NASA Blue Skies 2023 Technical Report

The Role of Hydrogen in Aviation Decarbonization

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Acronyms

CDR - Carbon Dioxide Removal

CORSIA - Carbon Offsetting and Reduction Scheme for International Aviation

IRA - Inflation Reduction Act

MOU - Memorandum of Understanding

OEM - Original Equipment Manufacturer

RPM - Revenue Passenger Miles

LH_2 - Liquid Hydrogen

SAF - Sustainable Aviation Fuel

TRL - Technology Readiness Level

CapEx - Capital Expenditures

Acknowledgements

This report would not have been possible without the insights of numerous experts. The authors of this report interviewed those listed below and would like to thank them for their generosity and time.

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Abstract

We are in a race to stop producing harmful emissions like carbon dioxide from every sector of the global economy. Aviation is responsible for about 3% of these emissions,[i] and 2-3 times more people are expected to be flying by 2050.[ii] This begs the question: how do we meet future demand and achieve what NASA and the global aviation community have coalesced around, which is a goal of net zero emissions by 2050, in a robust and equitable way? We believe that hydrogen is the answer.[iii]

This report begins by describing the levers that will help us achieve net zero aviation by 2050, including hydrogen's role in the broader decarbonization effort. It then describes the four stages of our proposed hydrogen supply chain: making hydrogen, moving it via pipelines and trucks, storage near airports, and last-mile delivery to the tarmac. Our vision is to connect hydrogen produced at the Department of Energy's Hydrogen Hubs with the nation's 30 largest airports to minimize infrastructure costs and maximize the impacted flight-miles. The report then presents a strategy for bringing the supply chain to life by drawing on key lessons from transportation electrification efforts and offers a timeline that guides stakeholders towards a future where 20% of revenue-passenger-miles are powered by hydrogen. **Since our proposal**, we have addresses some of the most pressing questions about the transition to hydrogen aviation, including social benefits (emissions reductions and environmental justice, safety, and green jobs), key barriers (water consumption, public perception, and infrastructure barriers), and policy recommendations (demonstrations, incentives, and regulations), informed by an optimization model developed by the team, literature reviews, and additional stakeholder interviews.

2050 Aviation Decarbonization Levers

The aviation sector produced approximately 1.2 billion tons of CO_2 in 2019. Several studies expect growing demand for air travel to produce over 2 billion tons of CO_2 annually by 2050 if a variety of efforts are not employed. These efforts include efficiency improvements, the use of alternative fuels, carbon dioxide removal, and purchasing carbon credits.[iv] The relative impacts of each of these approaches in achieving net zero aviation is summarized in Figure 1.

Figure 1: A list of various efforts that will reduce aviation emissions to net zero organized from greatest to least percent impact

Efficiency improvements will be critical to reduce aviation emissions. The Mission Possible Partnership estimates that over the past several decades, the aviation sector has improved efficiency by about 1%. Moving forward, annual improvements of about 2% will be needed to achieve 37% emissions reduction by 2050.[3] 60% of aviation emissions reductions are expected to come from using alternative fuel sources, including batteries, hydrogen (H_2), and sustainable aviation fuels (SAF). The market share that each fuel type claims will be largely determined by the range it can fly. Battery electric planes are expected to fly the short-range flights (<500 miles),[v] H_2 planes may fly mid-range flights (500-1,600 miles), and SAFs will likely dominate long-range flights (>1,600 miles).[3]

Although SAFs are expected to play the biggest role in reducing aviation emissions, they have two significant downsides: (1) Burning SAFs still produces tailpipe emissions, with the best SAFs reducing Jet A emissions up to 80%.[vi] (2) The production of SAFs requires vast quantities of land, water, and other resources dedicated to producing feedstocks making a conversion to 100% SAFs unrealistic.[vi] **Because of their decreasing energy efficiencies and increasing carbon intensities, this team believes battery electric planes should be adopted wherever possible, followed by H_2 planes, leaving SAFs to fuel the remaining furthest routes.**

Finally, carbon dioxide removal (CDR) and purchasing carbon credits will likely play a role in achieving net zero, although their roles should be minimized. These technologies allow airlines to continue producing emissions and then spend money to directly capture carbon dioxide (CDR) or pay others to remove carbon dioxide (carbon credits). In the pursuit of net zero aviation, this team believes the roles of efficiency improvements and alternative fuels should be maximized, and CDR and carbon credits should be viewed as a last resort.

Why Hydrogen

The U.S. finds itself in a race against time to minimize emissions across all sectors, and the clock is ticking. H_2 is a zero-tailpipe emission fuel that comes with numerous advantages:

Supply Chain Readiness

A significant amount of H_2 infrastructure already exists in the U.S.: There are more than 200 steam methane reforming facilities,[vii] 55 H_2 fueling stations in California,[viii] and approximately 1,600 miles of pipelines dedicated to H_2 transport.[ix] As a result, the technology readiness level (TRL) for H_2 technologies is high across the traditional supply chain: gaseous H_2 tube trailers and pipelines, liquid H_2 trucks, liquid H_2 storage vessels, steam methane reformers, etc. While newer production technologies, such as solid oxide fuel cells, are still around TRL 6, they are rapidly advancing and approaching commercialization.[x] See Appendix Table 1 for more information.

Economy-wide Decarbonization

Several "hard-to-decarbonize" sectors – including cement and steel manufacturing, heavy-duty transport, and shipping – are betting on H_2 to help them reduce emissions. As more H_2 is produced to meet growing demand, all will benefit from reduced prices and strengthened supply chains.

Federal Funding Availability

The recently passed Inflation Reduction Act (IRA) will subsidize H_2 production by up to $3/kg through the mid-2040s.[xi] The Bipartisan Infrastructure Law, passed in 2021, dedicates $8 billion to the mass production of H_2 at H_2 hubs across the nation.[xii] According to Princeton University Professor Jessie Jenkins, this production boost will significantly drive down production costs over time as private and public research advances and economizes electrolyzer technology.[xiii]

Aircraft Performance

Hydrogen-powered aircraft can go the distance. While aircraft powered only by fuel cells may be more limited–Universal H_2 and ZeroAvia's preliminary fuel cell-only aircraft concepts have expected ranges of 600 and 300 nautical miles, respectively–hybrid propulsion systems promise to make even trans-continental flight possible.[xiv,xv] Airbus' combination liquid hydrogen (LH_2) combustion and fuel cell aircraft have projected ranges of up to 2,000+ nautical miles.[xvi]

In-Flight Emissions Reductions

Aircraft powered by only fuel cells would theoretically eliminate all in-flight emissions, with the potential exception of water vapor. Aircraft utilizing LH_2 combustion would completely eliminate the CO_2 and particulate emissions associated with traditional aircraft but would increase the quantity of water vapor emitted. The nuances of H_2 aircraft emissions, including NO_x, are discussed in greater detail in the Appendix.

