Supplementary Information (SI) for Energy & Environmental Science.

Supplementary Information

Toward a Sustainable Energy Future Using Ammonia as an Energy Carrier: Global Supply Chain Cost and Greenhouse Gas Emissions

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Summary

Table S1. Country-specific economic parameters. ($: 2022 dollar)

Region	Country	ISO Country Code	Grid electricity price [c] [$/MWh]	Renewable Electricity LCOE [1, 2] [$/MWh]	Natural gas price [c] [$/10mmbtu -LHV]	Locational factor [3] [%; U.S. = 100%]	Labor Rate [4, 5 e] [%, U.S. = 100% = 39.03$/hr]	Tax rate [6, b] [%]	Inflation rate [7] [%]	Riskfree Rate [7] [%]	Country risk-premium for debt [7] [%]	Country equity-premium rate [7] [%]	WACC real [d] [%]	FCR [d] [%]
Africa	Algeria	DZ	15.9	46.2 [f]	10.3	92.5%	14.3%	26.0%	6.0%	8.9%	3.7%	7.8%	12.1%	19.0%
	Angola	AO	20.3	46.2 [f]	26.4	94.5%	2.7%	25.0%	20.0%	15.0%	7.9%	12.1%	14.9%	26.9%
	Egypt	EG	83.7	45.4	33.8	90.0%	11.2%	22.5%	11.4%	21.2%	9.2%	13.3%	25.2%	48.7%
	Equatorial Guinea	GQ	244.6	46.2 [f]	26.4	91.0%	25.5%	35.0%	2.7%	4.6%	11.0%	15.1%	15.6%	27.2%
	Libya	LY	176.3	46.2 [f]	2.0	92.5%	31.3%	20.0%	1.9%	5.1%	2.0%	6.1%	9.6%	13.2%
	Morocco	MA	113.2	52.9	109.0	92.0%	10.9%	32.0%	3.0%	4.4%	3.1%	7.2%	8.9%	13.6%
	Mozambique	MZ	95.8	46.2 [f]	26.4	91.0%	6.8%	32.0%	5.5%	8.1%	11.0%	15.1%	17.4%	31.1%
	Namibia	NA	144.1	46.2 [f]	[a]	91.0%	26.6%	32.0%	4.3%	7.5%	5.5%	9.6%	12.9%	21.2%
	Nigeria	NG	113.3	46.2 [f]	24.6	95.5%	8.7%	30.0%	17.0%	23.8%	9.2%	13.3%	23.7%	50.0%
	South Africa	ZA	54.7	40.3	125.3	93.5%	48.9%	27.0%	5.0%	7.2%	3.7%	7.8%	11.1%	17.2%
	Tunisia	TN	107.9	46.2 [f]	26.4	92.0%	7.4%	15.0%	7.1%	11.1%	11.0%	15.1%	20.9%	34.5%
Asia-Pacific	Australia	AU	76.3	33.5	60.0	102.5%	116.5%	30.0%	3.5%	5.1%	0.0%	4.1%	6.8%	10.2%
	Brunei	BN	63.9	57.9 [f]	44.9	92.5%	81.6%	18.5%	1.5%	2.9%	0.7%	4.9%	6.8%	9.2%
	China	CN	102.5	27.7	94.6	91.5%	10.7%	25.0%	1.7%	3.9%	0.9%	5.0%	7.5%	10.5%
	India	IN	127.5	38.3	33.2	88.5%	2.8%	34.9%	5.7%	6.7%	2.7%	6.8%	9.1%	14.9%
	Indonesia	ID	85.3	83.4	59.9	80.5%	11.1%	22.0%	2.8%	4.8%	2.3%	6.5%	9.1%	12.8%
	Japan	JP	185.8	97.8	123.1	108.0%	80.7%	30.6%	1.2%	4.2%	0.9%	5.0%	7.8%	11.3%
	Kazakhstan	KZ	58.5	57.9 [f]	21.2	92.5%	14.6%	20.0%	9.9%	9.2%	2.3%	6.5%	9.9%	14.9%
	Korea	KR	98.8	75.4	168.9	94.0%	70.1%	24.0%	2.4%	4.2%	0.6%	4.7%	7.2%	10.2%
	Malaysia	MY	104.4	57.9 [f]	65.9	87.5%	27.5%	24.0%	1.6%	4.4%	1.5%	5.6%	8.5%	12.0%
	Papua New Guinea	PG	417.2	57.9 [f]	93.7	89.5%	36.7%	30.0%	4.2%	7.2%	6.7%	10.8%	13.9%	22.8%
	Philippines	PH	185.8	57.9	93.7	89.5%	6.3%	25.0%	4.1%	5.4%	2.3%	6.5%	9.0%	13.1%
	Singapore	SG	138.1	57.9 [f]	128.4	92.5%	81.6%	17.0%	2.7%	4.4%	0.0%	4.1%	6.9%	9.4%
	Thailand	TH	103.2	57.9 [f]	87.5	89.0%	47.6%	20.0%	1.7%	3.6%	2.0%	6.1%	8.4%	11.4%
	Turkmenistan	TM	12.8	57.9 [f]	3.1	92.5%	10.2%	8.0%	8.0%	10.8%	7.9%	12.1%	18.1%	27.3%
	Uzbekistan	UZ	37.2	57.9 [f]	16.8	94.5%	9.2%	15.0%	11.9%	10.8%	4.4%	8.5%	12.5%	18.9%
	Vietnam	VN	81.8	49.4	54.1	88.0%	5.5%	20.0%	2.9%	5.9%	3.7%	7.8%	11.3%	16.2%
Europe	Azerbaijan	AZ	58.3	49.5 [f]	30.4	94.5%	10.0%	20.0%	6.8%	6.7%	3.1%	7.2%	9.7%	14.2%
	Belgium	BE	159.1	57.9	103.7	102.5%	144.2%	25.0%	3.5%	4.4%	0.7%	4.9%	6.9%	10.0%
	Czech	CZ	139.4	49.5 [f]	131.1	91.0%	32.7%	21.0%	7.1%	4.1%	0.7%	4.9%	5.2%	7.9%
	Denmark	DK	130.8	42.9	167.3	107.0%	138.3%	22.0%	3.0%	4.0%	0.0%	4.1%	6.3%	8.9%
	Finland	FI	105.7	42.6	136.2	108.0%	118.1%	20.0%	3.0%	3.9%	0.5%	4.6%	6.7%	9.3%
	France	FR	122.5	51.2	145.7	101.0%	115.1%	25.0%	3.1%	4.0%	0.6%	4.7%	6.6%	9.5%
	Germany	DE	163.8	55.9	144.9	103.0%	131.7%	30.0%	3.9%	4.2%	0.0%	4.1%	5.8%	8.9%
	Italy	IT	281.1	42.6	111.9	96.0%	99.1%	24.0%	3.4%	4.0%	2.7%	6.8%	8.4%	12.1%

