Global Hydrogen Review: Assumptions annex

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Global Hydrogen Review 2021: Assumptions

This annex collects the various assumptions that underpin the analyses throughout the *Global Hydrogen Review 2021.* For technologies, global averages are presented. However, several analyses in the report present regional examples, for which costs will vary with material and labour inputs and differ from the global average. These input parameters reflect choices made by the IEA on the basis of different sources of information consulted.

General Inputs

- All costs in USD (2019)
- Discount rate: 5%.
- Water costs are not considered.
- NZE = Net Zero Emissions by 2050 scenario

Fossil fuel prices

	Gas price (USD/MBtu)			Steam coal price (USD/tonne)		
Region	Today	NZE 2030	NZE 2050	Today	NZE 2030	NZE 2050
China	6.3	5.7	5.0	72	53	45
European Union	1.8	3.8	3.4	61	55	47
Japan	6.9	5.4	5.1	78	58	50
United States	2.3	2.1	2.2	45	24	22
Minimum	0.9	0.9	0.9	40*	24	22
Maximum	7.0	6.8	6.9	78	58	50

* The minimum value for steam coal price is based on regions that are not shown in the table.

Notes: MBtu = million British thermal units. Natural gas prices are weighted averages expressed on a gross calorific-value basis. The US natural gas price reflects the wholesale price prevailing on the domestic market. The European Union and China gas prices reflect a balance of pipeline and liquefied natural gas (LNG) imports, while the Japan gas price is solely LNG imports; the LNG prices used are those at the customs border, prior to regasification. Steam coal prices are weighted averages adjusted to 6 000 kilocalories per kilogramme.

Renewable electricity prices and full load hours

Solar PV

	LCOE (USD/MWh)			Full load hours (h)		
Region	Today	NZE 2030	NZE 2050	Today	NZE 2030	NZE 2050
Australia	37	21	14	2197	2333	2333
Chile	28	16	12	2899	2899	2899
China	20	14	11	2547	2547	2547
European Union	44	26	21	1393	1504	1504
India	25	15	11	2317	2549	2549
Japan	96	65	48	1473	1484	1484
Middle East	32	18	13	2722	2806	2806
North Africa	50	27	19	2523	2680	2680
United States	40	24	18	2177	2382	2485

Offshore wind

	LCOE (USD/MWh)			Full load hours (h)		
Region	Today	NZE 2030	NZE 2050	Today	NZE 2030	NZE 2050
Australia	75	38	25	4190	4589	4988
Chile	111	57	37	4939	5409	5880
China	93	43	27	2898	3454	4011
European Union	56	29	19	4450	4883	5317
India	108	56	37	3224	3489	3755
Japan	137	70	46	3806	4169	4531
Middle East	127	79	52	3324	3353	3645
North Africa	126	72	48	3312	3577	3842
United States	110	56	37	4153	4549	4944

Onshore wind

	LCOE (USD/MWh)			Full load hours (h)		
Region	Today	NZE 2030	NZE 2050	Today	NZE 2030	NZE 2050
Australia	48	42	38	3334	3416	3498
Chile	44	35	30	3474	3841	4208
China	39	34	33	3130	3130	3130
European Union	33	29	27	3566	3634	3702
India	47	38	34	2465	2634	2804
Japan	107	87	75	2765	3028	3291
Middle East	55	48	45	3183	3233	3282
North Africa	61	54	51	3239	3239	3239
United States	33	29	27	3915	3999	4083

Note: Renewable electricity generation costs and full load hours for good resource conditions in a region or country.

CO_2 prices and costs

CO_2 prices

Region	CO_2 price (USD/tCO_2)		
	Today	NZE 2030	NZE 2050
Advanced economies	20-27	130	250
Selected emerging market and developing economies*	10	90	200
Other emerging market and developing economies	0	15	55

* Includes Russia, Brazil, China, and South Africa.