Hydrogen Supply Chain

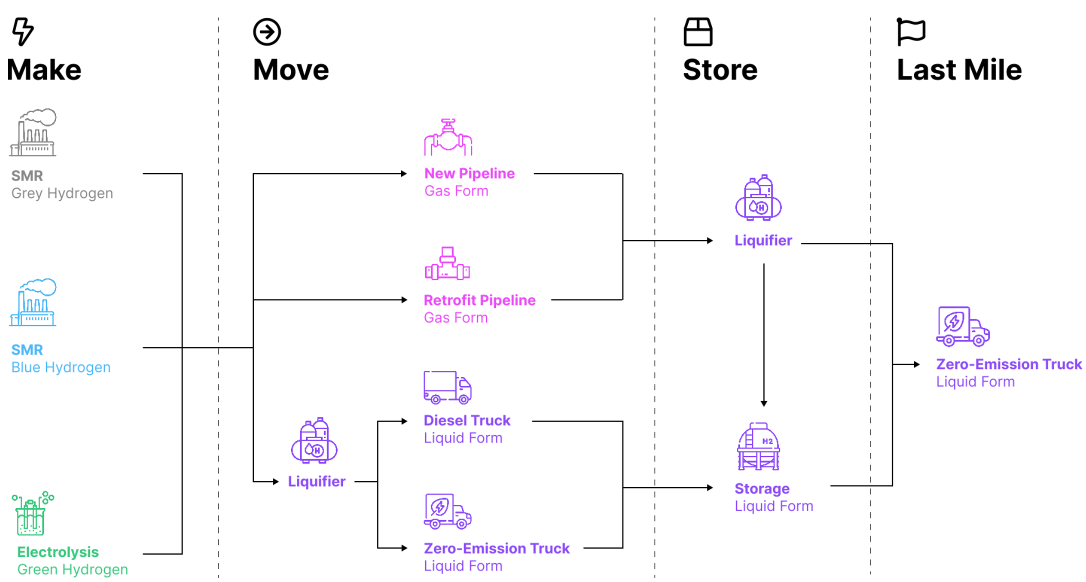


Figure 2: The hydrogen aviation supply chain broken up into four sections: Make, Move, Store, and Last Mile

Our supply chain is divided into 4 stages: **Make, Move, Store**, and **Last Mile**. During the **Make** stage, gray, blue, and green H_2 are produced,[xvii] predominantly at the DOE's H_2 hubs. The vision is to connect H_2 from an estimated 8 DOE-funded H_2 hubs with a representative version of the FAA's Core 30[xviii] airports (the 30 largest in the U.S.). Appendix Table 2 lists the predicted hub locations that were used for analysis in this report. Because investing in H_2 infrastructure at each airport is quite costly, our strategy is to minimize the number of airports that make the investment by focusing on the largest ones.

Once produced, H_2 **Moves** from the H_2 hubs to storage facilities at airports, either in gaseous form through pipelines or as a liquid on trucks. We assume that each airport deploying H_2 aircraft will **Store** H_2 about one mile away from the tarmac, likely at or near their existing fuel farm. The equipment necessary for H_2 storage and usage will include liquid storage tanks, a H_2 liquefier if gaseous hydrogen is piped in, and a H_2 refueling station if the airport adopts H_2 fuel cell ground support equipment and/or buses. Finally, zero-emission trucks will transport liquid H_2 the **Last Mile** between the storage facility directly to H_2 aircraft that need fueling.

Our Plan to Scale Up & Policy Recommendations

To bring this supply chain to life, we offer a framework for integrating hydrogen into the aviation sector. This paper draws on lessons learned from the Drive to Zero Program developed by CALSTART, a clean transportation non-profit. So far, 26 countries including the U.S. have signed on to the Drive to Zero Program's Memorandum of Understanding (MOU) committing them to work towards 100% zero-emission truck and bus sales by 2040.[xix] This section also draws on the proven policy framework developed by the California Air Resources Board (CARB) to commercialize low-carbon technologies. After interviewing both CALSTART's former Executive Vice President and Drive to Zero's Global Director as well as experts at CARB, the team identified five key steps to accelerating the deployment of zero-emission technologies, from transportation to aviation.

Step 1: Set Clear, Unifying Goals

Explanation: The Global MOU started with a clear goal of 100% zero-emission sales by 2040 based on California's Advanced Clean Trucks Rule and worked backward from there by setting incremental benchmarks.[xx]

Aviation Application: Similarly, our team envisions the aviation community uniting around a singular goal for H_2's role in the market by 2050 and working backward to achieve this goal. Based on our research, setting the goal of 20% of revenue passenger miles (RPM) flown being hydrogen-powered by 2050 seems ambitious yet realistic. [xxi, xxii]

Step 2: Fund Demonstration Projects

Explanation: After establishing a goal, the next step was bringing key stakeholders together for demonstration projects. They emphasized that government funding is key to enabling demonstration projects, and "once funding is available, industry will quickly follow."

Aviation Application: In the case of aviation, this will include convening the largest airports, major airlines, H_2 aircraft OEMs, H_2 producers and transport companies, the Federal Aviation Administration, and nonprofits. The DOE is a likely funding source for aviation decarbonization demonstration projects.

Policy Recommendations: Start with **demonstration projects**. While the Hydrogen Hubs become operational in the mid-to-late 2020's, we recommend the DOE administer a request for proposals (RFP) for airlines to fly commercial hydrogen flights between two to three airports. Ideally, these airports would be fueled by nearby H_2 hubs. These demonstrations would take place around 2035, providing several years to install infrastructure. Match funding by airlines would likely go towards subsidizing the cost of the aircraft and hydrogen transport, storage, and liquefaction infrastructure.

Step 3: Replicate Successes

Explanation: Once the initial demonstrations projects are operational, the key lessons should be identified and replicated. They noted that "industry alone cannot push progress fast enough. Government incentives and regulations are essential."