Region	Country	ISO Country Code	Grid electricity price [c)] [$/MWh]	Renewable Electricity LCOE [1, 2] [$/MWh]	Natural gas price [c)] [$/10mmbtu -LHV]	Locational factor [3] [%; U.S. = 100%]	Labor Rate [4, 5 e)] [%, U.S. = 100% = 39.03$/hr]	Tax rate [6, b)] [%]	Inflation rate [7] [%]	Riskfree Rate [7] [%]	Country risk-premium for debt [7] [%]	Country equity-premium rate [7] [%]	WACC real [d)] [%]	FCR [d)] [%]
	Netherlands	NL	138.2	46.7	92.1	102.5%	105.6%	25.8%	4.5%	4.3%	0.0%	4.1%	5.7%	8.6%
	Norway	NO	56.5	39.9	61.9	113.0%	148.3%	22.0%	3.7%	4.5%	0.0%	4.1%	6.4%	9.1%
	Poland	PL	121.2	51.6	114.7	92.5%	26.0%	19.0%	7.3%	6.0%	1.0%	5.2%	7.1%	10.3%
	Portugal	PT	156.6	60.4	142.1	91.0%	33.4%	21.0%	2.9%	4.1%	1.5%	5.6%	7.8%	10.8%
	Russia	RU	53.2	41.8	24.0	94.5%	16.4%	20.0%	6.8%	7.2%	3.7%	7.8%	10.7%	15.7%
	Spain	ES	142.0	33.5	117.0	93.0%	71.5%	25.0%	3.0%	4.2%	2.0%	6.1%	8.0%	11.5%
	Sweden	SE	98.4	37.8	190.2	110.0%	127.2%	20.6%	3.8%	4.2%	0.0%	4.1%	6.1%	8.7%
	Turkiye	TR	126.6	56.2	100.4	91.5%	18.6%	25.0%	34.7%	37.5%	7.9%	12.1%	27.5%	65.2%
	Ukraine	UA	110.5	95.8	81.1	93.0%	15.7%	18.0%	10.6%	8.9%	14.7%	18.8%	20.1%	34.6%
	United Kingdom	GB	156.5	35.6	109.7	107.0%	86.7%	25.0%	4.3%	4.2%	0.7%	4.9%	6.4%	9.4%
Middle East	Iran	IR	80.6	37.0 [f)]	21.7	90.0%	6.0%	25.0%	39.7%	36.7%	7.9%	12.1%	25.2%	59.1%
	Iraq	IQ	53.7	37.0 [f)]	22.4	92.0%	18.7%	15.0%	3.2%	6.3%	9.2%	13.3%	16.9%	25.3%
	Israel	IL	155.4	37.0 [f)]	63.0	93.0%	69.0%	23.0%	2.1%	4.3%	1.0%	5.2%	7.9%	11.0%
	Kuwait	KW	36.4	37.0 [f)]	29.8	94.5%	115.9%	15.0%	2.8%	4.5%	0.9%	5.0%	7.8%	10.4%
	Oman	OM	68.1	37.0 [f)]	25.8	95.5%	65.8%	15.0%	1.0%	3.9%	3.1%	7.2%	10.1%	13.4%
	Qatar	QA	46.1	37.0 [f)]	13.1	95.5%	146.2%	10.0%	1.4%	4.3%	0.6%	4.7%	8.3%	10.6%
	Saudi Arabia	SA	49.7	37.0	12.7	95.5%	80.3%	20.0%	1.8%	4.2%	0.9%	5.0%	7.8%	10.6%
	United Arab Emirates	AE	83.5	37.0 [f)]	17.5	95.5%	100.0%	9.0%	0.5%	4.1%	0.6%	4.7%	8.6%	10.8%
North America	Canada	CA	91.1	33.0	47.8	98.0%	91.8%	26.5%	3.3%	4.1%	0.0%	4.1%	6.1%	9.0%
	Mexico	MX	106.8	47.1	46.9	88.0%	11.9%	30.0%	5.2%	5.6%	2.3%	6.5%	8.3%	12.9%
	Trinidad and Tobago	TT	83.2	36.4 [f)]	34.1	92.0%	41.7%	30.0%	2.8%	4.0%	3.7%	7.8%	9.2%	13.9%
	United States	US	82.8	29.1	68.7	100.0%	119.1%	21.0%	4.0%	4.4%	0.0%	4.1%	6.2%	8.8%
South America	Argentina	AR	124.6	53.1	29.5	93.5%	51.2%	35.0%	70.0%	78.5%	14.7%	18.8%	49.9%	200.8%
	Bolivia	BO	91.0	38.0 [f)]	39.8	92.0%	12.9%	25.0%	1.5%	6.5%	12.2%	16.3%	19.8%	33.2%
	Brazil	BR	165.5	24.1	91.6	92.0%	24.3%	34.0%	5.8%	5.6%	3.7%	7.8%	9.0%	14.5%
	Chile	CL	177.8	43.0	88.1	93.0%	23.8%	27.0%	5.8%	5.4%	1.0%	5.2%	6.9%	10.5%
	Peru	PE	99.3	31.9	28.1	92.0%	15.6%	29.5%	4.4%	4.2%	2.0%	6.1%	7.2%	10.9%
	Venezuela	VE	108.0	38.0 [f)]	8.4	94.5%	1.0%	34.0%	4874.7%	52.5%	22.7%	26.8%	-3.5%	3.8%

[a)]: No NG data available for Namibia.
[b)]: Federal tax rate only if applicable.
[c)]: Prices are based on each government's energy statistics and reports, international agency's report.
d): Calculated.
[e)]: If not available in [4], average salary [5] was used to estimate the labor cost.
[f)]: Assumed to be continent-average.

Table S2. Country-specific upstream lifecycle GHG emission for mix-averaged NG and grid electricity. (Reference year: 2022)

Region	Country	ISO Country Code	Natural gas [kgCO2e/kgNG]	Grid electricity [kgCO2e/kWh]
Africa	Algeria	DZ	0.64	0.58
	Angola	AO	0.33	0.25
	Egypt	EG	0.50	0.57
	Equatorial Guinea	GQ	0.55	0.58
	Libya	LY	0.68	0.77
	Morocco	MA	0.71	0.80
	Mozambique	MZ	0.76	0.12
	Namibia	NA	a)	0.06
	Nigeria	NG	0.66	0.44
	South Africa	ZA	1.02	1.07
	Tunisia	TN	0.72	0.51
Asia-Pacific	Australia	AU	0.27	0.83
	Brunei	BN	0.26	0.78
	China	CN	0.62	0.61
	India	IN	0.64	0.89
	Indonesia	ID	0.46	0.88
	Japan	JP	0.72	0.55
	Kazakhstan	KZ	0.57	0.65
	Korea	KR	0.76	0.47
	Malaysia	MY	0.33	0.62
	Papua New Guinea	PG	0.41	0.72
	Philippines	PH	0.40	0.73
	Singapore	SG	0.61	0.49
	Thailand	TH	0.45	0.55
	Turkmenistan	TM	1.64	0.79
	Uzbekistan	UZ	0.72	0.71
	Vietnam	VN	0.45	0.44
Europe	Azerbaijan	AZ	0.34	0.66
	Belgium	BE	0.34	0.16
	Czech	CZ	0.71	0.75
	Denmark	DK	0.27	0.21
	Finland	FI	0.45	0.12
	France	FR	0.57	0.08
	Germany	DE	0.46	0.47
	Italy	IT	0.89	0.39
	Netherlands	NL	0.36	0.36
	Norway	NO	0.14	0.01
	Poland	PL	0.53	0.93
	Portugal	PT	1.03	0.19
	Russia	RU	0.47	0.43
	Spain	ES	0.80	0.22
	Sweden	SE	0.24	0.02
	Turkiye	TR	0.73	0.48
	Ukraine	UA	0.50	0.27

