

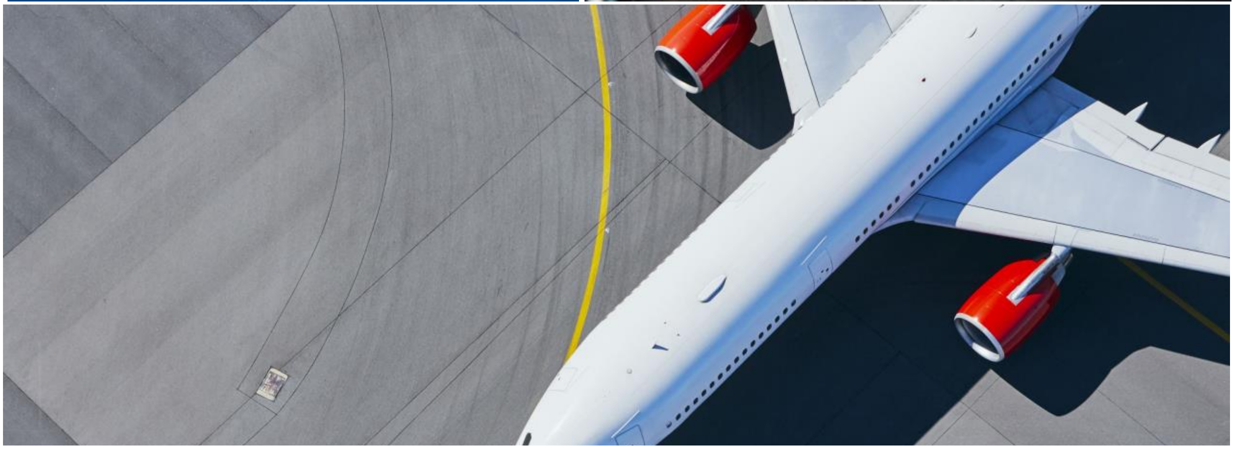

INDIA H2 DERIVATIVES & LOW-CARBON FUELS MARKET ASSESSMENT 2025-30

Industry Whitepaper

India Hydrogen Alliance, IH2A

DECEMBER 10 2024

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EXECUTIVE SUMMARY

This industry white paper has been prepared in anticipation of the significant green hydrogen and derivatives' project development and production, which is expected to fuel low-carbon green fuels for heavy-duty transport , specifically in long-haul trucking, shipping and aviation. This is a preliminary view, based on some assumptions on fleet offtake and industry inputs gathered by India Hydrogen Alliance (IH2A). It does not consider eFuels or green hydrogen derivatives exports as transport fuel. In summary, potential Domestic Transport eFuels Market Assessment 2030 by volume, may be estimated as follows, with the accompanying assumptions about offtake fleets and scale:

1) Green Methanol (Shipping & Trucking) – 194 mn ltrs (22 3000-TEU Vessels, 30 10-tonne Trucks)
2) Green Ammonia (Shipping & Trucking) – 263 mn ltrs (22 3000-TEU Vessels, 30 10-tonne Trucks)
3) LH2 + CGH2 Hydrogen (Trucking) – 19500 kgs (without LH2 storage)- 30 FC Trucks
4) Sustainable Aviation Fuel (SAF) – 15-45 mn ltrs. based on 1-3% blending on 74 flights (intl, dom)

KEY TAKEAWAYS

a) Shipping fleets are the volume driver for offtake – coastal shipping accounts for most of green methanol and green ammonia volumes.
b) SAF (as drop in fuel) is easiest to be prioritized in short (2-3 years) timeframe as it does not require any new Vehicle/Aircraft CAPEX and Re-Fueling Infrastructure.
c) Fleet & Re-Fueling Infra CAPEX for Green Methanol, Green Ammonia and Liquid/Compressed Gaseous H2 is significant so fleet owners will require financial support to add H2 vehicles into their fleets. Refueling infrastructure can be built around planned production clusters to reduce volume offtake risk, in hubs/ clusters, rather than in multiple locations.
d) Efficient Green Fuels Policy Design and Green Fuels Hubs can be implemented through collaborative approaches and consortiums, if we have to accelerate towards Low Carbon Transport (with H2 derivatives). Partnerships across stakeholders and jurisdictions are required e.g. SAF offtake will depend on India-EU collaboration on sustainable aviation. Similarly, green methanol or green ammonia offtake for maritime use-case requires close collaboration between India and Singapore, the regional bunkering fuel hub.