CO_2 transport and storage cost for CCUS

Region	(USD/tCO_2)		
	Today	NZE 2030	NZE 2050
United States	15	12	12
Middle East	15	12	12
Europe	56	33	33
China	16	12	12
Rest of the World	25	20	20

Production pathways

Hydrogen

Technology	Parameter	Units	Today	NZE 2030	NZE 2050
Water electrolysis	CAPEX*	**USD/kW_e**	1000-1750	400-440	320-340
	Efficiency (LHV)	**%**	64	69	74
	Annual OPEX	**% of CAPEX**	1.5 – 3	1.5 – 3	1.5 – 3
	Stack lifetime (operating hours)**	**hours**	50000	50000	50000
Natural gas reforming	CAPEX	**USD/kW_{H2}**	780	780	780
	Efficiency (LHV)	**%**	76	76	76
	Annual OPEX	**% of CAPEX**	4.7	4.7	4.7
Natural gas reforming w/CCUS	CAPEX	**USD/kW_{H2}**	1470	1470	1470
	Efficiency (LHV)	**%**	69	69	69
	Annual OPEX	**% of CAPEX**	4	4	4
	CO_2 capture rate	**%**	95	95	95
Coal gasification	CAPEX **	**USD/kW_{h2}**	1960	1960	1960
	Efficiency (LHV)	**%**	60	60	60
	Annual OPEX	**% of CAPEX**	5	5	5
Coal gasification w/CCUS	CAPEX ***	**USD/kW_{H2}**	2040	2040	2040
	Efficiency (LHV)	**%**	58	58	58
	Annual OPEX	**% of CAPEX**	5	5	5
	CO_2 capture rate	**%**	95	95	95

* Electrolyser CAPEX includes the electrolyser system, electric equipment, gas treatment, plant balancing, and engineering, procurement and construction (EPC). In the case of electrolysers using solar PV and offshore wind, the cost of the inverter is discounted.

** Stack lifetime can reach up to 95 000 h. The selected value (50 000 h) comes from IEA's analysis of the optimum economic lifetime, considering degradation issues.

*** For China, CAPEX is assumed to be 50% of the world average for coal gasification and 52% for coal gasification with CCUS.

Notes: 25-year lifetime and a 95% availability factor assumed for hydrogen production from natural gas, 25 year lifetime and 90% availability factor is assumed for the production of hydrogen from coal. Availability factors for electrolysis are based on the full load hours of electricity shown in the General inputs section. For water electrolysis, water costs and possible revenues from oxygen sales have not been considered in the cost analysis.

Hydrogen-based fuels

Haber – Bosch (Ammonia)

Parameter	Units	Today	NZE 2030	NZE 2050
CAPEX (including air separation unit)	**USD/(tNH_3/y)**	771	771	771
Annual OPEX	**% of CAPEX**	2.9%	2.9%	2.9%
Electricity consumption	**GJ/t_{NH3}**	2.2	2.2	2.2

Notes: 95% availability assumed for all equipment's. Assumed cost of hydrogen storage to achieve 8000h utilization rate: 3.3-4.9 USD/MWh H2.

Methanation (synthetic methane)

Parameter	Units	Today	NZE 2030	NZE 2050
CAPEX	**USD/kW_{prod}**	1000	840	500
Efficiency (LHV)	**%**	77	77	77
Annual OPEX	**% of CAPEX**	4	4	4
Variable O&M	**USD/MWh_{prod}**	4.8	4.0	2.4
Lifetime	**years**	30	30	30
Electricity consumption	**GJ_e/GJ_{prod}**	0.013	0.013	0.013

Notes: 95% availability assumed for all equipment's. Assumed cost of hydrogen storage to achieve 8000h utilization rate: 3.3-4.9 USD/MWh H2. Assumed cost of feedstock CO_2: 30 USD/tCO_2 (biogenic), 150-450 USD/tCO_2 (DAC - today), 70-240 USD/tCO_2 (DAC - long term).

Fischer-Tropsch (synthetic diesel)

Parameter	Units	Today	NZE 2030	NZE 2050
CAPEX	**USD/kW_{liquid}**	2330	1770	1000
Efficiency (LHV)	**%**	73	73	73
Annual OPEX	**% of CAPEX**	5	5	5
Variable O&M	**USD/MWh_{prod}**	5.9	4.7	2.3
Lifetime	**years**	30	30	30
Electricity consumption	**GJ_e/GJ_{liquid}**	0.018	0.018	0.018

Notes: 95% availability assumed for all equipment's. Assumed cost of hydrogen storage to achieve 8000h utilization rate: 3.3-4.9 USD/MWh H2. Assumed cost of feedstock CO_2: 30 USD/tCO_2 (biogenic), 150-450 USD/tCO_2 (DAC - today), 70-240 USD/tCO_2 (DAC - long term)