Region	Country	ISO Country Code	Natural gas [kgCO2e/kgNG]	Grid electricity [kgCO2e/kWh]
	United Kingdom	GB	0.37	0.27
Middle East	Iran	IR	0.50	0.53
	Iraq	IQ	0.56	0.93
	Israel	IL	0.13	0.55
	Kuwait	KW	0.37	0.54
	Oman	OM	0.29	0.47
	Qatar	QA	0.25	0.46
	Saudi Arabia	SA	0.23	0.74
	United Arab Emirates	AE	0.28	0.51
North America	Canada	CA	0.46	0.14
	Mexico	MX	0.51	0.40
	Trinidad and Tobago	TT	0.32	0.51
	United States	US	0.51	0.49
South America	Argentina	AR	0.56	0.38
	Bolivia	BO	0.39	0.34
	Brazil	BR	0.62	0.17
	Chile	CL	0.81	0.37
	Peru	PE	0.50	0.27
	Venezuela	VE	0.88	0.28

[a]: No NG data available for Namibia

Detailed TEA methodology

According to the Equations (1) - (3) in the main body, different economic parameters are applied by country and supply chain stage. This section aims to provide detailed economic calculation formulas and specific assumptions for the calculation of levelized cost of ammonia (LCOA) and levelized cost of hydrogen (LCOH). Equations (1) - (3) and following equations are based on the NREL Annual Technology Baseline calculation methodology.[8] The region-specific economic parameters required for the following calculations are shown in Table S1, while supply chain stage-specific economic parameters applied regardless of region are presented in Table S3. For cost data related to production plants, refer to Table 4 in the main body, and for downstream stages cost data, refer to Table S4.

The Fixed Charge Rate (FCR) is a factor that converts CAPEX to annualized cost, more specifically, it represents the amount of capital cost per unit $1 investment converted to annual cost. This is expressed as a function of the Weighted Average Cost of Capital (WACC) and ProFinFactor. For reference, WACC represents the weighted average cost of capital according to the proportion of capital sources (equity and debt). ProFinFactor is a value that converts the effect of reduced tax expenditure from the annual cost set by depreciating capital investment. Present Value of Depreciation (PVD) refers to the present value of the sum of annual depreciation calculated according to the MACRS method in this study.

$$FCR_{s,j} = \frac{WACC_{s,j}}{1 - \frac{1}{\left(1 + WACC_{s,j}\right)^{t}}} \times ProFinFactor_{s,j} \#(S1)$$

$$ProFinFactor_{s,j} = \frac{1 - TR_j \ \times PVD_{s,j}}{1 - TR_j} \#(S2)$$

$$WACC_{s,j} = \frac{1 + \left(1 - DF_{s,j}\right) \times e_j + DF_{s,j} \times d_j \times \left(1 - TR_j\right)}{1 + i_j} - 1 \#(S3)$$

$$PVD_{s,j} \ = \sum \frac{MACRS \ \ FD}{\left(\left(1 + WACC_{s,j}\right) \times \left(1 + i_j\right)\right)^{y}} \#(S4)$$

The CAPEX of the stage 's' located in the target country 'j' is calculated by adjusting the U.S. reference TOC of stage 's' (refer to Table 4 and Table S4) with the scaling factor (refer to Table S4), location factor (refer to Table S1), and ConFinFactor. ConFinFactor is an adjustment factor that additionally incorporates the cost due to financing during the construction period as a capital cost. Each stage of the supply chain, excluding storage and shipping, scales the TOC using a scaling factor of 0.6 from the reference capacity to match the capacity of the following stage (considering losses). For storage and shipping processes, a heuristic optimization approach was adopted to determine appropriate levels of tank (or tanker) sizing and number of tanks (or tankers) based on the size of the reference storage tank or tanker. This methodology was adapted from the MIT and ExxonMobil's Hydrogen Carrier Analysis Tool (HyCAT).[9] Additionally, as noted in each results section, this study assumed 100,000 kgNH_3/hr at gate arrival (i.e., production) for domestic production case or port arrival for overseas importation case.

$$CAPEX_{s,j} = TOC_s \times \left(\frac{Size_s}{Size_{s,0}}\right)^{SF} \times Location\ Factor_j\ \times ConFinFactor_{s,j} \#(S5)$$

$$ConFinFactor_{s,j} = \sum_{y=0}^{y=C-1} FC_{y,s,j} \times AI_{y,s,j} \#(S6)$$

$$AI_{y,s,j} = 1 + \left(1 - TR_j\right) \times \left(\left(1 + d_j\right)(y + 0.5) - 1\right) \#(S7)$$

For calculating the cost of capital in the target country 'j', the cost of debt (d_j) and cost of equity (e_j) are calculated using the following risk and margin adjustment formulas. The calculation considers the risk-free rate based on each country's government bond yield, country risk premium, and equity risk premium.[7] Additionally, for debt, a standardized assumption of 2% as a lending margin for large, private infrastructure debt is considered, and for equity, an equity premium of 2.4% is considered as a margin.

$$d_j = R_{riskfree,j} + R_{CRP,j} + 2\% \#(S8)$$

$$e_j = R_{riskfree,j} + R_{ERP,j} + 2.4\% \#(S9)$$

Detailed LCA methodology

According to the Equations (4) - (6) in the main body, different GHG emissions formula and assumptions are applied by country and supply chain stage. Equation (4) describes the Well-to-Gate (WTG) GHG emissions for domestically produced ammonia, Equation (5) describes the Well-to-Port (WTP) GHG emissions for imported ammonia, and Equation (6) describes the WTP GHG emissions for imported hydrogen (using ammonia as a carrier). When calculating emissions for each stage, the sum includes: 1) upstream life cycle GHG emissions due to feedstock and fuel consumption, and 2) direct GHG emissions. This section aims to describe the specific calculation formulas required for these emissions and the upstream life cycle emissions of country-specific mix-averaged natural gas and mix-averaged grid electricity, along with their derivation methods and background data. Equations (4) - (6) and the following calculation formulas are based on ISO 14040 and 14044 guidelines and the structure of the U.S. GREET 2022 model.[10] For region-specific upstream life cycle GHG emission parameters required for the following calculations, refer to Table S2, and for background data to calculate these parameters, refer to Tables S4 – S8.

