Supplementary Material – Part II

Towards a sustainable hydrogen economy: optimisation-based framework for hydrogen infrastructure development

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S2. Model parameters

S2.1. Demand parameters

Region g		Order of	Time period t									
NUTS	Name	penetration	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
C1	Tees Valley Durham	5	-	-	2,389	3,964	6,504	10,487	16,456	24,833	35,556	47,782
C2	Northumberl and Tyne Wear	5	-	-	2,858	4,741	7,780	12,544	19,684	29,704	42,531	57,155
D1	Cumbria	5	-	-	1,015	1,684	2,764	4,456	6,993	10,552	15,109	20,304
D3	Greater Manchester	2	3,512	7,024	10,535	17,480	28,683	46,244	72,569	109,507	156,796	210,710
D4	Lancashire	3	1,942	3,883	5,825	9,665	15,859	25,568	40,123	60,546	86,692	116,500
D6	Cheshire	2	1,374	2,747	4,121	6,837	11,219	18,088	28,385	42,833	61,330	82,418
D7	Mersey Side	2	1,825	3,650	5,475	9,084	14,905	24,031	37,711	56,906	81,480	109,497
E1	East Yorkshire and Northern Lincolnshire	5	-	-	1,868	3,099	5,086	8,199	12,867	19,417	27,801	37,361
E2	North Yorkshire	3	1,065	2,129	3,194	5,299	8,695	14,018	21,998	33,194	47,529	63,872
E3	South Yorkshire	4	-	-	4,664	7,739	12,699	20,474	32,129	48,483	69,419	93,289
E4	West Yorkshire	3	2,960	5,920	8,880	14,733	24,175	38,976	61,164	92,296	132,152	177,593
F1	Derbyshire and Nottinghamshire	2	2,831	5,662	8,493	14,091	23,122	37,278	58,499	88,275	126,395	169,856
F2	Leicestershire, Rutland and Northamptonshire	2	2,288	4,577	6,865	11,391	18,691	30,134	47,288	71,357	102,172	137,304
F3	Lincolnshire	3	940	1,879	2,819	4,677	7,675	12,373	19,417	29,300	41,953	56,379
G1	Herefordshire, Worcestershire and Warwickshire	2	1,732	3,464	5,196	8,622	14,147	22,809	35,793	54,012	77,336	103,928
G2	Shropshire and Staffordshire	2	2,077	4,153	6,230	10,336	16,960	27,344	42,910	64,752	92,713	124,593
G3	West Midlands	3	3,490	6,979	10,469	17,370	28,503	45,953	72,113	108,818	155,809	209,384
H1	East Anglia	1	3,591	7,182	10,772	17,873	29,328	47,284	74,201	111,969	160,320	215,447
H2	Bedfordshire and Hertfordshire	1	2,570	5,140	7,709	12,791	20,989	33,840	53,104	80,133	114,737	154,189
H3	Essex	1	2,622	5,244	7,866	13,051	21,415	34,525	54,180	81,757	117,062	157,314
I2	Outer and Inner London	1	11,694	23,388	35,082	58,208	95,512	153,988	241,650	364,650	522,116	701,645
J1	Berkshire, Buckinghamshire and Oxfordshire	1	3,372	6,745	10,117	16,786	27,544	44,408	69,689	105,160	150,571	202,345
J2	Surrey East West Sussex	1	4,067	8,133	12,200	20,241	33,214	53,548	84,032	126,804	181,562	243,992
J3	Hampshire and Isle of Wight	1	2,849	5,698	8,547	14,181	23,269	37,515	58,872	88,837	127,199	170,937
J4	Kent	1	2,545	5,090	7,635	12,668	20,787	33,514	52,592	79,362	113,633	152,705
K1	Gloucestershire, Wiltshire and Bristol/Bath Area	1	3,531	7,062	10,593	17,575	28,839	46,495	72,963	110,101	157,646	211,852
K2	Dorset and Somerset	2	1,692	3,384	5,075	8,421	13,818	22,278	34,960	52,755	75,536	101,508
K3	Cornwall and Isles of Scilly	5	-	-	1,102	1,829	3,001	4,838	7,592	11,456	16,404	22,044
K4	Devon	4	-	-	4,104	6,809	11,173	18,014	28,269	42,658	61,079	82,081
L1	West Wales and The Valleys	3	2,535	5,069	7,604	12,616	20,702	33,377	52,377	79,037	113,168	152,081
L2	East Wales	3	1,465	2,929	4,394	7,290	11,963	19,287	30,266	45,672	65,394	87,880
M2	Eastern Scotland	4	-	-	7,089	11,762	19,300	31,116	48,829	73,683	105,501	141,778
M3	South Western Scotland	4	-	-	8,135	13,497	22,147	35,706	56,033	84,554	121,067	162,695
M5	North Eastern Scotland	4	-	-	1,613	2,677	4,392	7,081	11,112	16,767	24,008	32,263
M6	Highlands and Islands	5	-	-	906	1,504	2,468	3,979	6,244	9,422	13,491	18,129
N0	Northern Ireland	2	-	-	6,365	10,561	17,329	27,938	43,842	66,158	94,727	127,299