Industrial applications

Steel

Route	Parameter	Units	Today	2030
Natural gas-based DRI-EAF	CAPEX	**USD/t$_{crude\ steel}$**	1087	-
	Annual OPEX	**% of CAPEX**	7.5%	-
	Electricity consumption	**GJ/t$_{crude\ steel}$**	2.9	-
	Natural gas consumption	**GJ/t$_{crude\ steel}$**	11.8	-
Natural gas-based DRI-EAF with CCUS	CAPEX	**USD/t$_{crude\ steel}$**	1169	-
	Annual OPEX	**% of CAPEX**	7.5%	-
	Electricity consumption	**GJ/t$_{crude\ steel}$**	3.3	-
-	Natural gas consumption	**GJ/t$_{crude\ steel}$**	11.8	-
	CO_2 capture rate	**%**	90	-
Hydrogen-based DRI-EAF	CAPEX	**USD/t$_{crude\ steel}$**	1784	1391
	Annual OPEX	**% of CAPEX**	7.5%	7.5%
	Electricity consumption	**GJ/t$_{crude\ steel}$**	16	15

Notes: 25-year lifetime and 95% availability assumed for all equipment. Hydrogen-based DRI-EAF parameters include the electrolyser costs (see Hydrogen table). The hydrogen requirement for this route is estimated to lie in the range of 47-68 kg/t of DRI, with the mid-point of this range used for the cost calculations. For the DRI-EAF routes, a 95% charge of DRI to the EAF is considered. An iron ore (58% Fe content) cost of USD 60/t and a scrap cost of USD 250/t is assumed for all process routes, regions and time periods. Costs of electrodes, alloys and other wearing components are considered as a part of the fixed OPEX.

Ammonia (NH_3)

Technology	Parameter	Units	Low	High
Natural gas SMR	CAPEX	**USD/tNH_3**	1910	1910
	Annual OPEX	**% of CAPEX**	2.5	2.5
	Gas consumption	**GJ/t$_{NH3}$**	32.1	32.1
	Electricity consumption	**GJ/t$_{NH3}$**	0.3	0.3
Natural gas ATR with CCUS	CAPEX	**USD/tNH_3**	2110	2110
	Annual OPEX	**% of CAPEX**	2.5	2.5
	Gas consumption	**GJ/t$_{NH3}$**	27.9	27.9
	Electricity consumption	**GJ/t$_{NH3}$**	1.5	1.5
Technology	**Parameter**	**Units**	**Today**	**NZE 2030**
Electrolysis	CAPEX	**USD/tNH_3**	2355	1234
	Annual OPEX	**% of CAPEX**	1.9 %	1.9 %
	Electricity consumption	**GJ/t$_{NH3}$**	36.0	33.5

Notes: 25-year lifetime and 95% availability assumed for all equipment. The electrolysis route parameters include the electrolyser costs (see Hydrogen table). The gas price assumptions for the low cost case is 2 USD/MBtu and for the high case 10 USD/MBtu.

Transport applications

Heavy-duty trucks

Technology	Parameter	Units	Today	2030 APS	2050 APS
All powertrains	Mileage	**km/year**	100 000	100 000	100 000
	Range	**km**	500	500	500
	Years of ownership	**years**	5	5	5
	Discount rate	**%**	10%	10%	10%
	Glider CAPEX	**USD thousand**	118	118	118
	Salvage value	**%[1]**	42	42	42
	Power	**kW**	350	350	350
FCEV	Fuel cell cost	**USD/kW**	376	181	60
	Hydrogen tank	**USD/kWh**	15.5	9.3	8
	Battery	**kWh**	3.3	3.3	3.3
	Fuel consumption	**MJ/km**	8.3	7	6.6
	Electric motor	**USD/kW**	55	42	35
	O&M	**USD/km**	0.1	0.1	0.1
	Delivered H_2 price	**USD/kg**	5.5	3.4	2.9
Hydrogen refuelling station	Size	**kg/day**	550	934	2645
	CAPEX	**USD/kg/day**	2343	1200	900
	Lifetime	**years**	30	30	30
	Utilisation	**%**	10%-30%	20%-50%	35%-75%
BEV	Battery cost	**USD/kWh**	328	119	60
	Battery size	**kWh**	820	791	705
	Fuel consumption	**MJ/km**	4.92	4.75	4.23
	O&M	**USD/km**	0.1	0.1	0.1
	Base electricity price[2]	**USD/kWh**	0.12	0.12	0.12
ICE (diesel)	Fuel consumption	**MJ/km**	13.1	-	-
	Motor	**USD/kW**	118	-	-
	O&M	**USD/km**	0.16	-	-
	Diesel price	**USD/lge**	1.51	-	-
ICE - Hybrid	Fuel consumption	**MJ/km**	-	7.6	7.6
	O&M	**USD/km**	-	0.16	0.16
	Syndiesel price	**USD/lge**	-	1.87-3.06	1.21-2.29

[1] Percentage of total vehicle cost (CAPEX) equivalent to the glider and powertrain-specific components.
[2] Excluding costs of installing and operating dedicated charging infrastructure.
Notes: O&M = operation and maintenance.