Aviation Application: Best practices from H_2 aviation demonstration projects should be paired with incentives and regulations to accelerate H_2 adoption at the Core 30 airports.

Policy Recommendations: After a successful demonstration project or two, then incentives should kick in followed by regulations a few years later.

Incentives could subsidize the upfront cost of hydrogen aircraft, airport infrastructure investments, and/or the price of H_2 flight tickets (i.e., make hydrogen flights cheaper than conventional flights to boost public interest). Interestingly, Universal H_2, a leading H_2 aviation startup, recommended subsidies go towards renewable electricity generation, electrolyzer costs, and water desalination to benefit cross-sector low-carbon H_2 commercialization.

Regulations could include an aviation-wide carbon tax or cap and trade system. They could also include a phase-out of the sale of jet fuel aircraft similar to California's Advanced Clean Trucks Rule that gradually bans diesel bus and truck sales. Two additional policy interventions that we recommend are reforms to speed up the permitting process for energy projects as proposed by Senator Joe Manchin[xxiii] and federal guidance towards approving hydrogen transport by rail.

Step 4: Education of Airport Employees & Public Outreach

Explanation: Public engagement is key to a successful large-scale transition.

Aviation Application: Airports are notoriously low-risk environments. For H_2 to be effectively integrated into an airport environment, both employees and the public should be well-educated about how fueling, aircraft appearance, and safety procedures will be different for H_2 than they are for traditional Jet A fuel.

Step 5: Cultivate International Cooperation

Explanation: "Decarbonization is an international effort."

Aviation Application: Expanding H_2 aviation beyond the U.S. will help decrease costs for all and increase the eventual likelihood of international H_2-powered flights. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) already exists as a pledge between countries to reduce aviation emissions and would provide a platform for H_2 to become a part of the global strategy.[xxiv]

Timeline to Success

Conversations with CALSTART thought leaders inspired this team to establish its own goal of 20% H_2 RPM by 2050 to work backwards from.[xxv] Several H_2-powered aircraft manufacturers, including global OEMs like Airbus and startups like Universal H_2 and ZeroAvia, are expected to bring H_2 aircraft to market between 2030 and 2035.[14,15] In the meantime, several milestones must be achieved across the H_2 supply chain to enable H_2 aircraft to scale up rapidly once they are deployed. The team developed the timeline below to help guide the transition. The national vision can be found as Appendix Figure 1.

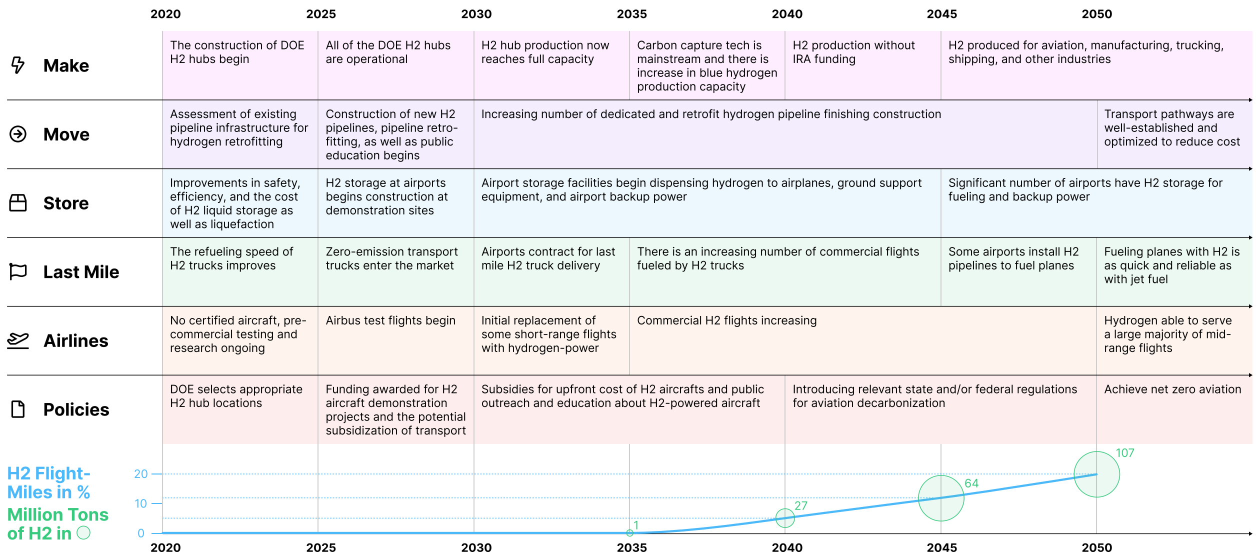


Figure 3: Timeline of milestones to achieve 20% domestic H_2 RPM by 2050

Optimization Model

To more robustly explore the nuances of a H_2 supply chain, we developed a multicriteria decision analysis (MCDA) model that is a mathematical representation of our framework. Our model finds the set of non-dominant solutions for supply chain configurations that balance the tradeoff between cost and emissions with a series of real-world constraints. We derived three key findings from our model results, which we summarize here and expand upon in subsequent sections:

1. Political initiative is needed to fundamentally minimize uncertainty surrounding costs, emissions, and reliability of the hydrogen supply chain, offering better decision-making capabilities for modelers and decision-makers alike.
2. Infrastructure development must account for both pipelines and trucks in the future aviation hydrogen economy. In the near-term, trucks will likely dominate as a nimbler, cheaper transportation option. In the long-term, pipelines offer a cost-effective, reliable, and lower-emissions option to deliver high volumes of H_2.
3. For green hydrogen to play a more dominant role throughout the U.S., zero-emission electricity generation prices will need to come down and novel regulatory strategies will need to be invented to incentivize truly net-zero forms of hydrogen production.

Figure 4 below shows the final outcomes of our model which selected an optimized network configuration for the four stages of our supply chain while balancing cost and emission objectives. We varied the weight of these objectives (preference weights) with a term called alpha (α) which ranged from 0-1; where 0 indicated fully optimizing for emissions; and 1 indicated fully optimizing for cost. In order to account for variability within the network, we ran this model over three discrete cumulative distribution functions for H_2 demand which we called market capitalization scenarios.