Table S1: NUTS codes, zones, order of penetration and demand (dem_{gt}) of regions g a long time periods t considered in this study.

S2.2. Hydrogen production, storage and filling station parameters

Product type *i*	Plant size *j*	Production technology *p*						
		SMR	SMR CCS	CG	CG CCS	BG	BG CCS	WE
GH2	Distributed	0.1–1.5	-	-	-	-	-	0–1.5e3
	Small	1.5–10	-	-	-	-	-	0–10e3
	Medium	10–150	10–150	-	-	15–150	15–150	10–100
	Large	200–1,100	200–1,100	200–1,100	200–1,100	200–1,100	200–1,100	-
LH2	Distributed	-	-	-	-	-	-	-
	Small	1.5–10	-	-	-	-	-	0–10e3
	Medium	10–150	10–150	-	-	15–150	15–150	10–100
	Large	200–1,100	200–1,100	200–1,100	200–1,100	200–1,100	200–1,100	-

Table S2: Minimum ($pcap^{min}_{ipj}$) and maximum ($pcap^{max}_{ipj}$) capacity of a hydrogen production plant of type p and size j producing product type i, in 10^3 kg H_2 d^{-1}.

Product type *i*	Plant size *j*	Production technology *p*						
		SMR	SMR CCS	CG	CG CCS	BG	BG CCS	WE
GH2	Distributed	3	-	-	-	-	-	2
	Small	14	-	-	-	-	-	13
	Medium	104	178	-	-	231	302	104
	Large	459	509	1,242	2,402	764	1,001	-
LH2	Distributed	-	-	-	-	-	-	-
	Small	29	-	-	-	-	-	28
	Medium	166	240	-	-	293	364	166
	Large	633	684	1,417	2,577	939	1,175	-

Table S3: Capital cost (pcc_{ipj}) of a production plant of type p and size j producing product type i, in 10^6 £.

Product type *i*	Plant size *j*	Production technology *p*						
		SMR	SMR CCS	CG	CG CCS	BG	BG CCS	WE
GH2	Distributed	2.17	-	-	-	-	-	4.55
	Small	2.07	-	-	-	-	-	4.30
	Medium	1.23	1.41	-	-	1.82	1.97	3.99
	Large	1.21	1.30	0.95	1.14	1.50	1.62	-
LH2	Distributed	-	-	-	-	-	-	-
	Small	3.31	-	-	-	-	-	5.50
	Medium	1.94	2.12	-	-	2.53	2.68	4.70
	Large	1.77	1.86	1.56	1.78	2.10	2.21	-

Table S4: Unit production cost (upc_{ipj}) for producing product type i in a production plant of type p and size j, in £ kg^{-1} H_2.

Product type *i*	Plant size *j*	Storage technology *s*	
		GH2	LH2
GH2	Small	0–0.37	-
	Medium	0.38–5	-
	Large	5.01–25	-
LH2	Small	-	0–9.5
	Medium	-	10–150
	Large	-	200–540

Table S5: Minimum ($scap^{min}_{isj}$) and maximum ($scap^{max}_{isj}$) capacity of a storage facility of type s and size j storing product type i, in 10^3 kg H_2.

Product type *i*	Plant size *j*	Storage technology *s*	
		GH2	LH2
GH2	Small	460	-
	Medium	5,670	-
	Large	28,090	-
LH2	Small	-	1,500
	Medium	-	5,680
	Large	-	18,450

Table S6: Capital cost (scc_{isj}) of a storage facility of type s and size j storing product type i, in 10^3 £.

