Hydrogen

"The strategic aspects of the hydrogen sector:
production of green hydrogen, storage distribution and its various applications ranging from heavy industries to road, rail, aviation mobilities."

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Foreword

VINCI believes that hydrogen will play a substantial role to achieve the decarbonized society we are collectively targeting by 2050. Our Group has leveraged its internal expertise to study the entire hydrogen value chain and identify potential opportunities for VINCI entities to get involved in the deployment at scale of green hydrogen. This collection of *Deep Dives* sheds some light on all aspects of the hydrogen sector from production to storage and distribution, and the various applications of hydrogen. They raise the following strategic considerations:

- Current **hydrogen production** is tied to fossil fuels and renewable hydrogen produced through electrolysis or steam reforming of biomass is today far from competitiveness.
- Technical and economic challenges arise as to how to **store and transport hydrogen** to end-users with different approaches possible for transporting hydrogen over short or medium distances or between continents.
- Opportunities for using hydrogen for **certain road mobility applications** should be pursued despite the current context where battery electric vehicles are becoming mainstream.
- **Fuel-cell trains** should be explored as a decarbonized alternative to diesel powered trains operating on unelectrified railway lines.
- Hydrogen powertrains could be the only game in town to address the looming decarbonization targets of **maritime and air transport** by 2050.
- The demand of **hard-to-abate industries** like steel and cement making, chemical production, and others, will account for the majority of low-carbon hydrogen by 2050.

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I.

Low-carbon Production

Today, hydrogen is viewed as a providential solution to reduce CO_2 emissions worldwide. In reality, current hydrogen production is tied to fossil fuels and low-carbon hydrogen far from competitiveness.

Shades of "grey": Hydrogen production today

96% of today's hydrogen production is derived from fossil fuels. In 2019, 70m tons of hydrogen were produced worldwide, 69% by steam reforming of natural gas, 27% by coal gasification. Hydrogen is dubbed "grey" or "brown" when produced with natural gas or coal respectively, owing to the carbon intensity of the processes: steam reforming emits 11kg of CO_2 eq per kg of hydrogen; coal gasification 19kg per kg of hydrogen. In sum, 830m tons of CO_2 emissions are attributable to these processes for the year 2019, accounting for 2% of the world's emissions.

Currently, the majority of hydrogen production is captive and used to refine oil (52% of world consumption) and to produce ammonia (43%) for fertilizers, while a fraction is used to propel rockets. The world's top producers are China and the United States, while Germany, the Netherlands, and Poland have Europe's largest grey hydrogen capacities, followed by Italy and France.

Switching to low-carbon and renewable hydrogen

The promise of low-carbon hydrogen production has been brought upon by water electrolysis. Instead of deriving H_2 from coal or gas, H_2 is extracted from water molecules with the help of electricity. Multiple electrolyzer technologies exist: alkaline and proton-exchange membranes are the more mature options, while solid oxide (also known as ultra-high temperature) electrolysis, expected to be more efficient and competitive, is in development phase.

By using electricity from renewable sources, one can thus create "green" hydrogen, or rather renewable hydrogen following the new European terminology[1]. The carbon intensity of hydrogen thus produced will range from 0.5 kg to 3.2kg CO_2 eq per kg of H_2 depending on the renewable source[2]. Additionally, renewable hydrogen can be produced through biomethane reforming, sourced from biomass. Using electricity from the grid will produce a low-carbon hydrogen in countries with a low-carbon electricity mix, and a carbon-rich hydrogen for countries which rely on fossil fuels for electricity production. In France, such hydrogen will have a carbon-intensity of around 3kg CO_2 eq per kg of H_2 ; in the European Union, the emissions amount to 14kg CO_2 eq per kg of H_2 . Finally, using gas or coal and sequestrating CO_2 emissions with CCS can lead up to a 95% emissions reduction compared to grey hydrogen, creating what is also considered low-carbon (previously "blue") hydrogen.

At 8-12€ per kg, renewable or low-carbon hydrogen is four to five times more expensive than fossil-based hydrogen for industrial end-users. For road mobility end-users, this hydrogen is 30-50% more expensive than diesel. To reach competitiveness and gain from scale effects, production by electrolysis will require public spending to develop electrolyzer "gigafactories". Countries are now competing in this new race to producing the most competitive low-carbon hydrogen, with Australia, China, the EU, Germany and France, among others, announcing ambitious electrolysis targets for 2030.

Decarbonizing industry and mobility

New applications will also create new demand, and drive prices down. For steelmakers, low-carbon hydrogen appears as one solution to decarbonize a fossil fuel-intensive process, while industrials are looking into switching their heating from coal or natural gas to H_2. Hydrogen can also be mixed with other gases and used in gas networks and community heating. However, no sector is put forward more than mobility. All segments believe low-carbon hydrogen will help reduce their dependence on oil: players in the automobile, public transport, long-distance road and maritime freight, commercial rail and aviation have publicly positioned themselves in favor of or against this new technology.