This plot captures the opportunity cost of building the cleanest supply chain network—calculated as the cost difference between the most and least emissive configuration—for each market capitalization scenario. This information is essential to decision makers deciding how to configure the supply chain and strategizing how hard to push for H_2 penetration into the aviation fuel market. We see that for the base case, the annual opportunity cost is roughly \$60 billion (2050 USD); for the mid case, \$146 billion; and for the high case, \$256 billion. This information is especially critical given that some industry experts consider anything below 80% H_2 market capitalization of domestic aviation fuel consumption by 2050 a catastrophic scenario for the climate and industry as a whole. It begs the question of whether we will have the political and social will to invest in the most carbon neutral future possible.

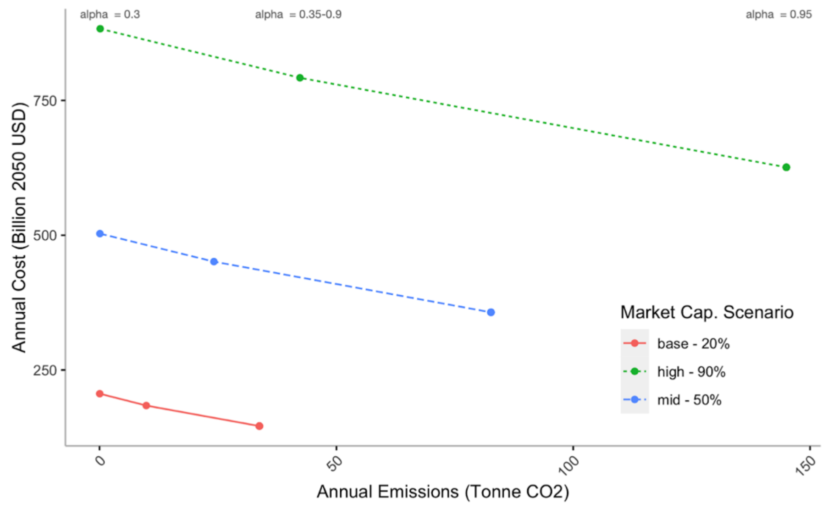


Figure 4: Pareto efficiency frontier for alpha [0.3,0.95], balancing tradeoff between cost and emissions over different H_2 market capitalization scenarios. Differences in cost and emissions between base and high market cap scenarios are $737 billion per year and 145 tonnes/year CO_2, respectively. Multiple optimal points are chosen per each alpha, which we resolve to model setup. Alpha range in final presentation truncated due to spurious outcomes resolved to modeling semantics. See appendix for details.

Supply Chain Logistics

Through extensive data collection and using some of the internal calculations of our model, we have answered 4 Key Questions about H_2 integration into the aviation sector for the 30 largest airports in the country (representative of the Core 30). Production, transportation, and storage costs were estimated using the quantities of H_2 calculated under the 20% domestic RPM scenario detailed in Question 1. Additional details, calculations, and the full list of the 30 airports analyzed can be found in the Appendix.

1. **Is it realistic:** Can the 30 largest airports in the continental U.S. alone be responsible for making 20% of all domestic revenue passenger miles (RPM) be powered by H_2 by 2050? If so, what percentage of their yearly RPM would need to be powered by H_2, and how much H_2 does this translate to?

   Yes, if the 30 largest airports each power about 27% of their annual RPM with H_2 in 2050, H_2 would power 20% of total domestic RPM. This would require between 11 and 17 MT (megatons) of H_2. A conversation with an engineer at the California Air Resources Board (CARB) revealed that CARB predicts a H_2 hub in their state would produce approximately 16 MT/year of H_2 by 2045. If these numbers prove true at all hubs (or even close to true), then meeting 20% H_2 RPM would demand less than 15% of H_2 hub capacities nationwide. As shown in Appendix Table 2, the H_2 hub expected to supply the most H_2 to airports is the one located in CA, and airports would demand less than 10% of this hub's total capacity.

2. **Fuel Cost and Emissions:** What are the cost and emissions implications of each color of H_2 in comparison with Jet A fuel?

   Thanks to generous IRA H_2 production credits (up to $3/kg), blue H_2 is expected to become cheaper than jet fuel,[xxvi] and both green and pink H_2 become cost-competitive with jet fuel. As technologies like electrolyzers and small modular reactors used in making green and pink H_2, respectively, increase in production and efficiency, all H_2 types may become competitive with jet fuel. We also see that green, pink, and blue H_2 emit less than 1/3 the emissions of jet fuel.

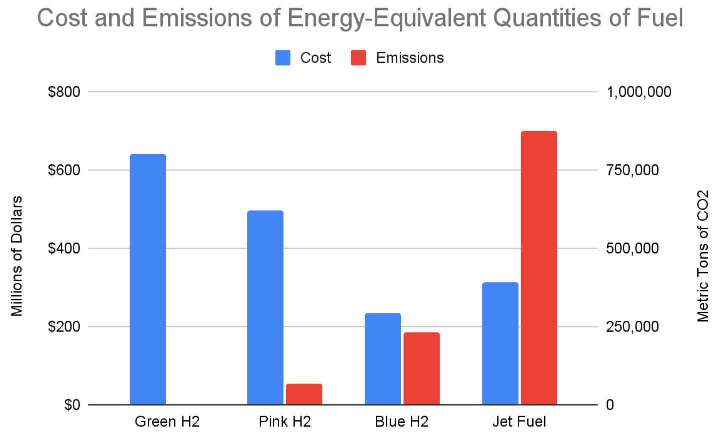


Figure 5: Expected costs and emissions of energy-equivalent quantities of H2 fuel and Jet A fuel for the "average" airport

3. **Transport Cost:** What are the CapEx costs associated with procuring pipelines or trucks to connect H_2 hubs with airports? Are trucks or pipelines more cost effective?

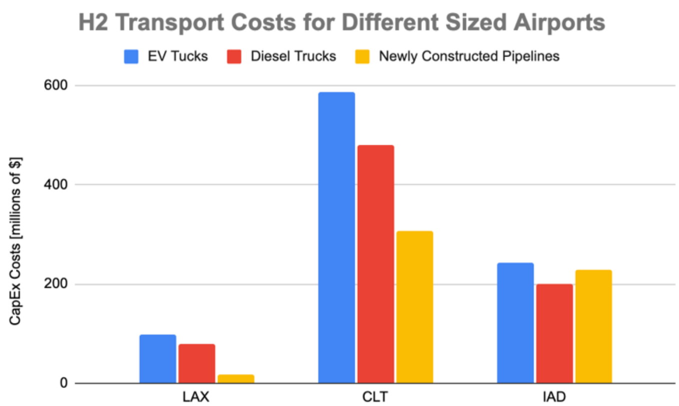


Figure 6: Total CapEx costs for transporting H2 to three airports that demand different H2 quantities: LAX (551 million kg), CLT (184 million kg), and IAD (102 million kg).