Product type *i*	Plant size *j*	Storage technology *s*	
		GH2	LH2
GH2	Small	460	-
	Medium	5,670	-
	Large	28,090	-
LH2	Small	-	1,500
	Medium	-	5,680
	Large	-	18,450

Table S7: Unit storage cost (usc_{isj}) for storing product type *i* in a storage facility of type *s* and size *j*, in £ kg H_2 d^{-1}.

Product type *i*	Plant size *j*	Filling technology *f*		
		GH2 – GH2 (Tanker)	GH2 – GH2 (Distributed)	LH2 – GH2 (Trailer)
GH2	Small	375	-	-
	Medium	750	-	-
	Large	1,500	1,500	-
LH2	Small	-	-	375
	Medium	-	-	750
	Large	-	-	1,500

Table S8: Maximum capacity ($fcap^{max}_{ifj}$) of a filling station of type *f* and size *j* supplying product type *i*, in kg H_2 d^{-1}.

Product type *i*	Plant size *j*	Filling technology *f*		
		GH2 – GH2 (Tanker)	GH2 – GH2 (Distributed)	LH2 – GH2 (Trailer)
GH2	Small	255	-	-
	Medium	510	-	-
	Large	1,020	1,830	-
LH2	Small	-	-	300
	Medium	-	-	600
	Large	-	-	1,200

Table S9: Capital cost (fcc_{ijf}) of a filling station of type *f* and size *j* supplying product type *i*, *in* 10^3 £.

S2.3. Hydrogen road transportation parameters

Road transportation mode l	Trailer	Tanker
Product type i	GH2	LH2
Fuel price (fp_{il}), in £ l^{-1}	1.63	1.63
General expenses (ge_{il}), in £ d^{-1}	5.93	5.93
Driver wage (dw_{il}), in £ h^{-1}	16.62	16.62
Maintenance expenses (me_{il}), in £ km_{-1}	0.072	0.072
Local fuel economy ($\widetilde{fe}_{il}$), in km l^{-1}	2.3	2.3
Regional fuel economy ($\overline{fe}_{il}$), in km l^{-1}	2.3	2.3
Load and unload time (lut_{il}), in h	2	2
Local average speed ($\widetilde{sp}_{il}$), in km h^{-1}	55	55
Regional average speed ($\overline{sp}_{il}$), in km h^{-1}	55	55
Transportation capacity ($tcap_{il}$), in kg H_2 $unit^{-1}$	650	4,370
Local transportation availability ($\widetilde{tma}_{il}$), in h d^{-1}	15	15
Regional transportation availability ($\overline{tma}_{il}$), in h d^{-1}	18	18
Capital cost of a transportation unit (tcc_{il}), in £ $unit^{-1}$	253,000	451,700

Table S10: Road transportation parameters.

S2.4. Hydrogen and CO_2 pipeline parameters

Diameter size $\check{d}$	Diameter ($\check{dia}_{\check{d}}$)	Maximum flowrate ($\check{q}_{\check{d}}^{max}$)	Capital cost ($\check{ccc}_{\check{d}}$)
1	50	1,524	550
2	60	3,429	660
3	70	5,334	770
4	80	7,238	880
5	90	9,143	990
6	100	11,048	1,100

Table S11: Diameter, maximum flowrate and capital cost of a hydrogen local pipeline of diameter size $\check{d}$, in cm, 10^3 kg H_2 d^{-1} and 10^3£ km^{-1} respectively.

Diameter size $\bar{d}$	Diameter ($\overline{dia}_{\bar{d}}$)	Maximum flowrate ($\bar{q}_{\bar{d}}^{max}$)	Capital cost ($\overline{ccc}_{\bar{d}}$)
1	30	591	960
2	40	1,122	1,280
3	50	1,652	1,600

Table S12: Diameter, maximum flowrate and capital cost of a hydrogen regional pipeline of diameter size $\bar{d}$, in cm, 10^3 kg H_2 d^{-1} and 10^3£ km^{-1} respectively.