In the short-term (prior to 2030), two trends seem to emerge. Hydrogen will be produced locally and regionally, creating decentralized "hubs" around cities and industrial sites. The main demand drivers will first be industry feedstock for refining and ammonia production, as well as emerging applications in buses, trains and light mobility.

In the long-term (after 2030), resolving the issue of transport and storage could allow for centralized production at more competitive sites on an international scale, paving the way to a global hydrogen trade. Australia, New Zealand and Morocco are already positioning themselves, along with Japan, South Korea and Germany as trading partners. With new applications in cars, trucks, airplanes and power generation, low-carbon hydrogen could become more competitive and replace fossil fuels on a broader scale.

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

[2] https://www.bilans-ges.ademe.fr/documentation/UPLOAD_DOC_FR/index.htm?hydrogene.htm

II.

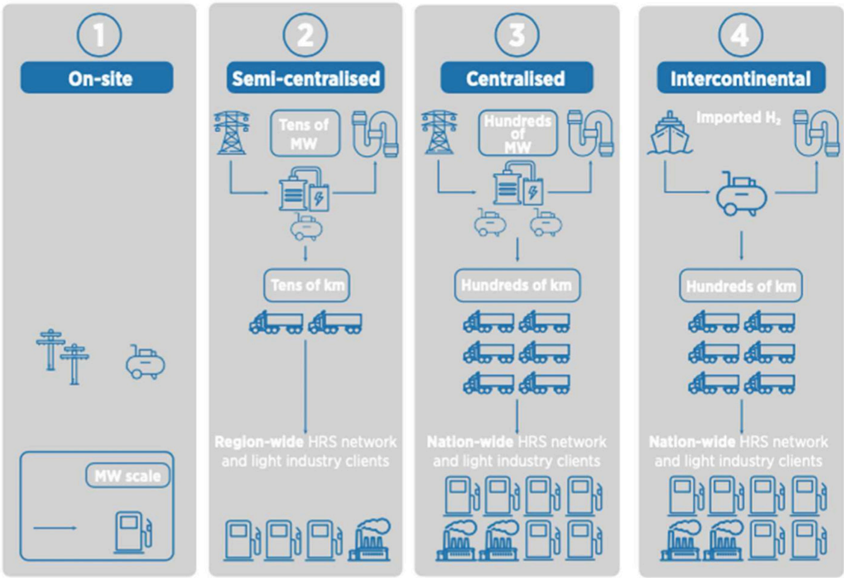
Transport and Storage

As explored previously, renewable hydrogen is defined as hydrogen produced through electrolysis of water using electricity from renewable sources such as solar photovoltaic, solar thermal, wind, geothermal or hydro sources. It also encompasses hydrogen produced by steam reforming of biomass. Following that, technical and economic challenges arise as to how to store and transport hydrogen to end-users: the H_2 industry is confronted with these key issues today.

On-site vs. centralized production

On-site production of hydrogen enables proximity with end-uses, reduced storage, and little to no transport costs. This scheme is currently in place for industrial clients around the world, which benefit from continuous captive production. This model will continue to exist for mobility uses where territorial hubs are promoted in calls for tenders or where national production is important for energy sovereignty, in France for example.

Regionally or nationally centralized production allows for gains from more competitive renewable energy sources as well as economies of scale, and is favored by gas industrials and the European Union. However, such a scheme can put production hundreds or thousands of kilometers from demand hubs, requiring dedicated hydrogen pipelines. Due to specific geographical features and energy policy choices, countries are also betting on an intercontinental exchange of hydrogen. As of today, Japan and Germany notably position themselves as importers; Australia, Morocco, Chile as net exporters. As a result, transport and storage costs can amount to up to three times the cost of hydrogen itself.



Source : IRENA, Hydrogen, A Renewable Energy Perspective
https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf

Transporting H_2 for short to medium distances

Under 400km, tube trailers containing up to 600kg of gaseous hydrogen at 150-250 bar are the most adopted option today, despite a cost of transport ranging from €0.5-€1.5 per kg H_2. Liquidhydrogen trailers which can hold up to 4,000kg of H_2 per shipment are less widespread and offer costs under €0.5 per kg H_2[1].
Up to 1,500km, pipelines can offer a more competitive option, around €0.2-€0.3 per kg H_2.
However, technical and regulatory challenges could curb the current natural gas networks' blending with H_2 or complete reconversion into pure hydrogen pipelines. Hydrogen is three times less dense than CH_4 and would require end-users to consume more gas to obtain the same energy. Additionally, networks have various blending tolerance limits, depending on country regulations: from 2-10% for long-distance transmission and up to 100% for some distribution networks. Constructing a new network dedicated to H_2 transport is an alternative to retrofitting envisioned by the European Union and the European Backbone Project[2], while both will require a clear and enforced regulatory framework.

Transporting H_2 between continents

Between continents, the retrofit or the construction of new hydrogen pipelines will lead to geopolitical challenges. This option is nonetheless considered by the EU and the European Backbone project, which see the Maghreb and Ukraine as possible trading partners.