We find that it is likely more cost effective for airports to select one transport method for delivering their H_2 – either as a gas through pipelines or as a liquid via heavy duty trucks – since the infrastructure complexities and CapEx costs required for each are so large. For the 30 airports considered, we find that their annual H_2 demand (under the 20% H_2 domestic RPM scenario) can each be met by one 36" dedicated H_2 pipeline. Lastly, we find that the most cost-effective option for the 26 largest airports is pipelines, and that the remaining smaller airports should use trucks (see IAD in Figure 6). This largely has to do with the quantity of H_2 demanded at an airport and the distance from an airport to its nearest H_2 hub. See Appendix for additional details. Also note that while we analyze battery electric trucks here, fuel cell trucks are rapidly improving and may be another viable option.

4. **Storage Cost:** Assuming a 25% on-site storage requirement, what is the CapEx cost associated with on-site liquid H_2 storage at airports?

At the highest H_2-demanding airport (LAX), an estimated seven on-site 3,218 m^3 capacity LH_2 storage spheres will be needed at a cost of around $54 million. Spherical, as opposed to cylindrical, storage tanks are used to store especially large volumes of LH_2, and the dimensions and costs of those used in this analysis come from the National Renewable Energy Lab's Hydrogen Demand Scenario Analysis Model (HDSAM).[xxvii] At the lowest demanding Core 30 airport (AUS), only 2 spheres would be needed, for a total cost of around $15 million. These costs represent a lower bound, as they only include the expected price of the storage spheres and associated piping and pumps, not labor or licensing costs. While expensive, Pittsburgh Airport and LAX are currently investing $1.5B and $6B in new terminals, signifying that airports are no strangers to hugely expensive expansion projects.

Social Benefits

Emissions Reductions and Environmental Justice

It has been shown repeatedly that the effects of climate change most often impact marginalized and low-income communities.[xxviii] Making H_2 the clean fuel of the aviation industry will help to catalyze the hydrogen economy which promises to bring decarbonization to many high polluting sectors. From an end-use perspective, the benefits are universal. Airports with H_2-powered ground support equipment (e.g., airport cargo loaders and wide-body aircraft tugs) and planes will make for cleaner, quieter airports—reducing the pollution burden of flight operations on nearby communities.[xxix]

The benefits of production are not as clear cut. As Figure 7 shows, green H_2 production is prioritized under preference weights that prioritize lower emissions. These preference weights also correspond to ranges for which the results of our model are most unconfident due to the prior-mentioned compounding of uncertainties when $\alpha < 0.3$ and $\alpha > 0.95$ (see Appendix Figure 2). Our results indicate that for green H_2 to be more of a contender with blue H_2 when optimizing for cost, the per unit cost of green H_2 must come down. Additionally, we find that in the presence of insufficient accounting of regional resource constraints or emissions/equity priorities, federal optimization (e.g., based on cost) will result in homogenous hydrogen production methods across the entire country. This may not equitably distribute benefits of clean (green) H_2. The result being that certain regions may be excluded or unintentionally self-exclude from the larger green economy—retrenching distributional emissions harms.

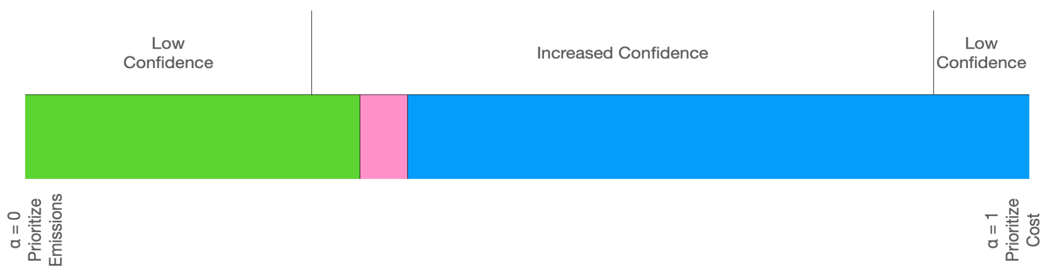


Figure 7: Average quantity and type of hydrogen production over all probabilistic scenarios for the given priority weights. Green hydrogen production is chosen for the most uncertain, emissions-prioritized regions. Pink hydrogen serves more as a transitional method of hydrogen production. Blue hydrogen would be the most dominant form of production over a range of priority weights.

Safety

Another social benefit is that **H_2 is *safer* than jet fuel** with respect to its impact on human health, environmental safety, and risk of fires. Whereas direct exposure to jet fuel can damage the liver, immune system, skin, and cause cancer, H_2 is neither toxic nor carcinogenic.[xxx] From an environmental safety lens, jet fuel can remain in soil for over a decade and leach into local groundwater. H_2, on the other hand, is likely to rise into the atmosphere and disperse because it 14 times lighter than air.[xxxi] Finally, H_2 poses less of a fire risk than jet fuel. H_2 is less likely to ignite than fossil fuels because it requires significantly higher oxygen levels and temperatures. If it does ignite, H_2 fires pose less of a risk than jet fuel fires because its flames burn upwards–rather than circumferentially–causing less damage to surroundings. H_2 also radiates much more slowly which decreases the risk of H_2 fires spreading to insulated components in the case of an airplane fire. [xxxii]

This is not to say that H_2 is completely safe. Safety precautions for H_2 deserve serious attention, especially because H_2 leaks easily and burns with an invisible flame. Given that the U.S. has over four decades of experience handling H_2, H_2 safety is not a new research area. Several organizations, including the Center for H_2 Safety and the Hydrogen Industry Panel on Codes, have worked together to create robust H_2 safety measures.[xxxi] H_2 will likely be deployed in several new sectors over the coming decades, which will require close monitoring and the advent of new safety measures. However, it is ultimately a massive leap forward from jet fuel in terms of safety.