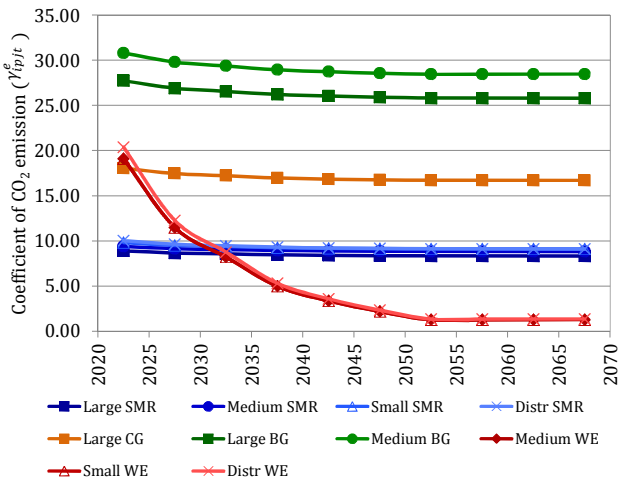
Diameter size $\underline{d}$	Diameter ($\underline{dia}_{\underline{d}}$)	Maximum flowrate ($\underline{q}_{\underline{d}}^{max}$)	Capital cost ($\underline{ccc}_{\underline{d}}$)
1	55	20,000	356.3
2	60	40,000	387.4

Table S13: Diameter, maximum flowrate and capital cost of a CO_2 onshore pipeline of diameter size $\underline{d}$, in cm, 10^3 kg CO_2 d^{-1} and 10^3£ km^{-1} respectively.

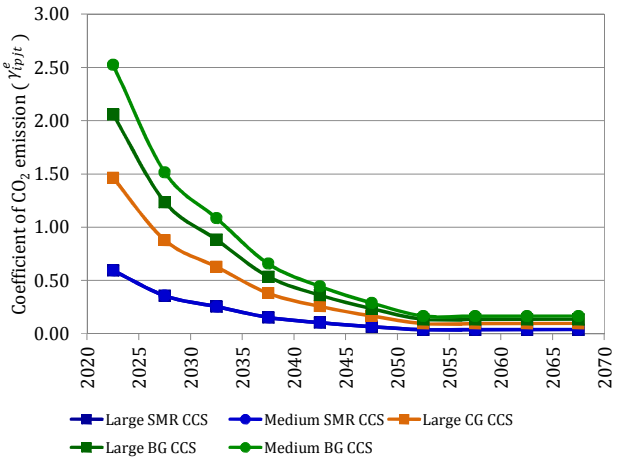
Diameter size $\underline{\underline{d}}$	Diameter ($\underline{\underline{dia}}_{\underline{\underline{d}}}$)	Maximum flowrate ($\underline{\underline{q}}_{\underline{\underline{d}}}^{max}$)	Capital cost ($\underline{\underline{ccc}}_{\underline{\underline{d}}}$)
1	55	20,000	489.7
2	60	40,000	527.6

Table S14: Diameter, maximum flowrate and capital cost of a CO_2 offshore pipeline of diameter size $\underline{\underline{d}}$, in cm, 10^3 kg CO_2 d^{-1} and 10^3£ km^{-1} respectively.