[1] https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

[2] https://assets.ctfassets.net/ztehsn2qe34u/5i78zQEKatV8IBTpbqpYmK/ead89d4df9c030407da338909fd1f9f5/European_Hydrogen_Backbone.pdf

Over 1,500km, maritime routes appear as safer and more cost-effective options. Gaseous hydrogen is not dense enough for such long distances, and alternatives are considered:

- Liquid hydrogen (LH_2), which is 4-5x more energy dense than gaseous H_2 (350 bars). However, hydrogen transforms from gas to liquid at -253°C, requiring high energy intensity for conversion and shipping: up to 30% of the initial hydrogen energy
- Ammonia (NH_3), which only requires 15 to 30% of the initial energy for conversion and reconversion, is already a tradeable asset and common industry feedstock. However, NH_3 is toxic and could pose problems for shipping
- Liquid Organic Hydrogen Carriers (LOHCs), molecules whose purpose is to transport H_2 in liquid form at ambiant temperature. However, conversion also consumes 35%-40% of the initial energy.

Currently, all three solutions hike the price of hydrogen at port up 100-300%. This includes conversion and reconversion costs at €1 to €2 per kgH_2 and shipping costs ranging from €0.3 to €1.2 per kgH_2[3].

The need for buffer storage

Solutions exist to store H_2 after production, as well as in passenger vehicles and trucks for hours or days, but present challenges. Pressurized at 700 bar, hydrogen tanks can hold a few kg of hydrogen and must be seven times bigger than gasoline tanks in cars and trucks. In buses or trains, tanks are pressurized at 350 bars, as volume is less of an issue. In the aviation sector, volume will prove one of the most challenging issues to solve, leading the tank of the future H_2 powered aircraft as one of the most critical components to design.

[4] https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf

Buffer storage at maritime hubs for hours or days prior to shipping, and inter-seasonal storage (hydrogen can be stored for months without losing power) call for new needs. Turning to VINCI Geostock's expertise in the oil and gas industry, solutions which offer hundreds of times tanks' capacity can be found:

- Salt-leached caverns, where hydrogen can be stored for €0.3-€0.6 per kg for 30 years. Developed since the 1970s in the UK and the 1980s in the US, commercial underground caverns can hold 4,000 tons of gaseous hydrogen, and up to a theoretical 20,000 tons.
- Porous aquifers or depleted oil or gas fields are yet-to-be-proven alternatives, which could offer a new life to passive assets. However, one should keep in mind that porous aquifers or depleted fields have been used in the past for "town gas", which could contain up to 50% of hydrogen.
- Mined rock caverns are another option currently exploited for oil and gas which could be adapted to hydrogen storage. This will require some R&D effort to develop an appropriate liner.

Multiple innovations are emerging to address storage challenges

New fuel cells which can be fed NH_3 instead of pure H_2 could ease intercontinental transport[5].
Cheaper separation technologies for gas from blended pipelines would increase the pace of adapting the network[6]. A hydrogen "powerpaste" with 10x the energy density of batteries developed by the Fraunhofer Institute paves the way for new mobility applications. Without the need for large tanks, drones and scooters could benefit from extended ranges[7]. All three innovations show that disruption will play a key role in the years to come.

In the end however, pipeline transport will most likely be driven by the adoption and enforcement of new regulations, allowing for them to become a regulated asset like existing CH_4 pipes. The agenda of the incumbent gas industry and of major hydrogen projects such as HyDeal will also shape developments. For maritime transport, technology standardization and eventual commodification would give the market better price signals and foster increased industrial adoption.

[5] https://www.fraunhofer.de/en/press/research-news/2021/march-2021/worlds-first-hightemperature-ammonia-poweredfuel-cell-for-shipping.html

[6] https://www.h2site.eu/fr/

[7] https://www.fraunhofer.de/en/press/research-news/2021/february-2021/hydrogen-powered-drives-for-e-scooters.html

III.

Road Mobility

We have explored how renewable hydrogen can be produced, stored and transported between production sites and demand regions and we will move along the value chain to focus on hydrogen applications ranging from road mobility, railway, aviation and to industrial applications. Here, we intend to shed some light on road mobility challenges and opportunities.

Context

The transport sector represents 30% of greenhouse gas emissions in France and 40% of carbon emissions. The road sector accounting for 94% of these emissions, the need to decarbonize all vehicles and mobility usages is real and urgent. If battery-based vehicles will become mainstream for passenger cars in the coming years, other mobility applications are still in need for disruptive decarbonized solutions.

Vehicles and usages

Given the heterogeneity of vehicles and mobility usages, no single technology will act as a *silver bullet* to decarbonize all types of vehicles and mobility applications. Instead, decarbonization will only be achieved by a combination of complementary technologies each relevant for specific vehicle segments or applications:

- **Passenger vehicles**

Lithium-ion batteries are today widely used in electric vehicles, and continuous improvements in battery technology (e.g. Lithium Ferro Phosphate or solid state batteries) will allow for cheaper and denser battery packs hence increasing market penetration of Battery Electric Vehicles (BEV) among zero emission passenger vehicles. If opportunities for other zero emission solutions remain given the challenges of BEV to reach price and performance parity with their internal combustion engine counterparts, it is unlikely that H_2

powered electric vehicles will fill that gap for the following reasons:

o Production prices compatible with city, subcompact and compact vehicle segments will be difficult to achieve given the cost of fuel cell stacks

o Privately owned vehicles rely on a global charging network and their mass adoption is restricted by the slow deployment of this infrastructure network

o Today, Toyota and Hyundai are the only two manufacturers selling fuel cell passenger vehicles, in limited volumes.