Green Jobs

The blossoming H_2 economy will create vast new employment opportunities. These jobs will span the supply chain, including areas such as CCS technology, electrolyzer and fuel cell manufacturing, pipeline installation, and the multiple end-uses of H_2. What truly sets H_2 apart from other alternative aviation fuels is that it will be deployed in so many sectors beyond aviation, including transportation, industry, and shipping which means that the jobs created will not be niche - they will be highly transferable, long-term employment opportunities that span multiple sectors.[xxxiii]

These jobs are already beginning to emerge. 20% of the application for the DOE's Hydrogen Hub funding is a Community Benefits Plan which requires applicants to consider labor engagement, workforce development, diversity, equity, inclusion, accessibility, and the federal Justice40 Initiative which ensures 40% of federal investments flow towards disadvantaged communities.[xxxiv, xxxv] Rather than recreate the wheel, the aviation community has the opportunity to invest in H_2 and scale up the green jobs already being designed to lift up communities most in need.

Key Barriers

Water Consumption

The three H_2 production pathways the DOE is funding through their H_2 hub network–pink, blue, and green–each consume significant water resources. Assuming the use of light water reactors, pink H_2 requires the most water, approximately 76-85 gallons of water per kg H_2 produced. Green H_2 is not nearly as water-intensive, requiring 19-28 gallons per kg H2,[xxxvi] because solar and wind do not require water to generate electricity unlike light water reactors. Blue H_2 requires the least water at 8-12 gallons per kg H_2. In this case, the water usage comes from several different sectors: the natural gas supply chain, cooling tower, and electricity.[xxxvii, xxxviii, xxxix]

Based on the projected 2050 demand for H_2 from the domestic aviation sector alone, we estimate the maximum water required at H_2 hub to exceed **88 billion gallons/year** (see Appendix for details on this calculation). This means states will have to allocate a significant portion of water resources to H_2 production, a difficult task for regions with pre-existing water stress. One example of an already-stressed state is California whose water demand exceeds 110% of available water supply.[xl] One potential solution for California and similarly stressed areas is the desalination of rivers and seawater. Reverse Osmosis (RO) has achieved a TRL of 9 with large-scale application globally, including 35% of Israel's freshwater coming from RO desalination,[xli] which demonstrates its ability to help address water scarcity issues.

Public Perception

Public acceptance of the use of H_2 in aviation is an important factor that, if not addressed, can become a barrier to commercializing hydrogen aviation. To understand the role of public acceptance of H_2 projects, we reviewed the work of Iana Iacob, a PhD student at Carnegie Mellon University focused on public perception of the hydrogen hubs and hydrogen aviation. Without public acceptance, hydrogen projects are at risk of facing pushback due to NIMBYism and environmental concerns. Numerous surveys indicate that the public's key concerns surrounding H2 relate to safety, regulation, and oversight. This applies to all stages of the supply chain, meaning that the public would like to see safety guaranteed by regulations and oversight for hydrogen production, transport, storage, use in aircraft, and CCS technology.

Research also suggests that the public is largely unaware of hydrogen as an energy carrier. This offers hydrogen stakeholders an opportunity to craft the narrative surrounding hydrogen. We recommend that hydrogen stakeholders and government proactively collaborate on hydrogen safety regulations over the coming years so that when hydrogen demonstration projects begin, the hydrogen community can point to existing regulations to help foster public trust. Regulation will specifically be key to enabling hydrogen transport via interstate pipelines, the primacy to store CO_2 underground for CCS technologies, and the storage of H_2 safe from attacks.

Infrastructure Barriers

Both pipelines and electric or diesel trucks pose their own unique challenges as H_2 delivery methods. Pipelines have much longer lifetimes and lower emissions per kg of H_2 delivered than trucks. Despite steep upfront costs, pipelines can be a very cost-effective option for delivering large amounts of H_2.[xlii] However, there has historically been significant resistance to the construction and installation of pipelines spanning large areas, for reasons such as geopolitics, ecological damage, exploitation of Native American lands, and drinking water contamination.[xliii,xliv,xlv] And even if a route was designed such that each of these concerns were addressed, a pipeline can take up to ten years to construct.[xlvi] A Senior Director of Operations at the San Diego Airport told the team that switching from delivering Jet A fuel on the tarmac with trucks to an underground pipeline system caused huge disruptions and including gates needing to close temporarily. Despite these drawbacks, there are over 1,600 miles of H_2 pipelines already in existence in the U.S., and pipelines are by far the most common delivery method of jet fuel to airports.[xlvii]

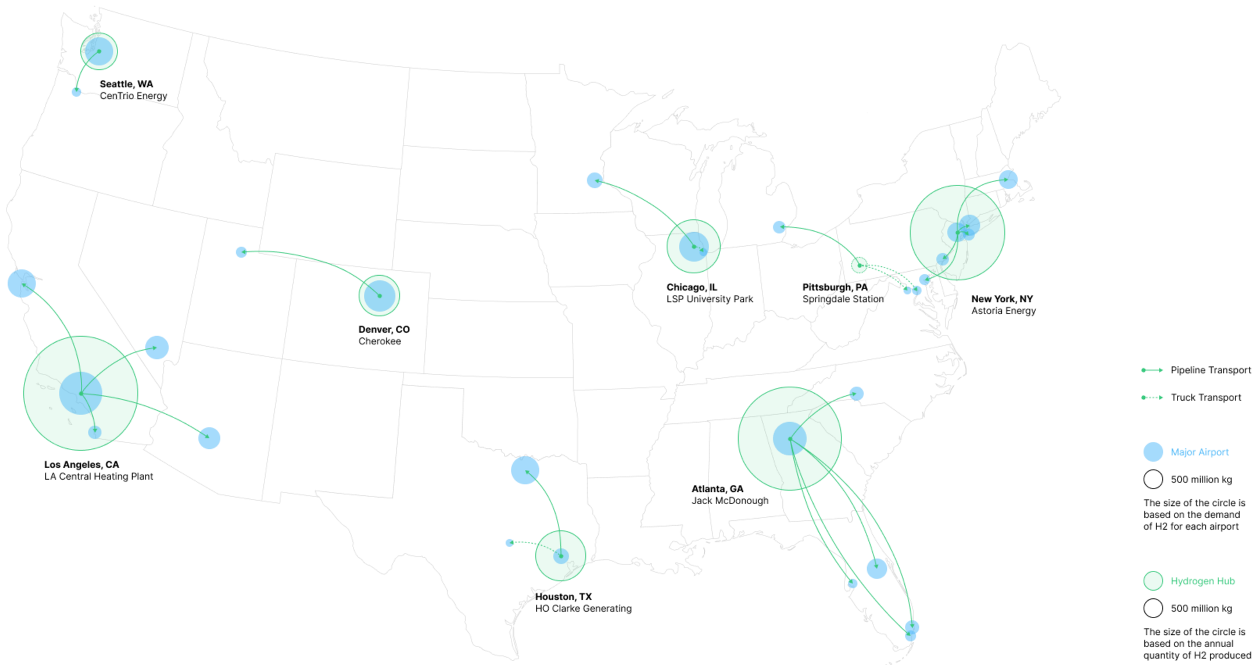
Trucks present a more flexible option. They do not require the permanent alteration of huge swaths of land, eliminating the huge time sink of route design and licensing for pipelines. Furthermore, they can be cost-effective options for customers who demand low to moderate quantities of H_2, and some studies have found them to be cost-effective (relative to pipelines) for longer delivery distances.[xlvi, xlviii] On the other hand, adding trucks to the road increases congestion, which in turn impacts the safety of all vehicles on the road, the quantity of vehicle emissions released into communities on roadways, and travel times. At busy airports, increased traffic on airport-access roads and the tarmac could pose a concern to airport operations. Furthermore, trucks delivering liquified H_2 suffer from the "boil off" of LH_2 where liquid H_2 increasingly escapes over time. A representative of Universal H_2 told the team that a possible solution is to establish a strict window–4 days was suggested–in which H_2 is delivered and used by aircraft.