GHG emission of each supply chain stage

The GHG emissions for each stage $GHG_{s,o\to t,A}$ and $GHG_{re,o\to t,A}$ are calculated through Equations (S10) - (S18). Here, $s \in S_A \;\; and \;\; c \in \{o, t\}$.

$$GHG_{s,o\to t,A} = GHG_{s,c,NG} + GHG_{s,c,Elec} + \; GHG_{s,c,MDO} \; + GHG_{s,c,onsite\; cO_2} \#(S10)$$

$$GHG_{reconv,o\to t,H} = GHG_{reconv,c,NG} + GHG_{reconv,c,Elec} + GHG_{reconv,c,onsite\; cO_2} \#(S11)$$

In the following equations, $U_{c,fuel}$ represents the upstream life cycle GHG emissions of the corresponding fuel in country c (refer to Table S2). $NG_s, Elec_s, MDO_s$ represent the fuel consumption in process s (refer to Tables 3 and S4). Note that we assume $U_{c,MDO}$ = 0.57 kgCO_2e/kg[10]. And EF_{NG} and EF_{MDO} are 2.62 and 3.19 kgCO_2e/kg[10], respectively.

$$GHG_{s,c,\,NG} = \; U_{c,NG} \; \times NG_s \#(S12)$$

$$GHG_{s,c,Elec} = U_{c,Elec} \; \times Elec_s \#(S13)$$

$$GHG_{s,c,MDO} = U_{c,MDO} \; \times MDO_s \#(S14)$$

$$GHG_{s,c,onsite\; CO_2} = \begin{cases} \quad Table\ 2 \quad , & s = p \\ EF_{NG} \; \times NG_s + EF_{MDO} \times MDO_s, & s \neq p \end{cases} \#(S15)$$

$$GHG_{reconv,t,\,NG} = \; U_{t,NG} \; \times NG_{reconv} \; \#(S16)$$

$$GHG_{reconv,t,Elec} = U_{t,Elec} \; \times Elec_{reconv} \#(S17)$$

$$GHG_{reconv,t,onsite\ CO_2} = EF_{NG} \times NG_{reconv} \#(S18)$$

Upstream life cycle GHG emission of natural gas and grid electricity

The calculation processes for $U_{c,Elec}$ and $U_{c,NG}$ are as follows:

The upstream life cycle GHG emissions of electricity vary depending on the electricity source. This study classifies them into three categories (national mix-averaged grid electricity, renewable electricity, and nuclear electricity). The upstream life cycle GHG emissions of mix-averaged (considering power generation mix) grid electricity by country were calculated as the sum of the 2021 scope 1 emissions for national grid power plants, scope 2 emissions, part of scope 3 emissions encompassing upstream, and emissions accounting for transmission and distribution losses (refer to Equation (S19)) reported by IEA and Carbon Footprint[11, 12]. The results are summarized in Table S2.

$$U_{c,Elec,Grid} = U_{c,Elec,scope\ 1} + U_{c,Elec,\ scope\ 2\&3} + U_{c,Elec,T\&D\ loss} \#(S19)$$

According to this study's criterion of counting only energy flow-related emissions and not embodied emissions (indirect emissions from materials, equipment, and labor) - which aligns with the definition criteria for clean ammonia and clean hydrogen in major countries[13, 14] - the upstream life cycle GHG emissions of renewable electricity are considered to be 0. Also, the upstream life cycle GHG emissions of nuclear-based electricity are considered positive values due to direct and indirect GHG emissions from processes such as uranium mining, refining, enrichment, and reconversion. For example, in the United States, this upstream life cycle emission corresponds to approximately 0.003 $kgCO_2e/kWh$[10].

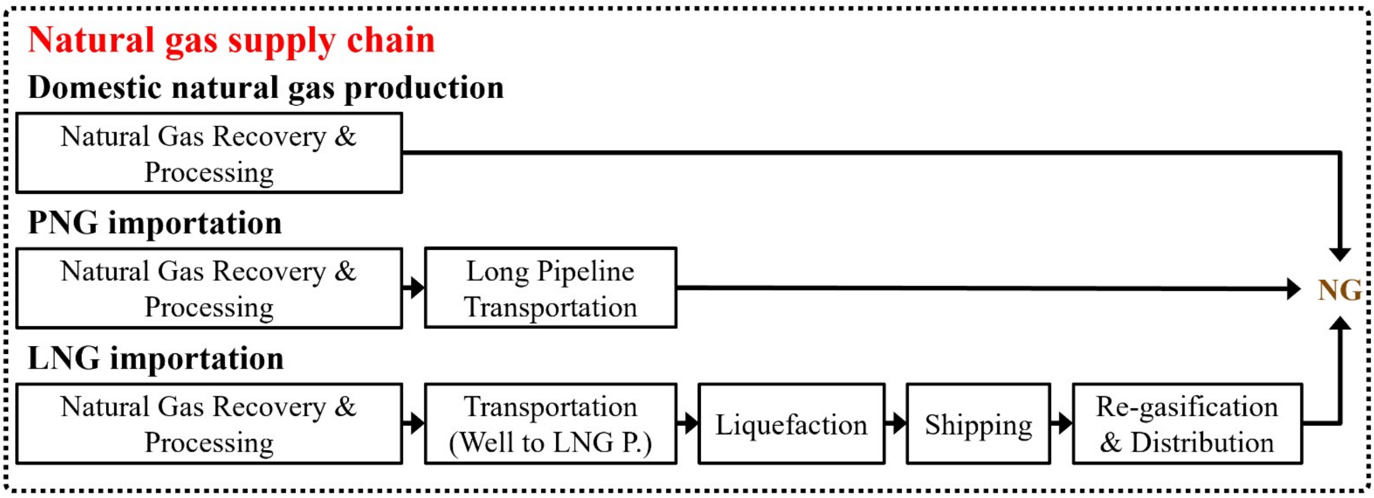

Figure S1, Flow diagram of natural gas supply chain

The upstream life cycle GHG emissions of natural gas by country (considering domestic production and import mix) were derived through separate spreadsheet-based in-house modelling. Figure S1 shows a flow diagram of natural gas supply chain. For each country, the proportions of domestic natural gas, natural gas importation through pipelines, and natural gas importation through LNG vary according to the balance of domestic natural gas resource availability and demand, and the availability of pipeline and LNG facilities. Therefore, the upstream emissions of national mix-averaged natural gas for each country are quantified as follows. $w_{c,D}$, $w_{c,P}$, $w_{c,L}$ represent the proportions of domestic production, PNG import, and LNG import for country 'c', respectively, and their values can be found in Table S5. (This inter-country export-import share data was calculated based on natural gas production by country and inter-country natural gas and liquefied natural gas trade data [15-18]). Additionally, import distances were investigated considering the distances between countries with export-import relationships and the existence and status of pipelines.

$$U_{c,NG} = w_{c,D} \times U_{c,domestic\ NG} + \sum_{e,c \in C} w_{e\to c,P} \times U_{e\to c,PNG} + \sum_{e,c \in C} w_{e\to c,L} \times U_{e\to c,LNG} \#(S20)$$

$U_{c,domestic\ NG}$ is calculated under the WTG emission scope of country 'c' that produces natural gas itself. This scope includes natural gas recovery and processing. The emissions of this process are calculated using the following Equation (S21). Here, fuel includes natural gas, grid electricity, diesel, and residual oil used as process fuel for the process. For CH_4 leakage emissions and CO_2 flaring emissions in the recovery and processing process, refer to Table S6[19-22]. Also, the fuel consumption $fuel_{R\&P}$ in the recovery and processing process is calculated with reference to Table S7[10, 23-26]. Note that EF_{Elec}= 0 (no direct emissions as it is electricity), $EF_{residual\ oil}$ = 3.20 kgCO$_2$/kg[27], and , $U_{c,diesel}$ and $U_{c,residual\ oil}$ use the U.S. average values (0.65 and 0.48 kgCO$_2$e/kg, respectively) universally, as they represent relatively small proportions of process fuel and have relatively small differences in upstream emission values between countries compared to natural gas and electricity. $U_{c,NG}$ iteratively references Equation (S20).