Hydrogen is often cited as a promising solution for heavier vehicles or long-distance use cases for which batteries provide insufficient range and impact the vehicle payload, including:

- Light duty vehicles

When combined with electric batteries hydrogen tanks and fuel cell stacks could provide better range to light duty vehicles. Renault and Stellantis are betting on this and recently announced their intention to grab 30% of the light duty vehicle market with battery-hydrogen hybrid electric vehicles.

- Buses, garbage trucks

Battery-hydrogen hybrid buses and garbage trucks are a reality today. If their higher costs, approximately 3 times the cost of their diesel counterparts, restrict them today to few units deployed as part of subsidized innovation projects, significant public funds in the coming years may provide the necessary support to ramp up vehicles sales to economically viable volumes.

- Long haul trucks

If only one vehicle is commercially available today (Hyundai Xcient Fuel Cell), existing players of the trucking industry as well as newcomers (e.g. Hyzon) have announced new long-haul models from 2023.

One exception in the industry's enthusiasm for hydrogen is Tesla. Tesla believes that improvements in battery technologies in the coming years will solve battery limitations for long haul applications. We should keep a close eye on the sale of their first heavy truck model, Tesla Semi, later this year.

Regardless, refueling times will always be in favor of hydrogen models even with the megacharger network envisaged by Tesla.

Energy efficiency

Today 55 kWh of electricity is necessary to produce 1Kg of gaseous hydrogen which itself contains the equivalent of 33,5 kWh of energy[1], which then produces 21 kWh of energy at the wheel of a vehicle when used through a fuel cell to produce electricity again[2].

A battery powered electric vehicles only requires 22 kWh of energy to achieve the same energy at the wheel, achieving thus a 2,5 more favorable energy conversion ratio than a hydrogen fuel cell car. Efficiencies of the hydrogen conversion chain will progress over time thanks to continuous improvements of electrolyzers and fuel cell stacks.

Let's also keep in mind that we have used internal combustion engines with efficiencies between 30 and 40% for more than 100 years. So global efficiency ratios are not the only decision factor and the capacity of each technology to address the operational needs (e.g. range, charging time...) of mobility services will also play a decisive role in selecting future technologies.

[1] Rapport de l'Académie des Technologies, Juin 2020 (p 52)

[2] Assuming efficiencies of 65% and 95% respectively at the fuel cell and electric motor level

Global emissions

To assess the real decarbonization benefits of hydrogen powered vehicles, emissions along their entire life cycle need to be considered. Recent studies confirm that fuel cell powered vehicles could be the least CO_2 emitting vehicles by 2030 if and only if hydrogen will be produced by renewable energy sources[3].

Other potential triggers for hydrogen mobility

- Retrofit

A new regulation in France allows since 2020 for the retrofit of internal combustion vehicles into electric vehicles[4]. Companies are now starting to provide retrofitting services in different vehicle segments including heavy trucks[5]. Time will tell if this retrofit industry will scale enough to become a real contributor to the hydrogen demand of the mobility sector.

- Hydrogen in internal combustion engines

Diesel engines could be retrofitted into H_2-HPDI (High Pressure Direct Injection) engines by adding gas injectors, spark ignition plugs, stronger valves, rods, crankshaft, and gasket to account for the higher diffusivity and combustion temperatures of hydrogen during combustion. If such vehicles achieve lower efficiency than fuel cell vehicles and are not fully zero emission as they still emit some NOx, they do provide an interesting solution for the existing engines and could be a bridging technology for heavy truck until new models have entirely replaced the existing fleet[6].

[3] Transport routier : Quelles motorisations alternatives pour le climat ? - Comparaison des émissions en Cycle de vie. Carbone 4, 2020

[4] https://www.ecologie.gouv.fr/tout-savoir-sur-retrofit-electrique

[5] https://www.eneo-ve.fr/

[6] https://www.ifpenergiesnouvelles.fr/article/ifpen-mise-mobilite-hydrogene

IV.

Rail Mobility

After exploring how low-carbon hydrogen can be produced, stored and transported, we began exploring various end-uses with road mobility. In this fourth focus piece, we would like to address hydrogen usage in rail mobility.
Fuel-cell trains are mature, operational, and will play an important role to address specific decarbonization needs in rail transport.

Context and opportunity for hydrogen-powered trains

In Europe, 46% of railway lines are unelectrified and operated with diesel-powered trains. In France, these lines are mostly regional lines but make up for 10% of passenger traffic and 15% of freight traffic. It is important to find decarbonization solutions to replace diesel engines by emission free alternatives without having to electrify these lines, which would require prohibitive expenses for low traffic density.