GREEN / LOW-CARBON LIQUID FUELS IN TRUCKING & MARITIME TRANSPORT

Green Methanol- Domestic Methanol eFuels Market Estimate by 2030

If India decides to pursue Green Methanol fuel for decarbonizing coastal shipping, it would decide to build Methanol production and offtake hubs, of different scales (this would be finally determined by the methanol project developer and offtake/fleet owner). Below are three different scale options, for project developers and fleet owner to consider and plan to incorporate green hydrogen derived methanol as a transport fuel. Project developers may consider green methanol as bunkering fuels export from India's East Coast to Singapore (SG has announced bunkering facility of 100,000 tpa/ 100 mn ltrs pa (or 600K by 2030) for NH3 and Methanol).

METHANOL TRANSPORT HUB A – Port Hub & Spoke (Shipping, Trucking)	METHANOL TRANSPORT HUB B Port Hub & Spoke (Shipping, Trucking)	METHANOL TRANSPORT HUB C Port Hub & Spoke (Shipping, Trucking)
194 mn litres with 22 Methanol-powered Shipping Vessels, 30 Trucks by 2030	97 mn litres with 11 Methanol-powered Shipping Vessels, 15 Trucks by 2030	50 mn litres with 5 Methanol-powered Shipping Vessels, 7 Trucks by 2030
ASSUMPTIONS: USD 6/ltr OR USD 1.2 bn fuel costs (254 mn pa), Vehicle Fleet CAPEX- USD 4 bn for 22 Mid-Sized Vessels (@ USD 175 mn/vessel) for 30 Trucks (@ USD 50,000/truck), by 2030. 40,000 MT H2 (8,000 MT pa) required	*ASSUMPTIONS:* USD 6/ltr, OR USD 600 mn fuels cost (120 mn pa) Vehicle Fleet CAPEX- USD 2 for 11 Vessels (@ USD 175mn /vessel) and for 15 Trucks (@ USD 50,000/truck), by 2030. 20,000 MT H2 (5,000 MT pa) required	*ASSUMPTIONS:* USD 6/ltr OR USD 300 mn fuel costs (50 mn/yr) Vehicle Fleet CAPEX- USD 1 bn for 5 Vessels (@ USD 175mn/vessel) and for 7 Trucks (@ USD 50,000/truck), by 2030.: 10,000 MT H2 (2,500 MT pa) required

Green Ammonia - Domestic Green Ammonia eFuels Market Estimate by 2030

Similar to Methanol, India can choose Green Ammonia as fuel for decarbonizing coastal shipping and trucking; and plan production around offtake hubs. Below are three different scale options, for project developers and fleet owner to consider and plan to incorporate green hydrogen derived ammonia as a transport fuel. *NOTE: Green Ammonia prices are estimated to be 130% more than Green Methanol.*

GREEN AMMONIA TRANSPORT HUB A – Port Hub & Spoke (Shipping, Trucking)	GREEN AMMONIA TRANSPORT HUB B-Port Hub & Spoke (Shipping, Trucking)	GREEN AMMONIA TRANSPORT HUB C- Port Hub & Spoke (Shipping, Trucking)
263 mn litres with 22 Ammonia-powered Shipping Vessels, 30 Trucks by 2030	132 mn litres with 11 Ammonia-powered Shipping Vessels, 15 Trucks by 2030	66 mn litres with 5 Ammonia-powered Shipping Vessels, 7 Trucks by 2030
ASSUMPTIONS: USD 8/ltr OR USD 2.1 bn fuel costs (420 mn pa), Vehicle Fleet CAPEX- USD 4.04 bn for 22 Vessels (@ USD 183 mn/vessel, and 30 Trucks (@ USD 150,000/truck), by 2030. 50,000 MT H2 (10,000 MT pa) required	*ASSUMPTIONS:* USD 8/ltr, OR USD 1 bn fuels cost (210 mn pa), Vehicle Fleet CAPEX- USD 2.02 for 11 Vessels (@ USD 183 mn/vessel) and 15 Trucks (@ USD 150,000/truck), by 2030. 25,000 MT H2 (5000 MT pa)	*ASSUMPTIONS:* USD 8/ltr OR USD 500 mn fuel costs (100 mn/yr) Vehicle Fleet CAPEX- USD 1.01 bn for 5 Vessels (@ USD 183 mn/vessel) and 7 Trucks (@ USD 150,000/truck), by 2030. 12500 MT H2 (2500 MT pa)

Green Hydrogen - Domestic Green Hydrogen eFuels Market Estimate by 2030

A conservative estimate of a 30 FCEV 28-tonnes Truck Fleet has been taken for the 2025-2030 period, and this fleet should require 19500 kgs of H2 fuel (in CGH2 and LH2 form), and significant infrastructure for storage and refuelling.