$$U_{c,domestic\ NG} = CO_{2,flaring,R\&P} + CH_{4,leakage,R\&P} \times GWP_{CH_4} + \sum_{fuel} fuel_{R\&P} \times (U_{c,fuel} + EF_{fuel}) \#(S21)$$

$U_{e\to c,PNG}$ additionally considers the process of transporting natural gas from foreign country e to country c through a pipeline. Consequently, as shown in Figure S1, it consists of a total of two processes: natural gas recovery and processing, and long pipeline transportation. The emissions of this process are calculated using the following formula. $L_{e\to c}$ represents the loss rate due to methane leaks during pipeline transportation. For CH_4 leakage emissions in the pipeline transportation process, a value of 5.9 gCH$_4$/TJ-km[10] was used, and for the pipeline distances between countries, refer to Table S5. Since the pipeline crosses countries, the average value of both countries was used for the upstream life cycle emissions of the fuel used. For the energy intensity used in pipeline transportation, refer to Table S8.

$$U_{e\to c,\ PNG} = L_{e\to c} \times U_{e,NG} + GHG_{e\to c,Pipeline} \#(S22)$$

$$GHG_{e\to c,\ Pipeline} = CH_{4,e\to c,\ Pipeline} \times GWP_{CH_4} + \sum_{fuel} fuel_{e\to c,\ Pipeline} \times \left(\frac{U_{e,fuel} + U_{c,fuel}}{2} + EF_{fuel}\right) \#(S23)$$

$U_{e\to c,LNG}$ additionally considers the processes of converting, transporting, and reconverting natural gas from foreign country e to country c through LNG. Consequently, as shown in Figure S1, it consists of a total of five processes: natural gas recovery and processing, pipeline transportation, liquefaction, LNG shipping, and regasification and distribution. The emissions of this process are calculated using the following formula. $L_{e\to c}$ represents the loss rate during LNG transportation. In this equation, s refers to the four downstream processes excluding NG recovery and processing among the previous processes. For data related to other downstream processes, refer to Table S6 (Liquefaction flaring) and Table S8 (Energy intensity and process fuel share). Additionally, CH_4 leakage in Liquefaction, Shipping, and regasification & distribution was used as 0.02g/MJ, 0.02%/day, and 0.0009 g/MJ, respectively[10, 28]. Furthermore, CO_2 direct emission of 0.290g/MJ[28] was additionally considered in Regasification & distribution. The pipeline distance from the natural gas production site to the LNG plant used distance values considering actual activity in each country[28]. For LNG ship transportation distances between countries, refer to Table S5.

$$U_{e\to c,\,LNG} = L_{e\to c} \times U_{e,NG} + \sum_{s} L_{s,e\to c} \times GHG_{e\to c,\,s} \#(S24)$$

$$GHG_{e\to c,\,Pipeline} = CH_{4,e,\,Pipeline} \times GWP_{CH_4} + \sum_{fuel} fuel_{e,Pipeline} \times \left(U_{e,fuel} + EF_{fuel}\right) \#(S25)$$

$$GHG_{e\to c,\,Lique} = CH_{4,e,\,Lique} \times GWP_{CH_4} + \sum_{fuel} fuel_{e,Lique} \times \left(U_{e,fuel} + EF_{fuel}\right) \#(S26)$$

$$GHG_{e\to c,\,Ship} = CH_{4,e\to c,\,Ship} \times GWP_{CH_4} + \sum_{fuel} fuel_{e\to c,\,Shipping} \times \left(\frac{U_{e,fuel} + U_{c,fuel}}{2} + EF_{fuel}\right) \#(S27)$$

$$GHG_{e\to c,\,Regas} = CO_{2,\,Regas} + CH_{4,c,\,Regas} \times GWP_{CH_4} + \sum_{fuel} fuel_{c,Regas} \times \left(U_{c,fuel} + EF_{fuel}\right) \#(S28)$$

Additional Datasets: Supplementary Information.xlsx

Complex two-dimensional background data used for the main analysis of global ammonia supply chains and result datasets in this study are provided in the **Supplementary Information (.xlsx file)**. The file contains the following worksheets:

- **Sheet "Country Code"**: Lists full names and ISO country code of the 63 countries.
- **Sheet "Voyage Distance"**: Provides voyage distances between countries. The representative port for each country was selected based on one or more of the following criteria:
    - Existing ports with large-scale ammonia handling capabilities.
    - Ports with ongoing construction of clean ammonia export/import facilities.
    - Ports having proximity to existing or planned ammonia production or demand centers.
    - Ports established infrastructure for handling other large-scale chemical and gas products (e.g., LNG)
- **Sheet "Ammonia Supply Chain"**: Provides levelized cost of ammonia (LCOA) and GHG emission for following 24 supply chain options. These 24 options are combinations of:
    - 4 production technologies options (and electricity source for production stage only):
        - "Blue": ATR-CCS-OC with grid electricity
        - "Gray": SMR with grid electricity
        - "Green": LTE with dedicated renewable electricity + hydrogen storage tank
        - "Yellow": LTE with grid electricity
    - 2 Electricity source for supply chain stages after production stage:
        - "Grid": Grid electricity
        - "Renew": Renewable electricity
    - 3 Shipping fuel (% share: LHV basis energy consumption):
        - "MDOship": 100% MDO
        - "MDONH3ship": MDO (91.6%) with boiled-off NH_3 (8.4%)
        - "NH3ship": 100% NH_3
    - Option code: format "Prod_Elec_Ship" (e.g. "Blue_Grid_MDOship").
    - Delivery amount: Fixed 100 tonNH_3/hr delivery for each corridor
- **Sheet "Hydrogen Supply Chain"**: Provides levelized cost of hydrogen (LCOH) and GHG emission for 24 following 24 supply chain options. These 24 options are combinations of:
    - 4 production technologies: Same as listed for the "Ammonia Supply Chain".
    - 2 Electricity source: Same as listed for the "Ammonia Supply Chain".
    - 1 Shipping fuel: Fixed to 100% MDO.
    - 3 Reconversion fuel:
        - "NH3reconv": Ammonia (part of delivered)
        - "NGreconv": Natural gas
        - "Elecreconv": Electricity
    - Option code: format "Prod_Elec_Reconversion" (e.g. "Blue_Grid_NH3reconv").

- Delivery amount: Fixed 17.2 tonH_2/hr delivery for each corridor

Tables

Table S3. Other economic assumptions.