There are close to 7,200 regional trains across Europe, with 83% of the fleet in Germany, Italy, the UK and France. The trains' average age is 20 years (on a 30 to 40-year life), but opportunities have already arisen to replace older trains. In France, public rail operator SNCF aims to phase out diesel trains by 2035.

Switching from diesel to H_2

Switching one regional train from diesel to hydrogen prevents the emission of 700 tons of CO_2 annually[1].
By 2030, predictions estimate a 10-30% replacement rate of the fleet, potentially preventing over a million tons of CO_2 emissions from the sector.
Specific solutions address specific use cases, with the promise of maintaining the level of service diesel engines provide – around 1,000km of range, 150-300 passengers capacity average, 140km/h average speed.
These are:

- Fully hydrogen-powered trains, suitable for completely unelectrified lines (e.g., in Germany, Italy or the rest of the world)
- Dual-mode H_2-electric trains equipped with a pantograph, suitable for partially electrified lines with a catenary (e.g., in France)

Both train models also carry a lithium-ion battery on-board, to provide boosts during acceleration phases and to store energy while braking.

[1] Based on the French electric mix for H_2 production and the charging of electric batteries onboard the trains.

Is the technology relevant?

Hydrogen is an attractive solution as opposed to batteries (heavier to carry on-board) and line electrification, which can be prohibitive for infrequently used lines (costs can represent €2-3m per km). Hydrogen finds its maximum relevance on such lines, where trains are fewer than 1/hour, or/and where the unelectrified distance covered exceeds 80-100km.

Freight transport can also benefit by switching to hydrogen, as freight engines remain a notable source of emissions for the industry. In Europe, freight trains encounter problems on lines where 90% of the distance is covered by a catenary, but the last tens of kilometers towards the loading zones are not. Today, diesel trains have to be used over these entire lines. Tomorrow, dual-mode engines could be relevant alternatives. In North America and around the world, where freight lines are very little electrified, full-hydrogen engines would be necessary with important battery boots. Fuel-cell freight developments are lagging behind regional passenger train developments, in part because of the power needs freight trains require. On average, freight trains weigh 15 times as much as a regional train. Shunter trains – equipped with particularly polluting engines and driving on storage and siding tracks – could also benefit from the switch. Fuel-cell shunters would be particularly relevant if operated with low idle time and on long distances daily.

Commercial developments initiated by all players

The world's leading manufacturers have been developing fuel-cell train models over the past decade.

- Alstom (France) has positioned itself on fuel-cell engines as early as 2014, with the conversion of its Coradia LINT line into full-H_2 Coradia iLINT trains. This model has already been ordered by regions in Germany, Austria, and the Netherlands. The dual-mode Régiolis is being developed for the French operator SNCF, while retrofit efforts are underway for UK regional fleets.
- Siemens' (Germany) Mireo, a direct competitor to the Coradia iLINT, has been ordered in Germany as soon as 2017. A dual-mode Mireo Plus B is expected to compete with Alstom's Régiolis although it is an electric-battery hybrid.
- Stadler (Switzerland) is developing its own Flirt H_2, expected to come into service in 2024
- BNSF (US) and Ballard (Canada) are developing a hybrid fuel-cell shunting engine
- CRRC (China) has developed hybrid H_2-supercapacitor tramways in China, operational since 2017 in Tangshan.

Synergistic opportunities with regional bus H_2 needs

At the regional level, it could be interesting for a mobility operator to combine the hydrogen needs of regional trains with those of regional buses. This would better distribute the high costs of production and distribution units over a larger range of vehicles and usages. Mutualization would also improve the utilization rates of electrolyzers by combining trains' sparse refueling needs with buses' more regular needs.

Sources: Alstom, UIC, ADEME, IAC Partners

V.

Air and Maritime Mobility

After exploring how low-carbon hydrogen can be produced, stored and transported, we began exploring various end-uses of hydrogen with road and rail mobility.

In this fifth focus piece, we are looking at hydrogen usage in air and maritime mobility.

Context

Air and maritime transport respectively emit 915 million tonnes and 940 million tonnes of CO_2 annually, accounting each for around 2,5% of worldwide CO_2 emissions. With significant demand growth projected over the next decades and looming decarbonization targets, the need for emission mitigation measures and low-carbon technologies is pressing in these two sectors. Both have pledged to cut their CO_2 emissions at least by half by 2050 vs 2005 levels for the aviation sector and vs 2008 levels for the maritime industry, with some key players even targeting carbon neutrality by 2050.

If change has been slow until now, the FitFor55 regulatory package proposed by the European Commission in July 2021 could induce more rapid change by strengthening the current cap-and-trade CO_2 market for aviation and creating a new CO_2 trading system for maritime emissions.