Buildings applications

Space and water heating

Technology	Parameter	Units	Values
Buildings	Space heat demand	kWh/sq.m	60-100
	Water heat demand	kWh/year	800
	Floor area	sq.m.	100
All technologies	Lifetime	years	15
	Operation & Maintenance	% of CAPEX/yr	3
Heat exchanger (district heat)	Efficiency	%	0.8-0.99
Electric resistance	Efficiency	%	1
Heat pump (air source)	Efficiency	%	2.5-4.5
	CAPEX*	USD/kW_{th}	400
Gas boiler	Efficiency	%	0.8-0.9
Gas heat pump	Efficiency	%	0.9-1.35
Chips and pellet stoves	Efficiency	%	0.5-0.85
Hydrogen boiler	Efficiency	%	0.85-0.95
	CAPEX*	USD/kW_{th}	250
Hydrogen hybrid heat pumps	Efficiency	%	2.2-3.2
	CAPEX*	USD/kW_{th}	450
Hydrogen fuel cell	Efficiency (cogeneration) **	%	0.75-0.95**
	CAPEX*	USD/kW_{el}	3500
Grid electricity	PEF***	-	1.25-3.75
District heat	PEF***	-	1.1-1.33
Hydrogen	PEF***	-	1.75-3.8

*All CAPEX are for 2030, in the Announced Pledges Scenario. Average cost in the selected regions.
**Cogeneration efficiency is the sum of thermal and electrical efficiency
***PEF: primary energy factor in 2020.
Notes. Ranges in efficiencies reflect technological variations.

Electricity generation

Co-firing in existing fossil thermal plants

Technology	Parameter	Units	Values
Natural Gas Combined Cycle plant	Modification to H2 combustion	USD/MWh_{th}	1.7
	LNG price	USD/MWh	20 - 29
	OPEX (excluding fuel)	USD/MWh_{th}	2
	Efficiency	%	51
Coal Ultra-Supercritical plant	Modification to NH3 combustion	USD/MWh_{th}	1.1
	Coal price	USD/MWh	7 - 14
	OPEX (excluding fuel)	USD/MWh_{th}	4
	Efficiency	%	44
Hydrogen fuel	Cost	USD/kg	1.5 – 2.5
Ammonia fuel	Cost	USD/t	300 - 500
CO_2	cost	USD/t	82-130

Notes. CAPEX of the existing plant is not taken into account as the model considers initial investment as sunk cost. Shipping distance 10 000 km. For assumptions on liquefaction and shipping, see Hydrogen Transport section.

Hydrogen transport

Pipelines

Technology	Parameter	Units	Hydrogen	LOHC	Ammonia
Pipelines	Lifetime	**years**	30	-	
	Distance	**km**	Function of supply route		
	Design throughput	**tH_2/day**	100/500/1000		
	Inlet pressure	**bar**	80		
	Gas density	**kg/m^3**	6.4	-	-
	Gas velocity	**m/s**	15	-	-
	CAPEX/km	**USD million/km**	0.49/0.86/1.2 2		
	Utilisation	**%**	90%		
Retrofit pipeline	CAPEX/km	**% of new built**	25%		
Gas compression	Capacity	**tH_2/day**	10		
	CAPEX	**MUSD**	2.3		
	Annual OPEX	**% of CAPEX**	10		
	Electricity use	**kWh/kg**	1.9		

Notes: Transmission pipeline for hydrogen gas based on Baufumé (2013):
Pipeline CAPEX (USD/km) = 4 000 000D^2 + 598 600D + 329 000; where D (internal diameter in cm) = √(F/v)/π*2*100; v = gas velocity (m/s); F (volumetric flow in m^3/s) = Q/ρ; Q = gas throughput (kg/s); ρ = gas density (kg/m3).
Sources: Baufumé et al. (2013), "GIS-based scenario calculations for a nationwide German hydrogen pipeline infrastructure".