		Production	Transportation 1 & 2	Storage & Loading	Shipping	Unloading & Storage	Reconversion
Scaling factor (SF)				0.6 b)			
Debt fraction (DF) [%]				47.7%[9]			
Construction duration (C) [years]		3			1 b)		
Capacity factor (CF) [%]		a)	80% b)		90% b)	80% b)	
Depreciation period (M) [years]		20			20 b)		
% of Capital Spent of Construction [%]	in 1st Year (FC_0)	8%			100% b)		
	in 2nd Year (FC_1)	60%			0% b)		
	in 3rd Year (FC_2)	32%			0% b)		
	in 4th Year (FC_3)	0%			0% b)		
Economic lifetime (t) [years]		40			40 b)		
OPEX rate [% CAPEX / year]		a)			4.0% b)		

a): Depends on production technology, see Table 2.
b): Assumed

Table S4. NH_3 downstream plants' mass-energy balance and cost information. [29-32]

	Transportation 1 & 2	Storage & Loading	Shipping	Unloading & Storage	Reconversion
Capacity	1.36 MTPA	36.7 kt/tank	51.8 kt/tanker	36.7 kt/tank	1.5 MTPA
TOC	0.55 M$/km	115 M$/tank	70 M$/tanker	115 M$/tank	787 M$
Electricity consumption	0.811 kWh/tonNH3-km	0.83 kWh/tonNH3	-	2.77 kWh/tonNH3	1.5 kWh/kgH2
NG consumption	-	-	-	-	9.7 kWh/kgH2
MDO consumption	-	-	1907 kgMDO/hr-tanker	-	-
Boil-off rate (flash)	-	0.006 % for loading	-	0.006 % for unloading	-
Boil-off rate (per day)	-	0.017 %/day for storage	0.02 %/day	0.017 %/day for storage	-
Additional stroage time	-	1 day	-	1 day	-
Note	-	-	32 km/h speed	-	Reaction loss: 2 %

Table S5. Natural gas supply mix and import distances

Target Country	Origin Country	Type	Distance [km] (one-way)	Share of amount [%]
Algeria	Algeria	Domestic	-	100.00%
Angola	Angola	Domestic	-	100.00%
Argentina	Argentina	Domestic	-	82.52%
Argentina	Bolivia	Import - Pipeline	441	9.59%
Argentina	Qatar	Import - LNG	16070	3.00%
Argentina	Trinidad and Tobago	Import - LNG	8364	0.11%
Argentina	United States	Import - LNG	12408	4.78%
Australia	Australia	Domestic	-	100.00%
Azerbaijan	Azerbaijan	Domestic	-	100.00%
Belgium	Algeria	Import - LNG	2834	0.40%
Belgium	Egypt	Import - LNG	5941	0.37%
Belgium	France	Import - Pipeline	74	0.77%
Belgium	Netherlands	Import - Pipeline	9	15.14%
Belgium	Norway	Import - Pipeline	808	57.08%
Belgium	Qatar	Import - LNG	11625	11.99%
Belgium	Russia	Import - Pipeline	1930	11.96%
Belgium	United Kingdom	Import - Pipeline	235	1.60%
Belgium	United States	Import - LNG	9234	0.70%
Bolivia	Bolivia	Domestic	-	100.00%
Brazil	Bolivia	Import - Pipeline	3150	17.07%
Brazil	Brazil	Domestic	-	58.92%
Brazil	Nigeria	Import - LNG	6282	0.27%
Brazil	Qatar	Import - LNG	15109	2.13%
Brazil	Trinidad and Tobago	Import - LNG	5808	0.61%
Brazil	United States	Import - LNG	9858	21.01%
Brunei	Brunei	Domestic	-	100.00%
Canada	Canada	Domestic	-	78.59%
Canada	Peru	Import - LNG	7654	0.07%
Canada	Trinidad and Tobago	Import - LNG	4191	0.52%
Canada	United States	Import - Pipeline	1126	20.83%
Chile	Argentina	Import - Pipeline	533	14.39%
Chile	Australia	Import - LNG	15881	0.21%
Chile	Chile	Domestic	-	21.07%
Chile	Equatorial Guinea	Import - LNG	12458	7.67%
Chile	Trinidad and Tobago	Import - LNG	7004	2.79%
Chile	United States	Import - LNG	7723	53.88%
China	Algeria	Import - LNG	15290	0.09%
China	Australia	Import - LNG	4489	12.12%
China	China	Domestic	-	58.16%
China	Egypt	Import - LNG	12144	0.48%
China	Indonesia	Import - LNG	3215	1.84%
China	Kazakhstan	Import - Pipeline	750	1.65%
China	Malaysia	Import - LNG	2658	3.26%
China	Nigeria	Import - LNG	17388	0.58%
China	Oman	Import - LNG	8677	0.61%
China	Peru	Import - LNG	18735	0.05%
China	Qatar	Import - LNG	9540	3.43%
China	Russia	Import - LNG	1000	1.72%
China	Russia	Import - Pipeline	963	2.11%
China	Trinidad and Tobago	Import - LNG	19368	0.17%
China	Turkmenistan	Import - Pipeline	966	8.77%
China	United Arab Emirates	Import - LNG	9516	0.29%
China	United States	Import - LNG	20087	3.46%
China	Uzbekistan	Import - Pipeline	650	1.19%
Czech	Russia	Import - Pipeline	1700	100.00%
Denmark	Germany	Import - Pipeline	300	62.10%
Denmark	Norway	Import - Pipeline	640	37.90%
Egypt	Egypt	Domestic	-	100.00%
Equatorial Guinea	Equatorial Guinea	Domestic	-	100.00%
Finland	Norway	Import - LNG	1469	0.26%
Finland	Russia	Import - Pipeline	200	99.74%
France	Algeria	Import - LNG	2772	9.71%
France	Belgium	Import - Pipeline	74	1.07%
France	Netherlands	Import - Pipeline	284	9.15%
France	Nigeria	Import - LNG	7940	7.61%
France	Norway	Import - Pipeline	840	37.14%
France	Qatar	Import - LNG	11564	1.24%
France	Russia	Import - Pipeline	1930	25.38%
France	Spain	Import - Pipeline	145	1.92%
France	United States	Import - LNG	9182	6.78%