Air mobility

Reducing aircraft emissions

In 2019, 4.5 billion passengers and 58 million tonnes of freight were carried by the world's airlines. With the aviation industry expected to double by 2050 (i.e. 8 billion passengers projected by 2050) it is essential to reduce aviation carbon emissions. To that end, several solutions could be leveraged in addition to continuously improving ground operation, air traffic and current technologies:

- **Sustainable Aviation Fuels (SAF)** produced from feedstock can be blended at up to 50% with conventional jet fuel and offer significant lifecycle carbon reductions without any modification to current aircrafts/engines and fuel distribution infrastructures. However, SAF don't offer a fully decarbonized option and depend on the availability of biomass or other feedstock.

- **Hydrogen** can be used by aircrafts in different ways

o **Green hydrogen** (i.e. produced through water electrolysis powered by renewable electricity sources) can be combined with CO_2, creating a lifecycle CO_2 reduction, to produce **synthetic biofuels** which, like SAF, can then be mixed with fossil fuels and used in conventional jet engines.

o Hydrogen in liquid form can be directly used as a fuel and **burned in modified gas turbines**

o **Hydrogen in liquid form can be converted into electric power** by a fuel cell and used by an aircraft powered by electric engines

To meet mass adoption, **hydrogen powered aircrafts will need to address the following challenges:**

o Given the low volumetric energy density of hydrogen, its **liquid form is preferred by the aviation industry** to store more energy onboard future aircrafts. Since this will require new aircraft and tank designs, **fleet turnover would need to accelerate.** A recent McKinsey/Fuel Cells and Hydrogen Joint Undertaking report projects only 40% of short-haul and medium-haul fleet replaced by 2050 in its most optimistic scenario.

- Electric engines are currently not suitable because of the instant take-off power needs of commercial aircrafts (except small ones with very limited number of seats).

Adapting airport platforms

The production and distribution of these alternative fuels will change airports as we know them today. If SAF or synthetic fuels will have no operational impact because their handling and distribution is identical to jet A1 conventional fuel, the introduction of gaseous and liquid hydrogen will require significant adaptation of airport platforms and regulations. Local production and distribution of hydrogen might be more adequate to address both airside and landside demands, i.e. demands from Ground Support Equipment, heavy duty mobility related to cargo and logistics activities, as well as demands coming from airport ecosystems. With the introduction of liquid hydrogen, cryogenic hydrogen handling would be required across the storage and distribution line, requiring airport operators to acquire new specific equipment and expertise.

Ultimately, the industry predicts that airports tomorrow will basically come down to **large hydrogen production and distribution hubs servicing both aviation and local hydrogen demands.**

Need for collaborative actions across the entire ecosystem

Today the entire value chain of aviation seems to be jumping on the hydrogen wagon to make it one of the center pieces of tomorrow decarbonized aviation:

- **Aircraft manufacturers** like Airbus show clear medium-term ambitions for hydrogen powered short and medium-haul, with long-haul on the longer term. Its rival Boeing remains notably out of the race at this stage. Pipistrel, which produces 10-passenger airplanes, has its first hydrogen model up and flying. Startups are also looking to disrupt this space; e.g. Universal Hydrogen with their modular pods for easier storage , ZeroAvia...

- **Airlines like British Airways,** SAS, EasyJet have expressed clear interest in hydrogen power planes
- **Airport operators** like VINCI Airports are launching first experiments (e.g. at Lyon St-Exupéry airport) to learn and start building valuable partnerships for hydrogen production and distribution on and around airports.

Maritime mobility

Approximately 90% of world goods are carried by sea. This represented in 2019 around 11 billion tonnes of freight and this demand is expected to grow anywhere from 50% to 250% by 2050.

Reducing vessel emissions

To reach the greenhouse gas emission reductions set by the International Maritime Organization the industry will have to leverage different technologies:

- For smaller vessels (river boats, ferries, barges):

o **Electric batteries** might be used but their low energy density limits them to lighter applications.

o **Hydrogen** in its liquid form could be used in fuel cells to power electric engines. The Norwegian operator Norled has just received a liquid hydrogen ferry, the "MF Hydra", with a capacity of 300 passengers and 80 cars[1].

- For larger vessels travelling across oceans (freighters, tankers...):

o **Liquefied Natural Gas** (LNG) already offers benefits in reduction of air pollutants (NOX, SOX, and particles) but doesn't provide a fully decarbonized solution as LNG is a fossil fuel that emits CO_2 (i.e. CO_2 reduction around 20%). If LNG carriers already use LNG for their propulsion, more and more vessels not carrying LNG switch to LNG as a greener fuel.

o **Biofuels** can be incorporated to diesel to start reducing CO_2 emissions and can even be considered carbon-neutral from a lifecycle viewpoint when not blended with diesel since the biomass used for their production absorbed CO_2. However, their limit lays in

[1] https://www.rechargenews.com/technology/worlds-first-hydrogen-powered-ferry-in-norway-to-run-on-green-gas-from-germany/2-1-976939

the availability of biomass (i.e. competition with food production)

o **Green ammonia** (NH_3) can be produced through the Haber-Bosch process which combines green hydrogen produced by electrolysis and nitrogen separated from the air. The ammonia can then be **either directly burned into an internal combustion engine or used through specific fuel cells** to produce electric power.