The high cost of H2 refuelling infrastructure is expected to depress H2 offtake as fuel (in CGH2 or LH2 form), in the 2025-30 period.

GREEN / LOW-CARBON DROP-IN FUELS IN SUSTAINABLE AVIATION (SAF) – 2030 Estimate

We have considered bio-fuels/HEFA pathway (non-H2) for SAF production, and assumed aggregated feedstock availability at Delhi/Mumbai clusters for aggregated HEFA production.

Airline Fleet Offtake timelines are critical and expected to start with 1% SAF blending, rising upto 3% blending. On the back of the EU Sustainable Aviation regulatory requirements. Only two routes one domestic (Mumbai-Delhi) and one international (Delhi-Paris) have been considered, and it is estimated that 122 flights annually (52 internationally and 22 domestically). NOTE: HEFA Price (Delhi, USD) is 30% more than ATF – despite this, it offers the lowest price differential as compared to other Green Fuel options. The table below provides SAF volumes for 1%, 2% and 3% blending on these flights:

SAF INTL + DOMESTIC FLIGHTS - 3% BLENDING	SAF INTL + DOMESTIC FLIGHTS - 2% BLENDING	SAF INTL + DOMESTIC FLIGHTS - 1% BLENDING
45 mn litres SAF with 122 Annual Flights (52 Intl, 22 Dom) by 2030	30 mn litres SAF with 122 Annual Flights (52 Intl, 22 Dom) by 2030	15 mn litres SAF with 122 Annual Flights (52 Intl, 22 Dom) by 2030
ASSUMPTIONS: USD 1200/ltr (HEFA pathway only) OR USD 54 bn fuel costs (USD 9 bn pa)	*ASSUMPTIONS:* USD 1200/ltr (HEFA pathway only) OR USD 36 bn fuel costs (USD 6 bn pa)	*ASSUMPTIONS:* USD 1200/ltr (HEFA pathway only) OR USD 18 bn fuel costs (USD 3 bn pa)

GREEN FUELS FOR HEAVY-DUTY TRANSPORT USE-CASE

Different Green Fuels expected to have different adoption rates, based on offtake readiness, economics and technical readiness/ viability. Across the four green fuels evaluated, SAF appears promising in the short term, followed by Methanol (for Shipping), following by Green Ammonia and H2 Trucking.

GREEN FUELS FOR HEAVY-DUTY TRANSPORT USE-CASE

Green/ Low-Carbon Fuel	Current Price*	Expected Commercial Adoption	Supply / Productions	Tech Readiness	Offtake Readiness
SAF	+30%	Developing	Developing	Developing	Ready
Green Methanol	+500%	Early Stage	Developing	Developing	Limited
Green Ammonia	+500%	Preliminary/ Pilots	Early Stage	Early Stage	Limited
Green H2	+500%	Preliminary/ pilots	Preliminary/ Pilot Stage	Early Stage	Limited

**compared to conventional fuels (ATF/ Diesel)*

ACKNOWLEDGMENTS

For preparation of this white paper, IH2A engaged with representatives from industry players companies operating across the H2 value-chain in India and globally, covering member and non-member companies, investors, government stakeholders and energy-transition experts.

A. KEY ASSUMPTIONS & METHODOLOGY

Project team has considered H2 and H2-derivative transport fuel types for three heavy duty transport use cases – Trucking, Shipping and Aviation; and estimated offtake from transport fleet sizes. Technical and economic assumptions for each use-case are below:

LONG-HAUL TRUCKING - E-METHANOL M100 TRANSPORT FUEL	
Vehicle Specs	N3 Rigid, Multi-Axel, 10-18 Tonne Trucks using M15 or M100 (Ashok Leyland)
Engine Specs	Diesel-Methanol Combustion (DMCC) tech, full load M-100
Fuel Efficiency	24.75 ltrs/ 100km, Diesel-Methanol Combustion (DMCC) tech, full load (**20.9 lters/no load)**
Fuel Cost (Production)	USD 706 per tonne / RMB 5100 per tonne
MRS Cost (Refueling Station)	MRS 4*40m3 storage tanks and 4 pumps with 16 guns - New MRS cUSD 500K, Retrofitted USD 4500
Annual Run - Kms/Vehicle pa (avg)	100,000 kms
GHG Emissions	103 gms CO2 / ltr (Methanol)
LONG-HAUL TRUCKING - LIQUID AMMONIA/ NH3 AS TRANSPORT FUEL	
Vehicle Specs	Dual-fuel Semi Truck (Amogy)
Engine Specs	NH3-Diesel ICE engines or NH3 FuelCell Engine
Fuel Efficiency	20.7 litres / 100 kms; 900 kWh for 1000 kms
Fuel Cost (Production)	$750-$888 per tonne
Cost of Vehicle	USD 150,000 estimated
Refueling Cost	USD 800K *based on assumption between methanol and H2 refueling
Annual Run - Kms/Vehicle pa (avg)	100,000 kms
GHG Emissions	0 kg CO2 / ltr. (NH3)
LONG-HAUL TRUCKING - LIQUID H2 AS TRANSPORT FUEL	
Vehicle Specs	19-35 tonnes GVW Truck (Ashok Leyland)
Engine Specs	LH2 Fuel Cell
Fuel Efficiency	9-9.2kg per 100km / conversion 1 kg of H2 is 14.128 Litres (keengas)/ 129 lts/100 kms
Fuel Cost (Production)	USD 4.3-8/kg in US by 2030
Cost of Vehicle	H2-ICE 1.4X = €154,000 / USD 160,000
HRS Costs	HRS - US 1.5-2.5 million/unit
Annual Run - Kms/Vehicle pa (avg)	100,000 kms
GHG Emissions	1.5 gms CO2 hp-hr) or 12 litres/ hp-hr; 0.125 kgCO2/ ltr. (LH2)

SHIPPING - METHANOL AS MARINE TRANSPORT FUEL	
Vehicle Specs	Sub-500 GRT, 1000-2000 TEU General Cargo Carrier/ Vessel (IW) OR 10,000-16,000 TEU Mid-Sized Container Vessel for Ocean/Coastal Shipping (Maersk)
Engine Specs	Dual-fuel engine for Methanol/BioDiesel-Bunkering Fuel
Fuel Efficiency	38.75 ton/100 kms at 38 kms/hr
Fuel density	791.4 kg/m
Fuel range tank	16 000 m3
Fuel Costs (Production)	USD 706 per tonne / RMB 5100 per tonne
Vehicle Cost	USD 175 million (New Methanol Ship)
Refueling Cost	MRS 4*40m3 storage tanks, 4 pumps with 16 guns - through barge, terminal and truck.
Annual Run - Kms/Vessel pa (avg)	86280 kms. (General Cargo Carrier)/ 280435 kms. (Mid-Sized Container Vessel)
GHG Emissions	103 gms of CO2/ ltr. (of methanol)
SHIPPING - AMMONIA AS MARINE TRANSPORT FUEL	
Vehicle Specs	Dual engine container vessel of 15000 TEU (Seaspan)
Fuel density	791.4 kg/m
Fuel range tank	20000 m3
Fuel Efficiency	42.65 ton/100 kms at 38 kms/hr
Fuel Costs (Production)	USD $200-1,000/ton
Vehicle Cost	USD 183 million.
Refueling Cost	New Refueling Station - USD 1.5 million
Annual Run - Kms/Vessel pa (avg)	280435 kms. (Mid-Sized Container Vessel)
GHG Emissions	0 kg of CO2

AVIATION - SAF/ E-KEROSENE ATF	
SAF Blending Ratio	1% Blending for all international flights by 2027, general blending roadmap of 1% by 2025 and 2% by 2028
Aviation Fleet Size (Indian carriers)	771
Daily Traffic	~3000 flights (domestic), ~500 flights (international)
Fuel Assumptions	Jet A1 fuel used in Indian turbine engines
Refueling Stations (Existing)	256 aviation fuel stations (IOCL, BPCL, HPCL, RIL)
SAF blending - Fleet Size	261 Airbus A320 Neo, Boeing 787-9 Dreamliners considered between Indigo, AirIndia and Vistara fleets for SAF blending pilots.
SAF Blending - Routes	Delhi-Paris/EU (International), Mumbai-Delhi (Domestic)
SAF Blending - Flights Per Year	208 international flights/aircraft, 104 domestic flights/aircraft
Fuel Production Tech. Pathways	HEFA, ATJ, PtL

The team has made assumptions on the percentage of the trucking/vessel/aircraft fleets that are estimated to run on H2, H2-derived eFuels (Methanol and/or Ammonia) and SAF, in the initial six-year period from 2025-30, and estimated total e-fuel consumption (in volume). This provides a National e-Fuels Domestic Market Estimate, based on domestic demand side projections and assumes that there are no supply constraints.