Conclusion

Decarbonizing our economy is the challenge of our generation. If we are to minimize global warming as fast as possible, **we must coalesce around a unified and realistic decarbonization vision**. H_2 emerges as a promising solution for decarbonizing aviation because it is projected to offer transcontinental, zero-emission flights and is already supported by high supply chain readiness and federal funding. We find that connecting the Department of Energy's H_2 hubs with the 30 largest airports creates a reliable source of H_2 supply and demand that would both help achieve NASA's 2050 net zero aviation goals and help spur cross-sector decarbonization. H_2 offers improved emissions reductions and environmental justice, safety, and transferrable green jobs. By addressing its key barriers like water consumption, public perception, and infrastructure challenges with proven policy initiatives, we believe H_2 offers the best chance to decarbonize aviation and the broader economy.

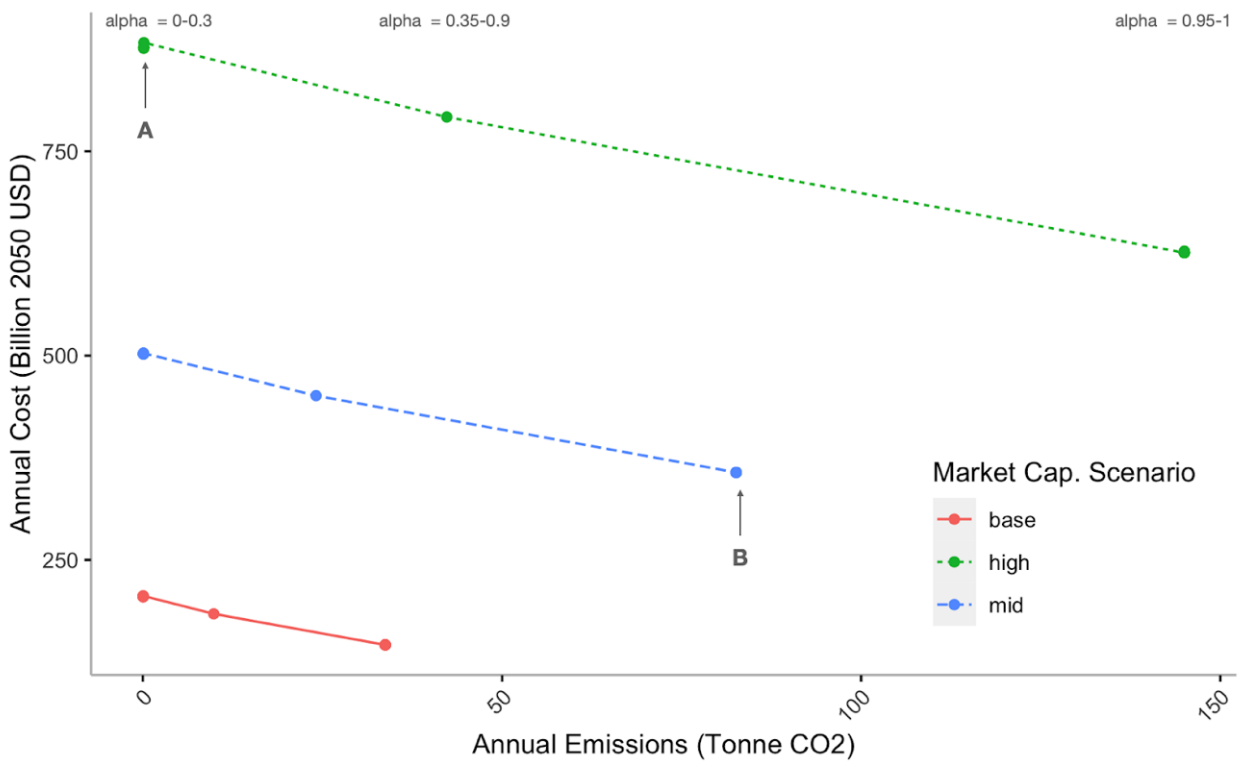
Appendix

Figures



Appendix Figure 1: Our national vision for connecting H_2 hubs to the Core 30 largest airports through pipelines and truck transport to reliably supply them with H_2 fuel.

The location of the H_2 hubs (in green circles above) are not predictions, only assumptions that allowed the team to analyze the best supply chain model for each of the Core 30 airports. The DOE is expected to announce the sites of the H_2 hubs in 2023-2024, and our vision of connecting H_2 hubs with the Core 30 airports can be reapplied to those locations.



Appendix Figure 2: Pareto efficiency frontier for alpha [0,1], balancing tradeoff between cost and emissions over different H2 market capitalization scenarios. Item "A" we show lower cost outcomes at alpha < 0.3 ; where the expected trend is that the outcomes monotonically decrease from alpha = 0. Item "B" shows slight uptick in cost at alpha > 0.95 at highest cost priority, which, also should be monotonically decreasing. We believe this unexpected outcome is due to modeling semantics i.e. formulation. Our formulation may insufficiently capture unforeseen real-world dynamics that cannot be fully characterized to date, given the nascent development (or nonexistence) of many features of the aerospace hydrogen economy.