S2.5. CCS parameters

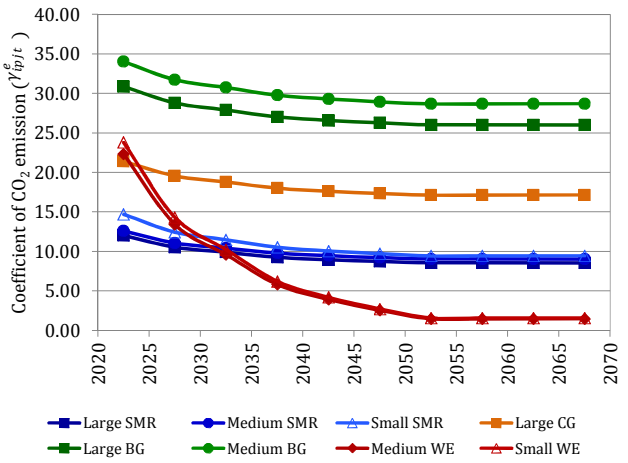


(a) Technologies without CCS

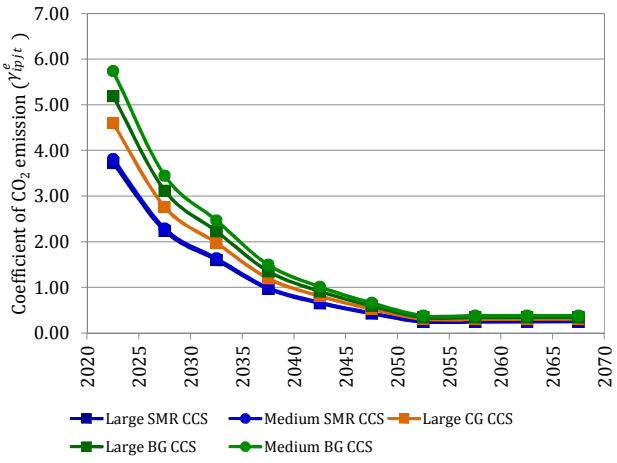


(b) Technologies with CCS

Figure S1: Coefficient of CO_2 emission for producing GH_2 in a production plant of type p and size j, in kg CO_2 kg^{-1} H_2.



(a) Technologies without CCS



(b) Technologies with CCS

Figure S2: Coefficient of CO_2 emission for producing LH_2 in a production plant of type p and size j, in kg CO_2 kg^{-1} H_2.

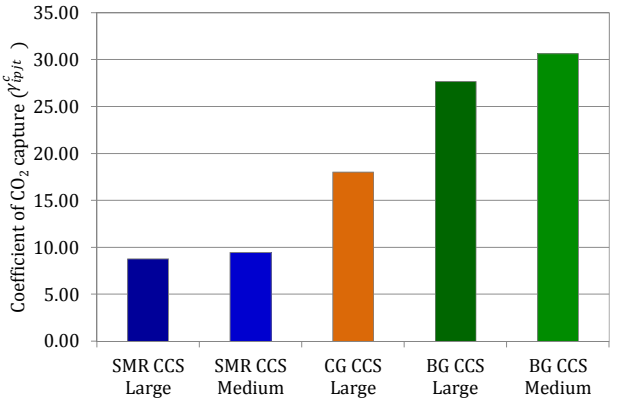


Figure S3: Coefficient of CO_2 capture for producing GH_2, LH_2 in a production plant with CCS of type p and size j, in kg CO_2 kg^{-1} H_2.

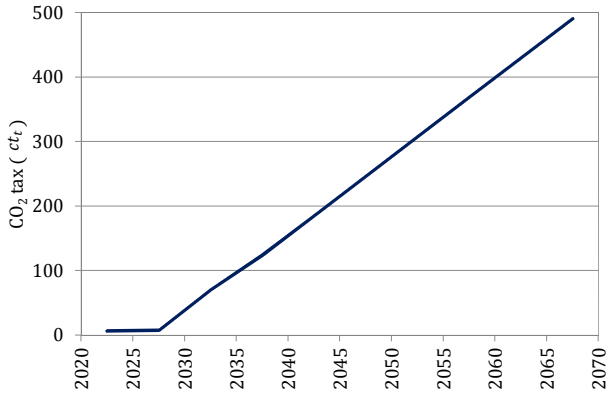


Figure S4: Carbon tax, in 10^{-3}£ kg^{-1} H_2.

S2.6. Additional information

Discount rate (dr), in %	3.5–10
Annual network operating period (α), in d y^{-1}	365
Economic life cycle of capital investments (n), in y	30
Storage time interval (β), in d	0.15
Ratio of pipeline operating costs to capital costs (δ)	0.05
Useful life of hydrogen production plants (Υ^p), in y	30
Useful life of hydrogen storage facilities (Υ^s), in y	40
Useful life of hydrogen filling stations (Υ^f), in y	30
Useful life of hydrogen road transportation modes (Υ^t), in y	15
Useful life of hydrogen and CO_2 pipelines (Υ^c), in y	50
Duration of time intervals (Υ), in y	5
Price of imported LH_2 (iip), in £ kg^{-1} H_2	4.03

Table S15: Additional parameters of the case study.

S2.7. CO_2 Reservoirs

Reservoir *r*		Total capacity
r2	East Irish Sea	1
r3	Northern and Central North Sea	7.1
r1	Southern North Sea	11

Table S16: Reservoirs and total capacity ($rcap^{max}_{r}$), in 10^{12}kg CO_2 d^{-1}.

S2.8. Port regions

Port region *g*	
L1	West Wales and The Valleys
J3	Hampshire and Isle of Wight
C1	Tees Valley Durham
E1	East Yorkshire and Northern Lincolnshire
M2	Eastern Scotland
N0	Northern Ireland

Table S17: Port regions.