Target Country	Origin Country	Type	Distance [km] (one-way)	Share of amount [%]
Germany	Belgium	Import - Pipeline	236	0.55%
Germany	Germany	Domestic	-	5.97%
Germany	Netherlands	Import - Pipeline	42	14.09%
Germany	Norway	Import - Pipeline	658	17.92%
Germany	Russia	Import - Pipeline	1230	61.47%
India	Algeria	Import - LNG	8621	0.17%
India	Australia	Import - LNG	8419	0.64%
India	Egypt	Import - LNG	5475	2.48%
India	India	Domestic	-	48.03%
India	Malaysia	Import - LNG	6008	0.14%
India	Nigeria	Import - LNG	13147	3.38%
India	Oman	Import - LNG	1254	2.85%
India	Qatar	Import - LNG	2008	22.96%
India	Russia	Import - LNG	10756	0.95%
India	Trinidad and Tobago	Import - LNG	15335	0.75%
India	United Arab Emirates	Import - LNG	1985	8.19%
India	United States	Import - LNG	17848	9.46%
Indonesia	Indonesia	Domestic	-	100.00%
Iran	Iran	Domestic	-	100.00%
Iraq	Iran	Import - Pipeline	1000	45.15%
Iraq	Iraq	Domestic	-	54.85%
Israel	Israel	Domestic	-	100.00%
Italy	Algeria	Import - Pipeline	2450	29.50%
Italy	Azerbaijan	Import - Pipeline	3500	9.49%
Italy	Egypt	Import - LNG	2428	0.33%
Italy	Italy	Domestic	-	4.19%
Italy	Libya	Import - Pipeline	520	4.25%
Italy	Netherlands	Import - Pipeline	1000	0.38%
Italy	Nigeria	Import - LNG	9210	0.35%
Italy	Norway	Import - LNG	6441	2.61%
Italy	Qatar	Import - LNG	8112	9.03%
Italy	Russia	Import - Pipeline	2750	38.40%
Italy	United States	Import - LNG	11912	1.47%
Japan	Australia	Import - LNG	5617	36.79%
Japan	Brunei	Import - LNG	4426	5.85%
Japan	Equatorial Guinea	Import - LNG	19839	0.36%
Japan	Indonesia	Import - LNG	4921	2.85%
Japan	Malaysia	Import - LNG	4978	14.35%
Japan	Nigeria	Import - LNG	19913	1.13%
Japan	Oman	Import - LNG	11197	2.63%
Japan	Papua New Guinea	Import - LNG	6378	4.83%
Japan	Peru	Import - LNG	15811	0.61%
Japan	Qatar	Import - LNG	12060	12.39%
Japan	Russia	Import - LNG	1758	8.02%
Japan	United Arab Emirates	Import - LNG	12036	1.83%
Japan	United States	Import - LNG	17161	8.36%
Kazakhstan	Kazakhstan	Domestic	-	88.79%
Kazakhstan	Russia	Import - Pipeline	156	11.21%
Korea	Australia	Import - LNG	5434	22.94%
Korea	Indonesia	Import - LNG	4680	5.78%
Korea	Malaysia	Import - LNG	4311	9.55%
Korea	Oman	Import - LNG	10455	10.70%
Korea	Qatar	Import - LNG	11318	27.78%
Korea	Russia	Import - LNG	943	4.70%
Korea	United States	Import - LNG	17855	18.54%
Kuwait	Algeria	Import - LNG	9232	0.39%
Kuwait	Egypt	Import - LNG	6086	1.57%
Kuwait	Kuwait	Domestic	-	70.82%
Kuwait	Nigeria	Import - LNG	13960	5.19%
Kuwait	Oman	Import - LNG	1291	1.55%
Kuwait	Qatar	Import - LNG	628	14.77%
Kuwait	Trinidad and Tobago	Import - LNG	15946	0.83%
Kuwait	United Arab Emirates	Import - LNG	811	1.14%
Kuwait	United States	Import - LNG	18459	3.76%
Libya	Libya	Domestic	-	100.00%
Malaysia	Australia	Import - LNG	3515	4.88%
Malaysia	Indonesia	Import - LNG	1963	0.82%
Malaysia	Malaysia	Domestic	-	94.09%
Malaysia	Nigeria	Import - LNG	15085	0.21%
Mexico	Indonesia	Import - LNG	21079	0.39%
Mexico	Mexico	Domestic	-	32.90%
Mexico	Trinidad and Tobago	Import - LNG	4111	0.11%
Mexico	United States	Import - Pipeline	250	66.59%
Morocco	Algeria	Import - Pipeline	760	81.03%
Morocco	Egypt	Import - LNG	3889	4.58%
Morocco	Morocco	Domestic	-	14.38%
Mozambique	Mozambique	Domestic	-	100.00%

Target Country	Origin Country	Type	Distance [km] (one-way)	Share of amount [%]
Namibia	#N/A	#N/A	#N/A	100.00%
Netherlands	Algeria	Import - LNG	2956	0.16%
Netherlands	Belgium	Import - Pipeline	45	3.18%
Netherlands	France	Import - Pipeline	284	1.54%
Netherlands	Netherlands	Domestic	-	42.30%
Netherlands	Nigeria	Import - LNG	8123	0.58%
Netherlands	Norway	Import - Pipeline	758	20.54%
Netherlands	Peru	Import - LNG	11653	0.67%
Netherlands	Qatar	Import - LNG	11747	0.26%
Netherlands	Russia	Import - Pipeline	1630	20.97%
Netherlands	Trinidad and Tobago	Import - LNG	7502	0.19%
Netherlands	United Kingdom	Import - Pipeline	232	2.30%
Netherlands	United States	Import - LNG	9356	7.32%
Nigeria	Nigeria	Domestic	-	100.00%
Norway	Norway	Domestic	-	97.75%
Norway	Russia	Import - LNG	21757	2.25%
Oman	Oman	Domestic	-	100.00%
Papua New Guinea	Papua New Guinea	Domestic	-	100.00%
Peru	Peru	Domestic	-	100.00%
Philippines	Philippines	Domestic	-	100.00%
Poland	Czech	Import - Pipeline	330	1.74%
Poland	Germany	Import - Pipeline	570	13.80%
Poland	Poland	Domestic	-	23.50%
Poland	Qatar	Import - LNG	13001	10.00%
Poland	Russia	Import - Pipeline	1000	44.21%
Poland	United States	Import - LNG	10080	6.74%
Portugal	Nigeria	Import - LNG	6225	50.17%
Portugal	Qatar	Import - LNG	9753	3.53%
Portugal	Russia	Import - LNG	18924	16.03%
Portugal	Spain	Import - Pipeline	400	2.72%
Portugal	Trinidad and Tobago	Import - LNG	6110	0.41%
Portugal	United States	Import - LNG	8454	27.15%
Qatar	Qatar	Domestic	-	100.00%
Russia	Kazakhstan	Import - Pipeline	944	0.98%
Russia	Russia	Domestic	-	96.82%
Russia	Turkmenistan	Import - Pipeline	2662	2.21%
Saudi Arabia	Saudi Arabia	Domestic	-	100.00%
Singapore	Angola	Import - LNG	13627	1.83%
Singapore	Australia	Import - LNG	3552	19.49%
Singapore	Brunei	Import - LNG	1265	0.00%
Singapore	Egypt	Import - LNG	9271	1.50%
Singapore	Equatorial Guinea	Import - LNG	14727	1.37%
Singapore	Indonesia	Import - LNG	1969	0.81%
Singapore	Indonesia	Import - Pipeline	800	53.73%
Singapore	Malaysia	Import - LNG	841	0.59%
Singapore	Malaysia	Import - Pipeline	300	13.47%
Singapore	Nigeria	Import - LNG	14801	0.70%
Singapore	Oman	Import - LNG	5804	0.10%
Singapore	Qatar	Import - LNG	6667	1.36%
Singapore	Russia	Import - LNG	5599	0.64%
Singapore	Saudi Arabia	Import - LNG	8265	0.48%
Singapore	United States	Import - LNG	21644	3.92%
Singapore	United States	Import - LNG	21644	0.00%
South Africa	China	Import - LNG	11697	0.00%
South Africa	Mozambique	Import - Pipeline	1400	98.05%
South Africa	South Africa	Domestic	-	1.95%
Spain	Algeria	Import - Pipeline	210	44.75%
Spain	Egypt	Import - LNG	2941	0.98%
Spain	France	Import - Pipeline	145	5.09%
Spain	Nigeria	Import - LNG	7082	11.99%
Spain	Norway	Import - Pipeline	985	2.96%
Spain	Peru	Import - LNG	11725	0.22%
Spain	Qatar	Import - LNG	8625	6.58%
Spain	Russia	Import - LNG	17796	9.10%
Spain	Trinidad and Tobago	Import - LNG	7271	3.09%
Spain	United States	Import - LNG	9784	15.25%
Sweden	Belgium	Import - Pipeline	515	0.20%
Sweden	Finland	Import - Pipeline	461	11.04%
Sweden	Germany	Import - Pipeline	200	2.78%
Sweden	Netherlands	Import - Pipeline	470	5.54%
Sweden	Norway	Import - Pipeline	350	70.44%
Sweden	Russia	Import - Pipeline	700	9.85%
Sweden	United States	Import - LNG	10495	0.16%
Thailand	Australia	Import - LNG	4695	2.40%
Thailand	Malaysia	Import - LNG	1682	3.68%
Thailand	Nigeria	Import - LNG	16170	2.96%
Thailand	Oman	Import - LNG	7215	0.87%