The maritime industry currently predicts that green ammonia could be the best path towards zero-carbon long haul sea shipping given its following benefits:

- Ammonia doesn't require large cryogenic onboard storage like liquid hydrogen, which could impact the available payload of large cargo ships
- Ammonia has twice the energy density of hydrogen and can be stored in its liquid form at ambient temperature
- Ammonia being today a major chemical feedstock used in several applications (e.g. fertilizers), the shipping industry is already used to handle ammonia, and storage and distribution infrastructures are already in place.

Vessels turnover

Vessel lifetimes typically range from 20 to 30 years depending on ship types (oil or gas tankers, container ships, general cargo ships, bulk carriers…). If biofuels can be used in existing engines, the use of hydrogen and ammonia would either require adaptations of current engines if burned directly as a fuel, or complete new powertrain lines if used through fuel cells. The latter option requires complete vessel replacement and would hence be linked to vessel turnover cycles.

Need for collaborative actions across the entire ecosystem

Partnerships and coalitions would be necessary across the maritime shipping value chain to finance research and development efforts and spread adoption throughout the industry. This is especially necessary for this industry as most technologies envisaged are still in their very early prototyping stage.

Maersk McKinney Moller Center for Zero Carbon Shipping[2] is an interesting example of industrial cluster with the ambition to define a common transition strategy and foster technology developments to meet the sector GHG emission reduction targets.

[2] https://zerocarbonshipping.com/

Conclusion

Air and maritime mobilities are still seeking for the most adequate energy to power their heavy and long-haul applications, for which electric batteries have significant limitations. If hydrogen will be one of the pathways enabling these industries to follow through on their pledge to cut their emissions by at least half by 2050 or even be carbon neutral at this date, challenges relating to the adaptation of port and airport infrastructures, slow aircraft and vessel turnovers, and interoperability inherent to intercontinental shipping, will need to be addressed by all stake holders of these industries, i.e. manufacturers (plane and boat OEMs), carriers (airlines, ship lines), and infrastructure operators (airports, ports operators).

Ongoing projects within VINCI

- Within **VINCI Energies**, Barillec Marine already contributes to this transition by developing electric or hybrid powertrains for maritime applications.
- **VINCI Airports** is currently launching a hydrogen hub at Lyon St-Exupéry airport in partnership with VINCI Construction and Eurovia capable of distributing between 500kg and 2 tonnes of hydrogen per day to address aviation, heavy and light-duty mobility and industrial needs in the region.
- **VINCI Construction's HyMobility business unit** dedicated to hydrogen projects is currently working on an ammonia production project at the Grand Port de Bordeaux and a river mobility project in Nanterre in collaboration with Shell.

Sources:
https://www.atag.org/facts-figures.html
https://ec.europa.eu/clima/policies/transport/shipping_en
https://www.icao.int/annual-report-2019/Pages/the-world-of-air-transport-in-2019_fr.aspx
https://spectrum.ieee.org/why-the-shipping-industry-is-betting-big-on-ammonia

VI. Industrial Applications

The first five focuses were dedicated to the production, transport and storage of low-carbon hydrogen. We also explored mobility applications, which today get most of the media's light. However, predictions estimate that demand will largely be driven by industry applications, not mobility. By 2050, an estimated 60-75% of demand will come from steelmakers, cement plants, chemical makers, and others, while just 20-25% will come from mobility and 5-15% from urban and industrial heating[1].

Hydrogen is indeed an important decarbonation lever for these industries, which have been covered by a carbon tax in Europe for years. Its recent hike (from 15€ per ton of CO_2 in 2019 to close to 60€ in 2021) has pushed investment towards processes with a limited carbon footprint; hydrogen is now being implemented as a driving solution.

Steelmaking: transforming a century-old industry

Steel can be produced in two ways. In a blast furnace, where iron ore is transformed into liquid iron at very high temperature by burning coke (a derivative of coal), which serves as both fuel and reducing agent (72% of world production). Or, by using direct reduced iron (DRI) and steel scraps in an electric arc-furnace (28% of world production, concentrated mostly in the US and Europe). Both processes are highly carbon intensive. Blast furnace steel making emits on average 1.8 ton of CO_2 per ton of steel (and up to 2.8t of CO_2 per t of steel for the most emtting installations) while DRI steel making emits up to 1 ton of CO_2 per ton of steel.

World steel production was responsible for 8% of worldwide greenhouse gas emissions in 2018, calling for urgent decarbonation solutions. French-Indian ArcelorMittal (world's biggest steelmaker by revenue) and South Korean POSCO (the fifth biggest) both announced plans to become "carbon neutral" by 2050. From ArcelorMittal's point of view, two solutions exist:

- One where blast furnaces are equipped with a Carbon Capture device, to feed the emitted CO_2 back into the steel-making process (CCU process).
- One where DRI is produced using hydrogen, and then mixed in an electric arc furnace to produce the end-product.