S2.9. Distances

Region g	Local delivery distance	Region g	Local delivery distance	Region g	Local delivery distance
C1	31	F2	40	J4	34
C2	42	F3	43	K1	49
D1	46	G1	43	K2	44
D3	20	G2	44	K3	34
D4	31	G3	17	K4	46
D6	27	H1	63	L1	65
D7	15	H2	30	L2	49
E1	33	H3	34	M2	76
E2	51	I2	20	M3	65
E3	22	J1	43	M5	45
E4	25	J2	42	M6	113
F1	39	J3	36	N0	67

Table S18: Local delivery distance of hydrogen road and pipeline transportation ($\bar{l}_{lgg\prime}$) in region g , in km.

Connection g	g'	Distance road transportation	Connection g	g'	Distance road transportation	Connection g	g'	Distance road transportation
C1	C2	66	E1	H1	231	G3	K1	145
C1	D1	149	E2	E4	40.2	G3	L2	188
C1	D4	168	E2	F1	133	H1	H2	163
C1	E2	78.9	E2	F3	114	H1	H3	135
C1	E3	159	E2	M2	324	H1	I2	189
C1	E4	105	E3	E4	55.7	H2	H3	92.2
C2	D1	95.1	E3	F1	60.6	H2	I2	53.7
C2	D4	213	E3	F3	81.3	H2	J1	77.6
C2	M2	167	E3	G2	76.3	H2	J2	155
D1	D4	142	E4	F3	115	H2	J3	152
D1	E2	187	E4	G2	133	H3	I2	65.8
D1	E3	261	F1	F2	44.8	H3	J2	136
D1	E4	188	F1	F3	66.6	H3	J4	76.8
D1	M2	148	F1	G1	131	I2	J1	96
D1	M3	154	F1	G2	84.6	I2	J3	128
D3	D4	53.7	F1	G3	82.2	I2	J4	64.3
D3	D6	64.9	F1	H1	195	I2	K1	190
D3	D7	56.4	F2	F3	87.3	J1	J2	177
D3	E1	156	F2	G1	116	J1	J3	106
D3	E3	61.4	F2	G2	97.4	J1	K1	118
D3	E4	71.6	F2	G3	70.2	J1	K2	163
D3	G1	177	F2	H1	187	J1	L2	170
D3	G2	71.5	F2	H2	112	J2	J3	104
D4	D7	51.4	F2	H3	185	J2	J4	84.6
D4	E4	99.5	F2	J1	124	J3	J4	170
D6	D7	29.2	F2	J2	264	J3	K1	118
D6	E1	220	F2	K1	188	J3	K2	110
D6	F3	197	F2	L2	231	K1	K2	59.1
D6	G1	159	F3	H1	166	K1	K4	126
D6	G2	79.8	F3	H3	226	K1	L1	128
D6	G3	122	G1	G2	112	K1	L2	71.6
D6	K1	254	G1	G3	65.3	K2	K4	77.4
D6	L1	231	G1	J1	101	K3	K4	139
D6	L2	244	G1	J3	195	L1	L2	66.4
D7	E2	158	G1	K1	100	M2	M3	74.3
D7	F1	159	G1	L1	176	M2	M5	203
D7	G2	91.6	G1	L2	133	M2	M6	250
E1	E2	63.7	G2	G3	71.6	M3	M5	235
E1	E3	107	G2	J1	192	M3	M6	271
E1	F3	76.6	G2	L1	248	M5	M6	168
E1	G2	180	G3	J1	124			

Table S19: Connections and regional delivery distance of hydrogen road transportation ($\bar{l}_{\mathrm{Trailer},gg\prime}$ and $\bar{l}_{\mathrm{Tanker},gg\prime}$) between regions g and g', in km.

