiments I, II and III are included in Table 5, Table 6, and Table 7, respectively. In Experiment I, a parameter variation of the maximum coverage distance is performed where (A)-(E) refer to the rollout phase and (F)-(J) refer to the mature phase. In Experiment II, the on-site and off-site hydrogen production supply alternatives are investigated and in Experiment III, a parameter variation on the average number of daily deliveries allowed per HRS is performed.

Table 5: The optimisation model output for Experiment I.

EXPERIMENT I	A	B	C	D	E	F	G	H	I	J
MAXIMUM COVERAGE DISTANCE (KM)	5	10	20	30	40	1	2	3	4	5
TOTAL COST (MILLION £)	34	25	21	17	15	1,846	1,845	1,844	1,842	1,841
NUMBER OF HRSS	14	10	8	6	5	190	189	188	185	182
CAPACITY OF LARGEST HRS PER ANNUM (KG/YEAR)	92,326	219,066	311,393	383,250	383,250	8,431,980	8,431,980	8,431,980	8,431,980	11,265,615
CAPACITY OF LARGEST HRS PER DAY (KG/DAY)	253	600	853	1,050	1,050	23,101	23,101	23,101	23,101	30,865
CAPACITY OF SMALLEST HRS PER ANNUM (KG/YEAR)	24,530	24,543	24,543	24,543	24,543	253,121	253,121	289,176	289,176	289,176
CAPACITY OF SMALLEST HRS PER DAY (KG/DAY)	67	67	67	67	67	693	693	792	792	792
AVERAGE CAPACITY OF HRSS PER ANNUM (KG/YEAR)	55,447	77,626	97,033	129,377	155,252	2,002,457	2,013,052	2,023,759	2,056,577	2,090,477
AVERAGE CAPACITY OF HRSS PER DAY (KG/DAY)	152	213	266	354	425	5,486	5,515	5,545	5,634	5,727
AVERAGE NUMBER OF DELIVERIES PER HRS PER ANNUM	56	78	98	130	156	1011	1015	1020	1034	1039
AVERAGE NUMBER OF DELIVERIES PER HRS PER DAY	0	0	0	0	0.43	3	3	2.80	3	2.85
PORTION HRSS ONLY ON-SITE SUPPLY	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
PORTION HRSS ONLY OFF-SITE SUPPLY	1.00	1.00	1.00	1.00	1.00	0.25	0.24	0.24	0.22	0.21
PORTION HRSS ON-SITE & OFF-SITE SUPPLY	0.00	0.00	0.00	0.00	0.00	0.74	0.75	0.75	0.77	0.77
NUMBER OF 1MW ON-SITE	0	0	0	0	0	13	13	13	13	13
NUMBER OF 5MW ON-SITE	0	0	0	0	0	67	68	68	70	70
NUMBER OF 10MW ON-SITE	0	0	0	0	0	34	34	34	34	34
NUMBER OF 30MW ON-SITE	0	0	0	0	0	26	26	26	26	23
NUMBER OF 50MW ON-SITE	0	0	0	0	0	2	2	2	2	3

Table 6: The optimisation model output for Experiment II.

EXPERIMENT II	A	B
MAXIMUM NUMBER OF DELIVERIES PER HRS PER DAY	0	Unlimited
TOTAL COST (MILLION £)	2,179	1,265
NUMBER OF HRSS	115	114
CAPACITY OF LARGEST HRS PER ANNUM (KG/YEAR)	10,459,868	12,284,571
CAPACITY OF LARGEST HRS PER DAY (KG/DAY)	28,657	33,656
CAPACITY OF SMALLEST HRS PER ANNUM (KG/YEAR)	253,121	253,121
CAPACITY OF SMALLEST HRS PER DAY (KG/DAY)	693	693
AVERAGE CAPACITY OF HRSS PER ANNUM (KG/YEAR)	3,347,952	3,344,063
AVERAGE CAPACITY OF HRSS PER DAY (KG/DAY)	9,172	9,162
TOTAL NUMBER OF DELIVERIES IN SYSTEM P.A.	0	379521
AVERAGE NUMBER OF DELIVERIES PER HRS P.A.	0	3389
AVERAGE NUMBER OF DELIVERIES PER HRS PER DAY	0	9.28
PORTION HRSS ONLY ON-SITE SUPPLY	1.00	0.02
PORTION HRSS ONLY OFF-SITE SUPPLY	0.00	0.98
PORTION HRSS ON-SITE & OFF-SITE SUPPLY	0.00	0.00
NUMBER OF 1MW ON-SITE	0	0
NUMBER OF 5MW ON-SITE	29	1
NUMBER OF 10MW ON-SITE	25	1
NUMBER OF 30MW ON-SITE	41	0
NUMBER OF 50MW ON-SITE	20	0

Table 7: The optimisation model output for Experiment III.

EXPERIMENT III	A	B	C	D	E	F	G
MAXIMUM NUMBER OF DELIVERIES PER HRS PER DAY	2	3	4	5	6	7	8
TOTAL COST (MILLION £)	1,982	1,845	1,728	1,630	1,554	1,501	1,454
NUMBER OF HRSS	159	189	188	183	176	171	163
CAPACITY OF LARGEST HRS PER ANNUM (KG/YEAR)	10,459,868	8,431,980	8,431,980	8,431,980	8,431,980	8,431,980	8,431,980
CAPACITY OF LARGEST HRS PER DAY (KG/DAY)	28,657	23,101	23,101	23,101	23,101	23,101	23,101
CAPACITY OF SMALLEST HRS PER ANNUM (KG/YEAR)	253,121	253,121	253,121	253,121	253,121	253,121	253,121
CAPACITY OF SMALLEST HRS PER DAY (KG/DAY)	693	693	693	693	693	693	693
AVERAGE CAPACITY OF HRSS PER ANNUM (KG/YEAR)	2,405,167	2,013,052	2,023,759	2,079,053	2,167,209	2,236,383	2,338,292
AVERAGE CAPACITY OF HRSS PER DAY (KG/DAY)	6,589	5,515	5,545	5,696	5,938	6,127	6,406
TOTAL NUMBER OF DELIVERIES IN SYSTEM P.A.	109920	189761	236282	271497	296927	316588	329230
AVERAGE NUMBER OF DELIVERIES PER HRS P.A.	700	1015	1270	1500	1706	1873	2045
AVERAGE NUMBER OF DELIVERIES PER HRS PER DAY	1.9	2.8	3.5	4.1	4.7	5.1	5.6
PORTION HRSS ONLY ON-SITE SUPPLY	0.01	0.01	0.01	0.01	0.01	0.01	0.01
PORTION HRSS ONLY OFF-SITE SUPPLY	0.11	0.24	0.38	0.52	0.61	0.70	0.74
PORTION HRSS ON-SITE & OFF-SITE SUPPLY	0.88	0.75	0.61	0.47	0.38	0.29	0.25
NUMBER OF 1MW ON-SITE	10	13	19	19	18	9	10
NUMBER OF 5MW ON-SITE	54	68	53	34	24	19	15
NUMBER OF 10MW ON-SITE	45	34	21	18	15	13	11
NUMBER OF 30MW ON-SITE	27	26	21	15	12	11	7
NUMBER OF 50MW ON-SITE	6	2	2	2	0	0	0