Target Country	Origin Country	Type	Distance [km] (one-way)	Share of amount [%]
Thailand	Qatar	Import - LNG	8078	8.98%
Thailand	Thailand	Domestic	-	79.08%
Thailand	Trinidad and Tobago	Import - LNG	20542	0.83%
Thailand	United States	Import - LNG	22361	1.20%
Trinidad and Tobago	Trinidad and Tobago	Domestic	-	100.00%
Tunisia	Algeria	Import - Pipeline	680	71.57%
Tunisia	Tunisia	Domestic	-	28.43%
Turkiye	Algeria	Import - LNG	2643	10.15%
Turkiye	Azerbaijan	Import - Pipeline	693	14.95%
Turkiye	Egypt	Import - LNG	1107	2.29%
Turkiye	Iran	Import - Pipeline	2577	15.99%
Turkiye	Nigeria	Import - LNG	9167	2.42%
Turkiye	Qatar	Import - LNG	6791	0.51%
Turkiye	Russia	Import - Pipeline	930	44.65%
Turkiye	Trinidad and Tobago	Import - LNG	9356	0.33%
Turkiye	Turkiye	Domestic	-	0.67%
Turkiye	United States	Import - LNG	11869	8.03%
Turkmenistan	Turkmenistan	Domestic	-	100.00%
Ukraine	Ukraine	Domestic	-	100.00%
United Arab Emirates	Nigeria	Import - LNG	13534	0.26%
United Arab Emirates	Qatar	Import - Pipeline	377	26.74%
United Arab Emirates	United Arab Emirates	Domestic	-	73.00%
United Kingdom	Algeria	Import - LNG	2489	0.89%
United Kingdom	Belgium	Import - Pipeline	235	2.28%
United Kingdom	Netherlands	Import - Pipeline	232	2.81%
United Kingdom	Nigeria	Import - LNG	7656	0.10%
United Kingdom	Norway	Import - Pipeline	1166	38.43%
United Kingdom	Peru	Import - LNG	10964	0.98%
United Kingdom	Qatar	Import - LNG	11281	6.71%
United Kingdom	Russia	Import - LNG	20452	3.65%
United Kingdom	Trinidad and Tobago	Import - LNG	6914	0.18%
United Kingdom	United Kingdom	Domestic	-	39.40%
United Kingdom	United States	Import - LNG	8641	4.58%
United States	Canada	Import - Pipeline	2953	9.13%
United States	Mexico	Import - Pipeline	250	0.01%
United States	Trinidad and Tobago	Import - LNG	4174	0.07%
United States	United States	Domestic	-	90.80%
Uzbekistan	Uzbekistan	Domestic	-	100.00%
Venezuela	Venezuela	Domestic	-	100.00%
Vietnam	Vietnam	Domestic	-	100.00%

Table S6. Natural gas – fugitive emission information

Country	Recovery and processing		Liquefaction
	CH4 Leakage [g/MJ]	NG Flaring [gCO2e/MJ]	NG Flaring [gCO2e/MJ]
Algeria	0.308	1.277	2.875
Angola	0.119	0.301	0.758
Argentina	0.272	0.724	-
Australia	0.064	0.088	0.149
Azerbaijan	0.124	0.033	-
Belgium	0.169	-	-
Bolivia	0.184	0.114	-
Brazil	0.166	0.271	-
Brunei	0.054	0.296	0.144
Canada	0.160	0.091	1.266
Chile	0.169	0.185	-
China	0.139	0.113	1.266
Czech	0.169	-	-
Denmark	0.169	-	-
Egypt	0.229	0.490	1.552
Equatorial Guinea	0.271	0.365	0.010
Finland	0.169	-	-
France	0.165	0.092	-
Germany	0.095	0.037	-
India	0.256	0.645	-
Indonesia	0.189	0.461	0.221
Iran	0.291	0.359	-
Iraq	0.130	4.241	1.266
Israel	0.030	0.030	-
Italy	0.023	0.002	-
Japan	0.243	0.054	-
Kazakhstan	0.296	0.701	-
Korea	0.169	3.675	-
Kuwait	0.095	0.186	0.521
Libya	0.288	2.657	-
Malaysia	0.083	0.721	0.045
Mexico	0.130	2.756	1.266
Morocco	0.069	-	-
Mozambique	0.266	5.020	-
Namibia	0.169	-	-
Netherlands	0.002	0.012	-
Nigeria	0.272	2.703	0.267

Country	Recovery and processing		Liquefaction
	CH4 Leakage [g/MJ]	NG Flaring [gCO2e/MJ]	NG Flaring [gCO2e/MJ]
Norway	0.001	0.014	9.854
Oman	0.130	0.728	0.134
Papua New Guinea	0.169	0.147	0.071
Peru	0.264	0.195	0.163
Philippines	0.115	1.519	-
Poland	0.113	0.236	-
Portugal	0.169	-	-
Qatar	0.118	0.046	0.144
Russia	0.189	0.377	0.244
Saudi Arabia	0.095	0.215	0.521
Singapore	0.169	-	-
South Africa	0.169	23.135	-
Spain	0.169	5.310	-
Sweden	0.169	-	-
Thailand	0.145	0.363	-
Trinidad and Tobago	0.134	0.052	0.675
Tunisia	0.212	3.578	-
Turkiye	0.169	0.245	-
Turkmenistan	1.067	0.483	-
Ukraine	0.261	0.345	-
United Arab Emirates	0.130	0.095	1.284
United Kingdom	0.055	0.707	-
United States	0.187	0.120	0.069
Uzbekistan	0.383	0.510	-
Venezuela	0.407	4.147	-
Vietnam	0.169	1.284	-

Table S7. Natural gas recovery and processing - efficiency and process fuel shares.

Region	Efficiency	Process fuel share			
		NG [%]	Electricity [%]	Diesel [%]	Residual oil [%]
Africa	95.97%	84.90%	1.33%	11.59%	2.18%
Asia / Australasia	96.00%	80.61%	6.32%	11.00%	2.07%
Europe	97.02%	77.75%	9.63%	10.62%	2.00%
Middle East	98.51%	63.76%	25.90%	8.70%	1.64%
North America	94.95%	79.45%	7.67%	10.85%	2.04%
Russia & Central Asia	96.58%	82.59%	4.01%	11.28%	2.12%
South & Central America	96.74%	84.90%	1.33%	11.59%	2.18%
OVERALL (All regions)	96.53%	80.31%	6.67%	10.96%	2.06%

Table S8. Natural gas downstream - efficiency and process fuel shares.

Region	Efficiency	Process fuel share			
		NG [%]	Electricity [%]	Diesel [%]	Residual oil [%]
Pipeline	1185746 J/ton-km	98.00%	2.00%	0.00%	0.00%
Liquefaction	94.73%	98.00%	2.00%	0.00%	0.00%
LNG shipping	39239 J/ton-km for origin to destination 33093 J/ton-km for back-haul	98.00%	2.00%	0.00%	0.00%
Regasification	99.67%	52.84%	47.16%	0.00%	0.00%

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