Supplementary Information 1 – Hydrogen demand estimation

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Global hydrogen demand evolution

Hydrogen demand estimation follows a mixed top-down and bottom-up approach, where the energy demand for different sectors is chosen in a top-down manner from IEA's net-zero scenario[1]. Using the final energy and feedstock demand values in each sector, we identify the proportion of the demand that can be met by hydrogen. To do so, we first identify on a sector-by-sector basis the electrification potential based on sectoral characteristics and existing outlooks such as IEA's World Energy Outlook[1], IRENA's World Energy Transitions Outlook[2] and DNV's Energy Transition Outlook[3]. Then, the part of the demand that cannot be met by electrification (mainly feedstock demand), or it is very costly and difficult to electrify (such as high temperature industrial heating and very long-haul heavy road transport) is assumed to be met by hydrogen, synthetic fuels produced from hydrogen and bio-energies. This remaining energy and feedstock demand depending on its type and sector is assessed one-by-one in the global level. The relative share of hydrogen and hydrogen-based products and bio-energies is then determined based on availability of different bio-feedstock and a top-down allocation following the existing penetration levels in the existing outlooks.

This assessment follows on three types of calculation: energy replacement, feedstock replacement and process shift.

- Energy replacement: In this case, hydrogen directly provides the required energy either via combustion (using its lower heating value of 120 MJ/kg) or fuel cells. For instance, natural gas demand for heating in the industry can be met partially by electricity (low- and mid-temperature heating), but high temperature heating will require combustion of hydrogen[4]. This demand is considered in energy terms, that reaches as high as 7.2 EJ (60 MtH_2) by 2050, including recycling.
- Feedstock replacement: Here, using the stochiometric analysis, we identify the needed moles of hydrogen to replace either 1 mol of natural gas as feedstock or to produce synthetic fuels that can replace fossil fuels. For instance, hydrogen demand for methanol production follows a stochiometric approach, where it directly replaces natural gas, eliminating the steam methane reformation process. 1 mol of natural gas would produce 1 mol of methanol, while via direct hydrogen use, 1 mol of methanol requires 3 moles of hydrogen (Fischer-Tropsch reaction[5]). Including the process efficiency, to produce 26.7 Mt methanol estimated in IEA's net-zero scenario, about 5.3 MtH_2 will be needed by 2050[6].
- Process shift: Replacement of fossil energy sources by hydrogen in some cases can require completely new processes. In this case, hydrogen replaces the fossil feedstock based on the stochiometric equilibrium of the two reactions to produce the same quantity of the final product. This is the case for steelmaking. Hydrogen direct reduction can replace blast furnace reaction that consumes coal and is associated with significant CO_2 emissions. In this case, 25 kg of hydrogen is needed to produce 1 ton of steel via direction reduction route[7], while in the primary steel production process via blast furnace reaction, about 770 kg of coal is consumed[d].

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[d] https://www.bhp.com/what-we-do/products/metallurgical-coal

We assume that by 2050 the whole primary steel production will be based on hydrogen direct reduction, and via an interpolation from zero in 2020 to 100% in 2050, we assume 1/3 of the global primary steel energy and feedstock demand is met by hydrogen direct reduction. Therefore, hydrogen penetration in the global iron and steel production by 2030 and 2050 reach 20% and 60% of the sector's energy and feedstock demand), amounting to 55 Mt and 135 Mt of global hydrogen demand.

Following these three types of calculation, potential hydrogen demand is estimated for iron and steel, chemicals, fertilizers, methanol, cement, recycling, other high temperature industrial heating, road transport, maritime transport, aviation, buildings, and electricity generation. The estimations distinguish between each of the four main hydrogen derivative molecules: gaseous pure hydrogen, ammonia, methanol, and e-kerosene. The overall global hydrogen demand reaches 598 MtH_{2eq} by 2050. This can be further broken down to 253 MtH_{2eq} for industry, 215MtH_{2eq} for transport, 125 MtH_{2eq} for electricity production and 5 MtH_2 for the buildings sector (via hydrogen blending in the natural gas network). Looking at hydrogen derivatives, these demand values account for 389 MtH_2 of pure hydrogen, 104 MtH_{2eq} (589 $MtNH_3$) of ammonia, 25MtH_{2eq} (133 $MtCH_3OH$) of methanol and 80MtH_{2eq} (184 Mt) of e-kerosene. **Table SI1.1** summarizes hydrogen demand in each of the studies sectors in 2050 and the share of the final energy and feedstock demand that is met by hydrogen and its derivatives by the studied date. Clean hydrogen represents 21% of the final energy consumption by 2050 in a scenario with IEA's NZE scenario values.