This market assessment has been prepared on the basis of assumptions made about production cost, capex requirements, fuel efficiency and mileage, of the different H2 and H2-derived eFuel types. Changes on these assumptions will affect the projected e-Fuels market size. *NOTE: assumptions have been made for domestic transport use-case only, and not combined with export-oriented projects and export offake.*

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PART A: Low-Carbon Fuels for Long-Haul Trucking

We started with making assumptions about the number of Green Methanol, Ammonia and Hydrogen Trucking fleets that could be expected to be deployed over the next five years, from 2025-2030. Subsequently fuel volume estimates were made. These are detailed below.

While liquid H2 is the most efficient fuel of the three, it is also significantly more expensive to produce as well as lower in density. Methanol is comparatively lower in fuel efficiency (25 litres/100 kms) but is relatively cost-effective. (Please note that eefficiency plays a major role in determining fuel volume) As the maturity of the green fuels production pathways improves, fuel costs can be expected to stabilize after 2027 (not factored in the current model).

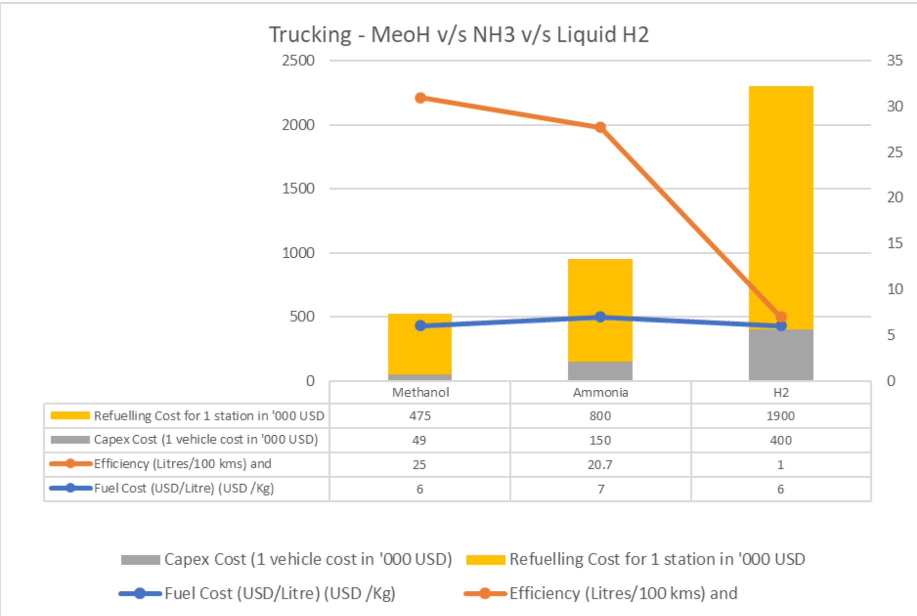
A1. LOW-CARBON METHANOL/ AMMONIA/ LH2-FUELLED TRUCKING FLEETS (EST.)

				No. of Low-Carbon Vessels Deployed						
Low Carbon Trucking	Fleet Type	Capacity	Distance	2025	2026	2027	2028	2029	2030	TOTAL
Base Case: Diesel	N3 Rigid Multi-axel Truck	28 tonnes	Long haul - 1000 kms							
Methanol Trucks	M100 HDV	10 tonnes	Long Haul - 1000 kms*	0	2	4	4	8	10	**28**
Ammonia Trucks	Semi-truck, NH3 fuel cell	10 tonnes*	Long haul - 1000 kms	0	2	4	6	8	10	**30**
H2 Trucks	FCEV trucks	28 tonnes	Mumbai - Delhi (1500 kms)	0	2	4	6	8	10	**30**
TOTAL				0	6	18	34	58	88	88

A2. LOW-CARBON TRUCKING FLEETS – WITH METHANOL/ AMMONIA/ LH2 OFFTAKE VOLUMES (EST.)