Connection g	g'	Distance pipe transportation	Connection g	g'	Distance pipe transportation	Connection g	g'	Distance pipe transportation
C1	C2 *	83.88	E2	E3	83.04	H2	H3 *	109.83
C1	D1 *	139.47	E2	E4	36.4	H2	I2	46.96
C1	E2 *	68.57	E2	F3 *	100.38	H2	J1 *	77.43
C2	D1	103.31	E3	E4	52.04	H3	I2	49.92
C2	M2 *	154.65	E3	F1	49.3	H3	J4 *	55.42
D1	D4 *	128.86	F1	F2	37.94	I2	J1	92.87
D1	E2	163.06	F1	F3 *	72.92	I2	J2	74.81
D1	M2	120.52	F1	G2	67.88	I2	J4	60.12
D1	M3 *	161.31	F2	F3 *	118.93	J1	J2	131.33
D3	D4 *	48.98	F2	G1 *	97.83	J1	J3 *	111.96
D3	D6 *	64.05	F2	G2 *	88.72	J1	K1	99.05
D3	D7	45.57	F2	G3	56.11	J2	J3	103.02
D3	E3	52.05	F2	H1 *	167.2	J2	J4	71.84
D3	E4	57.37	F2	H2 *	129.2	J3	K1	111.02
D3	F1	93.25	F2	J1	100	J3	K2 *	97.7
D3	G2	56.03	F3	H1 *	178.8	K1	K2 *	67.94
D4	D7	41.13	G1	G2	90.97	K2	K4 *	68.6
D4	E2 *	147.33	G1	G3	37.99	K3	K4	118.74
D4	E4	74.27	G1	J1	81.64	L1	L2 *	52.77
D6	D7	56.16	G1	K1 *	100.72	M2	M3 *	65.11
D6	G2 *	55.58	G1	L2 *	111.05	M2	M5 *	235.05
D6	L2	197.74	G2	G3	60.82	M2	M6	216.3
E1	E2 *	68.54	G2	L2	181.48	M3	M5 *	219.64
E1	E3	95.26	H1	H2 *	146.99	M3	M6	200.89
E1	F1	126.36	H1	H3 *	118.23	M5	M6	133.82
E1	F3 *	75.99						

* Connections in the exiting natural gas infrastructure

Table S20: Connections and regional delivery distance of hydrogen pipelines ($\bar{l}_{\mathrm{Pipe},gg'}$) between regions g and g', in km.

Connection g	g'	Distance onshore pipeline	Connection g	g'	Distance onshore pipeline	Connection g	g'	Distance onshore pipeline
C1	C2	83.88	E2	E3	83.04	H2	H3	109.83
C1	D1	139.47	E2	E4	36.4	H2	I2	46.96
C1	E2	68.57	E2	F3	100.38	H2	J1	77.43
C2	D1	103.31	E3	E4	52.04	H3	I2	49.92
C2	M2	154.65	E3	F1	49.3	H3	J4	55.42
D1	D4	128.86	F1	F2	37.94	I2	J1	92.87
D1	E2	163.06	F1	F3	72.92	I2	J2	74.81
D1	M2	120.52	F1	G2	67.88	I2	J4	60.12
D1	M3	161.31	F2	F3	118.93	J1	J2	131.33
D3	D4	48.98	F2	G1	97.83	J1	J3	111.96
D3	D6	63.91	F2	G2	88.72	J1	K1	99.05
D3	D7	71.92	F2	G3	56.11	J2	J3	103.02
D3	E3	52.05	F2	H1	200.61	J2	J4	71.84
D3	E4	57.37	F2	H2	129.2	J3	K1	111.02
D3	F1	93.25	F2	J1	100	J3	K2	97.7
D3	G2	56.03	F3	H1	212.21	K1	K2	67.67
D4	D7	67.47	G1	G2	90.97	K2	K4	68.6
D4	E2	147.33	G1	G3	37.99	K3	K4	118.74
D4	E4	74.27	G1	J1	81.64	L1	L2	52.77
D6	D7	82.5	G1	K1	100.72	M2	M3	65.11
D6	G2	55.58	G1	L2	111.05	M2	M5	274.76
D6	L2	197.74	G2	G3	60.82	M2	M6	216.3
E1	E2	68.54	G2	L2	181.48	M3	M5	259.35
E1	E3	95.26	H1	H2	146.99	M3	M6	200.89
E1	F1	126.36	H1	H3	118.23	M5	M6	133.82
E1	F3	75.99						

Table S21: Connections and delivery distance of onshore CO_2 pipelines ($\underline{l}_{\mathrm{Pipe},gg'}$) between regions g and g', in km.

Collection point region g		Reservoir r		Distance offshore pipeline
D7	Mersey Side	r2	East Irish Sea	150
M5	North Eastern Scotland	r3	Northern and Central North Sea	213
H1	East Anglia	r1	Southern North Sea	100

Table S22: Connections and delivery distance of offshore CO_2 pipelines ($\underline{l}_{\mathrm{Pipe},gg'}$) between region g and reservoir r, in km.