Table SI1.1. Hydrogen demand (MtH_{2eq}) and its final energy and feedstock demand penetration in each sector in 2050

Sector	Subsector	2050 hydrogen penetration (%)	2050 hydrogen demand (MtH_{2eq})	Hydrogen end-use form
Industry	Iron & Steel	60%	135	H_2
	Fertilizer	100%	44	NH_3
	Other chemicals	27%	5	CH_3OH
	Cement	13%	9	H_2
	Heat & other	-	60	H_2
Transport	Light road	5%	10	H_2
	Heavy-duty road	40%	75	H_2
	Shipping	70%	50	NH_3 & CH_3OH
	Aviation	50%	80	$C_{12}H_{26}$ (representative)
Power	Electricity generation	3%	125	H_2 & NH_3
Buildings	Gas blending	0.7%	5	H_2

Key assumptions

In the short run, it is assumed that fertilizer production and other current uses of hydrogen are fully decarbonised by 2030. By this date, clean hydrogen penetrates in other sectors, mostly for primary steel production (20% of steelmaking and 1/3 of the primary steel production to become decarbonized via hydrogen direct reduction), transport sector and electricity supply (1% of global power generation). During the period from 2030 and 2050, clean hydrogen production and its end uses reach higher maturity and clean hydrogen decarbonises completely primary steel, fertilizer and methanol production and complements electric vehicles in the road transport.

Following the IEA's 2023 revision of its Net-Zero Emissions pathway[e], it is assumed that 70% of the shipping final energy demand and 50% of the aviation final energy demand will be satisfied by hydrogen-based fuels (hydrogen, ammonia, methanol and synthetic jet fuel). The remaining fuel demand is expected to be met by biofuels and very marginally by fossil fuels that will be offset by negative GHG-emitting industries (notably direct air capture and bioenergy carbon capture and storage).

Country decomposition of hydrogen demand

The global sectoral hydrogen demand values calculated in the previous section are ~~then~~ broken down into national values for each country in the considered scope (74 most promising countries regarding large-scale and low-cost green and blue hydrogen supply potentials). This breakdown is based on future population from the United Nations' World Population Prospects[f], GDP from Economist Intelligence Unit's global forecasting hub estimations[g], maritime[h] and aerial[i] traffic and IEA's energy consumption and electrification projections[1]. **Table SI1.2** highlights the parameters considered for decomposition of each of the sectoral demand values among the studied countries.

Table SI1.2. Correlation parameters with each clean hydrogen demand sector assumed for the country decomposition

Sector	Subsector	Parameter correlated to demand	Source
Industry	Iron & Steel	GDP	The Economist Intelligence Unit[f]
	Fertilizer	Population corrected with historical supply	The UN World Population Prospects[e]
	Other chemicals	GDP	The Economist Intelligence Unit[f]
	Cement	GDP	The Economist Intelligence Unit[f]
	Heat & other	GDP	The Economist Intelligence Unit[f]
Transport	Light road	GDP	The Economist Intelligence Unit[f]
	Heavy-duty road	GDP	The Economist Intelligence Unit[f]
	Shipping	International maritime traffic, overall shipping fuel consumption by country and adjustments with port traffic	International Energy Agency's Sankey Diagram[j], International Energy Agency's International Shipping[g] and The Global Economy's port traffic[k]
	Aviation	International aerial traffic and overall aviation fuel consumption by country	International Energy Agency's Sankey Diagram[i], Knoema[h] and The Global Economy's jet fuel consumption[l]
Power	Electricity generation	Final electricity demand	International Energy Agency[1]
Buildings	Gas blending	Buildings final energy demand	International Energy Agency[1]

International Energy Agency's Sankey Diagram[i] is used for aggregated demand data for maritime and aerial transport. Maritime transport includes both domestic and international shipping and the overall fuel consumption by country is adjusted to port traffic within that country[j]. Aviation demand breakdown follows jet fuel consumption patterns, based on summing the fuel demand of all of the