		Expected Fuel Requirement (ltrs).							
Low Carbon Trucking	Fuel/ Vessel pa, ltrs	2025	2026	2027	2028	2029	2030	TOTAL	
Methanol Trucks	16,088	0	32175	64350	64350	128700	160875	450450	Litres
Ammonia Trucks	13,455	0	26910	53820	80730	107640	134550	403650	Litres
H2 Trucks (in Kgs)	650	0	1300	2600	3900	5200	6500	19500	Kgs

Green Methanol Vs. Ammonia Vs. LH2 Offtake (Volumes) for Trucking – 2025-30



PART B: Low-Carbon Maritime Fuels for Shipping & Inland Waterways

We have considered Methanol and Ammonia vessels for coastal shipping only, started with making some assumptions about the number of Green Methanol, Ammonia and Hydrogen Trucking fleets that could be expected to be deployed over the next five years, from 2025-2030. Subsequently fuel volume estimates were made. These are detailed below.

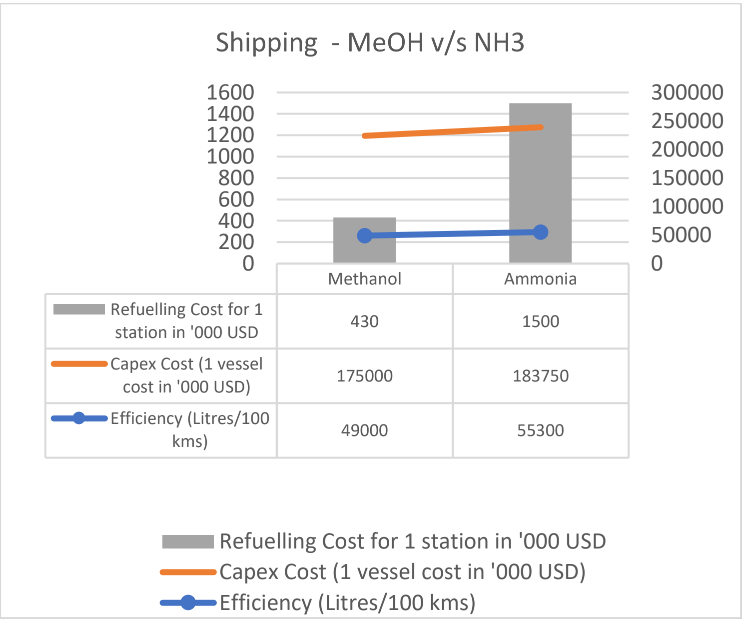
B1. LOW-CARBON MARITIME FLEETS- METHANOL & AMMONIA FUELLED VESSELS/FLEETS (ESTIMATED)

				No. of Low-Carbon Vessels Deployed						
Low Carbon Maritime	Fleet Type	Capacity	Distance	2025	2026	2027	2028	2029	2030	TOTAL
Methanol Vessels	Container Ship/Cargo Carrier	2000-3000 TEU	790 km	0	2	2	4	6	8	**22**
Ammonia Vessels	Dual-fuelled Container ship	2000-3000 TEU	790 km	0	2	2	4	6	8	**22**
TOTAL				0	4	8	16	28	44	44

B2. LOW-CARBON MARITIME FLEETS – WITH METHANOL & AMMONIA OFFTAKE VOLUMES (ESTIMATED)

		Expected Fuel Requirement (ltrs).						
Low Carbon Maritime	Fuel/ Vessel pa, ltrs	2025	2026	2027	2028	2029	2030	TOTAL
Methanol Vessels	**8800000**	0	17600000	17600000	35200000	52800000	70400000	**193600000**
Ammonia Vessels	**11950000**	0	23900000	23900000	47800000	71700000	95600000	**262900000**
TOTAL		0	41500000	41500000	83000000	124500000	166000000	456500000

Green Methanol (New Vessel) Vs. Ammonia (Volumes) for Shipping/Maritime Use – 2 Graphs, 2025-30



PART C: Sustainable Aviation Fuel (SAF) for Low-Carbon Aviation

We have considered 1% SAF blending on International and Domestic Flights on two sectors- Delhi-Paris and Mumbai-Delhi. SAF volumes will increase if the 1% blending is increased to 3%.

Production of SAF using the HEFA pathway is currently the most cost-effective (USD 0.99/litre for 1% blending) of all approved pathways. The cost, however, is majorly dependent on the type and quality of feedstock. As RE costs and production costs for green hydrogen reduce, PtL is expected to become affordable towards 2030.