Seaborne transport

Technology	Parameter	Units	Liquefied hydrogen	LOHC	Ammonia
Ship[1]	Capacity/ship	**$t_{carrier}$**	11 000	110 000	26 000
	CAPEX/ship	**USD million**	412	76	50
	Ship speed	**km/h**	30	30	30
	No. of ships used		Function of distance		
	Boil-off rate[2]	**%/day**	0.2%	-	-
	Flash rate[3e]	**%**	1%	-	-
Import terminal	Capacity/tank	**$t_{carrier}$**	3600	62000	57000
	No. of tanks	**#**	Based on days of storage needed for a given ship loading frequency		
	CAPEX/tank	**USD million**	320	35	97

Technology	Parameter	Units	Liquefied hydrogen	LOHC	Ammonia
	Electricity use	**kWh/kgH₂**	0.2	0.01	0.02
	Boil-off rate	**%/day**	0.1	-	-
Export terminal	Capacity/tank	**$t_{carrier}$**	3200	52000	35000
	No. of tanks		Based on days of storage needed for a given ship loading frequency		
	CAPEX/tank	**USD million**	290	42	68
	Annual OPEX	**% of CAPEX**	4%	4%	4%
	Electricity use	**kWh/kgH₂**	0.61	0.01	0.01
	Boil off rate	**%/day**	0.1%	-	-
Liquefaction	Installed capacity	**tH_2/day**	Confidential	-	-
	Capacity CAPEX	**MUSD**	Confidential		-
	Annual OPEX	**% of CAPEX**	Confidential	-	-
	Electricity use	**kWh/kgH₂**	Confidential	-	-
Conversion[4]	Installed capacity	**kt_{Tol}/y**	**-**	5500	-
	Plant CAPEX	**USD million**		270	
	Annual OPEX	**% of CAPEX**	-	4%	-
	Electricity use	**kWh/kgH₂**	-	1.5	-
	Natural gas use	**kWh/kgH₂**		0.2	
	Start-up toluene	**kt**	-	500	-
	Toluene cost	**USD/t_{Tol}**	-	400	-
	Toluene markup	**kt_{Tol}/y**	-	200	-
Reconversion[5]	Capacity	**$kt_{carrier}$**	-	5500	2000
	CAPEX	**USD million**	-	890	660
	Annual OPEX	**% of CAPEX**	-	4%	4%
	Heat required	**kWh/kgH₂**	-	13.6	9.7
	Plant power	**kWh/kgH₂**	-	0.4	-
	H_2 purification (PSA) power	**kWh/kgH₂**	-	1.1	1.5
	H_2 recovery rate	**%**	-	90%	99%
	PSA H_2 recovery rate	**%**	-	98%	85%

[1] Ship carrying liquid hydrogen and ammonia use carrier gas for propulsion; LOHC ship uses heavy fuel oil. It is assumed that fuel consumption can be obtained from carrier gas in the storage tank, so the fuel for the ship would not incur an additional energy penalty.

[2] The boil-off gas is the gas that spontaneously evaporates from liquefied gas at extremely low temperatures

[3] The flash rate is the rate of loss that occurs upon each loading/unloading of cryogenic liquefied gas.

[4] Conversion: LOHC = Toluene +H2 → MCH. Toluene mark-up is the quantity of new toluene required reach year. Data for ammonia conversion are included in the table on ammonia production above.

[5] Reconversion: LOHC = MCH → Toluene + H_2; Ammonia = NH_3 → N_2 +H_2.

Notes: PSA = Pressure swing adsorption. System lifetime assumed to be 30 years, unless stated otherwise; utilisation of production, conversion and reconversion capacity = 90%.

Sources: IAE (2016), “Institute of Applied Energy (Japan) data based on “Economical Evaluation and Characteristic Analyses for Energy Carrier Systems (FY 2014–FY 2015) Final Report”; ETSAP (2011), *LOHC Ship Cost from: Oil and Natural Gas Logistics*; IMO (2014), *Third IMO Greenhouse Gas Study 2014*.

Trucks

Technology	Parameter	Units	Hydrogen	LOHC	Ammonia
Trucks	Depreciation period	years	12		12
	CAPEX	kUSD	LH_2: 1000 GH_2: 620		410
	Annual OPEX	% of CAPEX	5		5
	Speed	km/h	50		50
	Driver cost	USD/h	23		23
	Net capacity	kgH_2	LH_2: 4300		2600
			GH2: 1000		
	Loading / Unloading time	hrs	LH2: 3 GH2: 1.5		1.5

Note: LH_2 = liquid hydrogen. GH_2 = gaseous hydrogen. The costs of compressing or liquefying hydrogen before transport, or to convert it to liquid carriers (incl. ammonia) are given in the tables above for pipeline or ship transport.

Sources: Reuß, M. et al. (2017), "Seasonal storage and alternative carriers: A flexible hydrogen supply chain model"; Reuß et al. (2019), "A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany".

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