[e] https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach
[f] https://population.un.org/wpp/
[g] https://www.eiu.com/n/solutions/viewpoint/market-indicators-and-forecasts/
[h] https://www.iea.org/reports/international-shipping
[i] https://knoema.com/data/consumption+jet-fuel
[j] https://www.iea.org/sankey/#?c=World&s=Final%20consumption
[k] https://www.theglobaleconomy.com/rankings/port_traffic/
[l] https://www.theglobaleconomy.com/rankings/jet_fuel_consumption/

airports in a country[k]. Pure hydrogen demand for industry and road transport and methanol demand for the industry are correlated with the future GDP growth projections. Therefore, 289 MtH_2 of 2050 pure hydrogen demand (204 MtH_2 for the industry and 85 MtH_2 for the road transport sectors) and 5 MtH_{2eq} (27 $MtCH_3OH$) of methanol demand are broken down among between countries in proportion of their future GDP projections from the Economist Intelligence Unit's future projections. As ammonia demand for fertilizers is correlated to the agriculture products' demand, and therefore the population, we consider future population growth as the main indicator of future ammonia demand for fertilizers. Such a correlation follows the assumption that food security over the globe reaches a standardized level. Using the future population projections of the United Nations[e] and 2050 ammonia demand for fertilizer production of 44 MtH_{2eq} (249 $MtNH_3$), we break this demand down for each of the considered countries. The same calculation method is used for the intermediary horizons for 2030, 2035, 2040 and 2045.

Methanol and ammonia demand breakdown for maritime transport and e-kerosene demand for aviation follow the current maritime and aerial traffic and fuel consumption of each country, to account for national and international passenger transports, international bunkers and freight transport. Assuming a 50% e-kerosene penetration for overall aviation fuel consumption, and a 70% ammonia and methanol penetration (equally) for maritime transport by 2050, 80 MtH_{2eq} of e-kerosene, 30 MtH_{2eq} of ammonia and 20 MtH_{2eq} of methanol consumption values are broken down between the key consumers over the globe. Hydrogen and ammonia demand for electricity production and hydrogen blending in the natural gas networks follow the future electricity demand and buildings' gas demand projections of IEA's net-zero pathway[1], where 10% of buildings' gas demand and 4% of global electricity demand by 2050 are satisfied by hydrogen and ammonia. The final demand values for each sector and each main region are summarized in **Figure SI1.1** below.

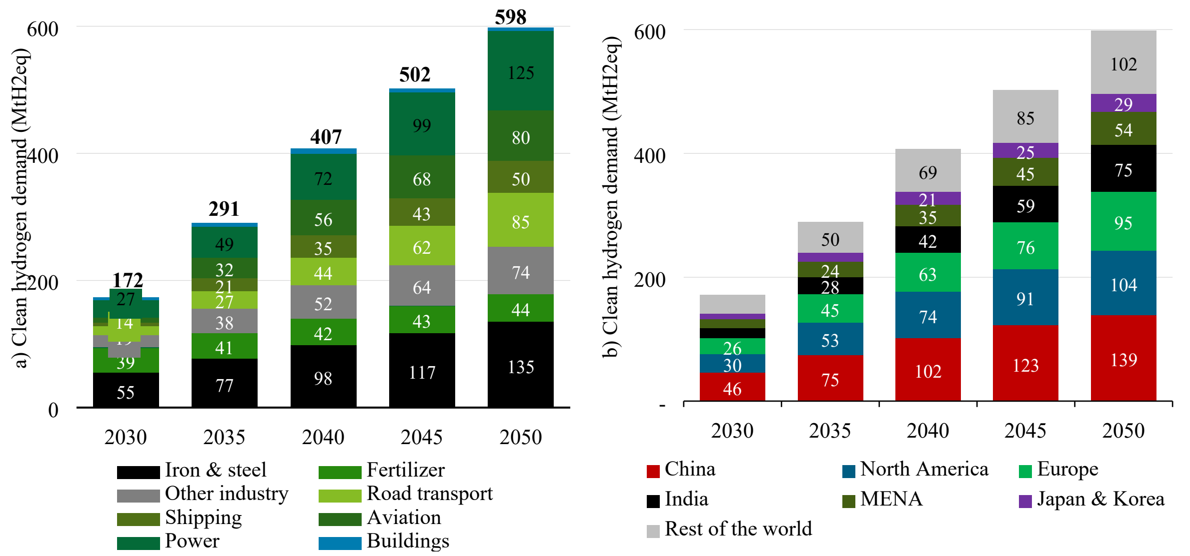

Figure SI1.1. Global clean hydrogen demand evolution by (a) end-use sector and (b) region between 2030 and 2050.

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