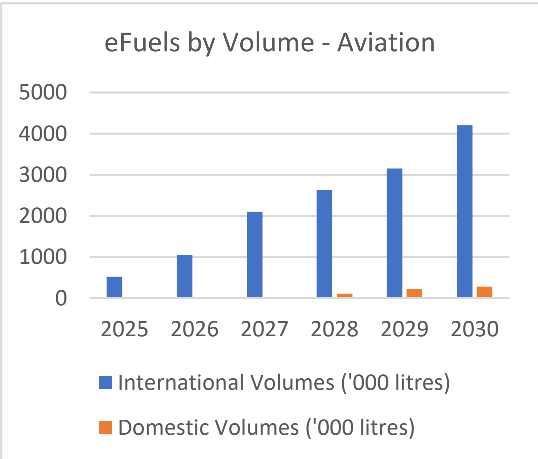
C1. SAF BLENDING (1%) FOR AVIATION FLEETS, INTERNATIONAL & DOMESTIC (ESTIMATED)

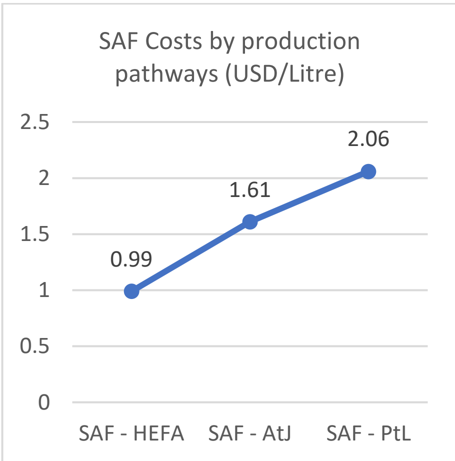
Low Carbon Aviation					2025	2026	2027	2028	2029	2030	TOTAL
Base Case: ATF (Jet A1)	Boeing 787-9 (Dreamliner)	296 pax.	126,372 litres fuel capacity, 14010 kms range, 920 km/	Delhi - Paris (6582 kms) 9 hours 25 mins							
Base Case: ATF (Jet A1)	A320 Neo	186 pax.	26730 litres fuel capacity, 6300 kms range, 840 kms/hr	Mumbai - Delhi (1136 kms) 2 hours 20 mins							
SAF (1% blending)	Boeing 787-9 (Dreamliner)	296 pax.	126,000 litres fuel capacity, 13,530 kms range, 903 km	Delhi - Paris (6582 kms) 9 hours 25 mins	2	4	8	10	12	16	**52**
SAF (1% blending)	A320 Neo	186 pax.	26730 litres fuel capacity, 6300 kms range, 840 kms/hr	Mumbai - Delhi (1136 kms) 2 hours 20 m	0	0	0	4	8	10	**22**
TOTAL (Pax.)					**2**	**6**	**14**	**28**	**48**	**74**	**74**

C2. SAF BLENDING FOR AVIATION FLEETS, INTERNATIONAL & DOMESTIC- OFFTAKE VOLUMES (ESTIMATED)

Low Carbon Aviation	**No. of flights per p**	**1% Blending (SAF n**	2025	2026	2027	2028	2029	2030	**TOTAL**
SAF (1% blending)	208	**1263.72**	525708	1051415	2102830	2628538	3154245	4205660	**13668396**
SAF (1% blending)	104	**267.3**	0	0	0	111197	222394	277992	**611582**
TOTAL (Pax.)			**525707.52**	**1051415.04**	**2102830.08**	**2739734.4**	**3376638.72**	**4483652.16**	**14279978**

SAF Blending Offtake by International & Domestic Fleets (Volumes) –, 2025-30





DISCLAIMER

This white paper has been developed proactively by India Hydrogen Alliance after discussions with multiple stakeholders from the industry, potential offtake organisation, equipment manufacturers, investors, technical agencies and the government. The takeaways from the paper are intended to support evidence-based decision making, for building the market for green hydrogen and hydrogen-derivatives (eFuels, Ammonia and Low-Carbon Fuels), in the intended heavy-duty transport use-case.

The takeaways are intended to supplement other government and private sector efforts to grow the hydrogen economy and the trade in hydrogen-derivatives, by estimating fleet-side offtake across three transport modes (trucking, shipping and civil aviation).

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