DRI is the prevalent route for several projects in Europe,

[1] Synthesis of a Leonard literature review of 25 reports, white papers and market demand projections

given that the CCU process is still carbon dependent and that the CO_2 used is still considered "emitted" under EU rules. Among projects, we can cite:

- ArcelorMittal's Hamburg plant, which was the group's first to transition its DRI process from natural gas to hydrogen in 2019.
- HyBrit, a swedish ambition to create a completely fossil-free value chain from mine to finished steel, with fossil-free pellets, fossil-free electricity, and hydrogen. The project launched in 2020, with Swedish iron ore miner LKAB, steelmaker SSAB and electricity-provider Vattenfall.
- Thyssenkrupp (Germany) and Voestalpine (Austria), where both firms are testing combined hydrogen-DRI, in their Duisburg and Linz plants respectively.

Cement production

Production of cement is achieved by heating a finely ground mixture of limestone, clay and sand in a rotary kiln at up to 1,450°C. Clinker is thus produced, and then dried and crushed into cement products. CO_2 is created as a by-product of the chemical reaction, as well as emitted by fossil fuels burnt to heat the kiln. Emissions intensity ranges from 500 to 700 kg of CO_2 per ton of cement product. Yearly, **this industry is responsible for 8% of worldwide greenhouse gas emissions**, also calling for urgent decarbonation solutions.

- Leading the path, CEMEX (Mexico) has unveiled its objective of net-zero cement production in 2050. After a first test in Spain in 2019, the group has been including hydrogen in alternative fuel-mix for all its burners in Europe. CEMEX is now planning a worldwide rollout in the coming years.
- Similarly, HeidelbergCement (Germany) is experimenting a combined hydrogen-plasma fuel mix for its cement plant in Ribblesdale (UK).
- Vicat (France) is also positioning itself on H_2, indirectly. The group aims to use the kilns' waste heat to produce hydrogen through Ultra-High Temperature (UHT) electrolysis. It will then feed it to captive light utility vehicles and combine it with CO_2 captured from the kilns smokes to produce e-methan and e-methanol . Vicat is a shareholder of GENVIA, a specialist in UHT electrolysis and a joint venture between Schlumberger, CEA, AREC, Vicat and VINCI Construction.

Chemicals

- Refining

Currently, 52% of hydrogen demand is met by refineries, but 96% of the hydrogen used is fossil. Switching from fossil to renewable hydrogen is an important step to decarbonize current uses.

o In 2018, Shell put a 10MW electrolyzer into service at its Rheinland plant (Germany), the largest electrolyzer for refining end-use. Today, Shell plans to scale it up to 100MW and to serve other end-uses, such as Sustainable Aviation Fuels.

o In a similar effort, TotalEnergies is developing a 40MW electrolysis project with ENGIE at its refinery in La Mède (France). Set to open in 2024, the project would allow the plant to meet 10% of its hydrogen needs from renewable sources.

However, switching refineries from fossil to renewable hydrogen will require more public support than any other end-uses, to rapidly ramp up. Fossil hydrogen costs around 1-1.5€/kg, whereas renewable hydrogen costs anywhere from 5 to 10€/kg relative to geographies.

- Ammonia production

Ammonia production currently represents 43% of fossil hydrogen demand and transitioning to renewable H_2 would mean decarbonizing fertilizers, shipping, and even power generation. Projects illustrate this transition:

o Ammonia producer Yara (Norway) and energy provider ENGIE (France) are developing a "green ammonia" plant in Australia, with a 10MW electrolyzer on-site. It is set to become the largest in Australia.

o Additionally, countries are investing in ammonia projects with the sole intent to use ammonia as a hydrogen carrier for export purposes. These countries include Chile and Australia for example.

Carbon capture as the corner stone for low carbon hydrogen

If water electrolysis using renewable electricity sources is a promising approach to produce carbon free hydrogen, the growing demand for hydrogen in the coming years will also require other solutions to produce low carbon hydrogen in mass. Carbon capture associated with current production methods based on fossils, like Steam Methane Reforming, would hence play a significant role in the production of low carbon hydrogen for the years to come.

Creating industrial hubs is needed to boost other uses

Industrial hubs, where a regionally centralized electrolyzer produces quantities of hydrogen sufficient for the main end-use, as well as enough for other industrial and mobility clients, are necessary and often at the heart of national strategies, such as the French strategy.

One more example of such hubs is GET H_2 in Germany's Niedersachsen and Nordrhein-Westfalen Länder. The project regroups 7 stakeholders, and its first leg is set to be completed in 2024. Pipelines will link an RWE electrolysis plant to two BP refineries, one Evonik chemical plant and a cavern storage facility. By 2030, the second leg aims to connect the pipelines to a Salzgitter steelmaking plant as well as the Netherlands for export purposes.

Such hub projects will allow for auxiliary mobility uses and other industries which rely on fossil fuels in their processes (methanol production, glass, ceramics…) to benefit from cheaper hydrogen, to secure long-term demand and to drive decarbonization goals.

Sources:
World Steel Association, Global Cement and Concrete Association, IRENA, Methanol Institute, Calcia, French Senate report on steel-making,GET H2 Project

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