When <0.3 and >0.95 our results did not follow expected trends, indicating a possible discrepancy in how we modeled one or more sections of the supply chain from intended reality. At first this consideration seemed like an error, but when delving into the specifics of our modeling choices, we concluded that our "best guess" was only as accurate as the political and technical reality of the supply chain. As indicated throughout the analysis, high uncertainty at all levels of the H_2 supply chain make for unstable modeling dynamics. Given the relatively small deviations in optimized outcomes at the tail-ends of our curve, we will feel confident in our findings, but encourage further exploration into the matter once hydrogen hubs are selected and net H_2 demand for the aviation sector is established.

Tables

Appendix Table 1: Technology readiness levels (TRL) for hydrogen technologies discussed in this report (including sources to TRL justification)

Make		**Move**		**Store**		**Use**	
Electrolysis – PEM	9[xlviii]	Dedicated Hydrogen Pipeline	9[xlix]	Liquid Hydrogen Storage	9[l]	Hydrogen Powered Aircraft	7-8[li]
Electrolysis – Alkaline	9[xxiv]	Retrofit Hydrogen Pipeline	4-5[lii]	Liquefaction	9[liii]		
Electrolysis – Anion	2-3[xxiv]	Hydrogen Pipeline Blending	6-7[liv]				
Electrolysis – Solid Oxide	5-6[xxiv]	Hydrogen Truck Refueling (Diesel)	9[lv]				
Steam Methane Reformation (SMR)	9[lvi]	Hydrogen Truck Refueling (Zero-Emission)	6-7[xxxi]				
Autothermal Reformation (ATR)	8-9[xxxii]						
Reverse Osmosis (RO)	8-9[lvii]						

Appendix Table 2: Predicted locations of the 8 DOE-funded H_2 Hubs used for analysis. City and state predictions were made by selecting cities with large economies whose industries could benefit from H_2 production in the area. Hub sites were selected on the basis of being large power plants in these areas.

Hub Site	**City & State**	**Coordinates (decimal degrees)**	**Expected H_2 Production [MT]**
LA Co. Central Heating Plant	Los Angeles, CA	(34.05617, 118.2432)	1.474
CenTrio Energy Plant	Seattle, WA	(47.60683, 122.3417)	0.480
Cherokee Generating Station	Denver, CO	(39.80783, 104.9648)	0.532
HD Clarke Generating Station	Houston, TX	(29.64633, 95.45167)	0.656
LSP University Park	Chicago, IL	(29.64633, 87.7515)	0.695
Jack McDonough Power Plant	Atlanta, GA	(33.82433, 84.475)	1.329
Springdale Generating Station	Pittsburgh, PA	(40.54567, 79.76683)	0.211
Astoria Energy Power Plant	New York City, NY	(40.7825, 73.89633)	1.218

Appendix Table 3: The 30 airports being considered for 4 Key Questions, the calculated quantity of H_2 each would demand under the 20% H_2 RPM scenario, the closest of the 8 H_2 hubs under consideration, and the distance to the closest hub.

Airport (IATA Code)	**H2 Demand [millions of kg]**	**Nearest H2 Hub (State)**	**Distance to Nearest H2 Hub [miles]**
LAX	551.64	CA	12.27
ATL	435.13	GA	13.23
DEN	392.84	CO	15.91
ORD	381.73	IL	37.84
SFO	365.15	CA	337.56
DFW	358.18	TX	243.16
SEA	355.71	WA	10.98
LAS	304.67	CA	223.83
PHX	282.98	CA	360.59
JFK	273.57	NY	11.62
MCO	262.84	GA	416.79
EWR	249.21	NY	15.55
BOS	241.30	NY	184.99
MSP	207.43	IL	363.57
IAH	199.93	TX	24.26
CLT	184.40	GA	222.64
FLL	179.59	GA	594.24
SAN	169.60	CA	109.66
PHL	166.61	NY	94.67
DTW	166.46	PA	218.53
LGA	148.83	NY	1.29
MIA	146.67	GA	608.37
BWI	139.47	NY	183.89
SLC	139.25	CO	375.43
PDX	125.29	WA	139.87
TPA	120.51	GA	419.87
DCA	109.11	PA	186.24
MDW	106.46	IL	23.71
IAD	102.61	PA	165.14
AUS	98.30	TX	137.63

Appendix Table 4: Water requirement for each hydrogen hub

Hub Site	City & State	Expected Green H_2 Production [MT/year]	Expected Blue H_2 Production [MT/year]	Expected Pink H_2 Production [MT/year]	Water Consumption [gal/year]
LA Co. Central Heating Plant	Los Angeles, CA	1.474			3.69 Billion
CenTrio Energy Plant	Seattle, WA	0.480			
Cherokee Generating Station	Denver, CO	0.532			
HD Clarke Generating Station	Houston, TX	0.656			
LSP University Park	Chicago, IL	0.695			
Jack McDonough Power Plant	Atlanta, GA	1.329			
Springdale Generating Station	Pittsburgh, PA	0.211			
Astoria Energy Power Plant	New York City, NY	1.218			

In-Flight Emissions: A Deeper Dive

In-flight emissions from today's aircraft can be broken down into four segments: CO_2, NO_x (nitrous oxides), particulate emissions, and water vapor.[lviii] As previously discussed, fuel cell powered-aircraft would theoretically produce no emissions; since no fuel is being burned, no CO_2 or particulate emissions are created and the air is not heated from combustion such that NO_x is formed. On the other hand, fuel cells do produce water vapor and heat in addition to electricity; only if the water vapor and heat are internally collected and condensed by a heat exchanger will water vapor not be introduced into the atmosphere.[lix] Due to range limitations, LH_2 combustion will likely be used in tandem with fuel cells for aircraft serving longer trips. LH_2 combustion will not result in CO_2 or particulate emissions, and has the potential to produce lower NO_x emissions by running lean and premixed.[lx] However, burning LH_2 does result in approximately 2.6 times the water vapor emissions of kerosene-based fuels.[lxi] While the contrails which can form from this water vapor are known to contribute to global warming, it is important to note that they dissipate after a few hours at most, unlike atmospheric CO_2, which can remain trapped in the sky for hundreds of years.[lxii,lxiii]

Water Consumption

Based on demand from surrounding airports, our model allocates the following annual H_2 production to each of the eight hubs (shown in megatonnes (MT)):

1. California: 45.16 MT
2. Washington: 11.23 MT
3. Colorado: 12.42 MT
4. Texas: 15.31 MT
5. Illinois: 16.23 MT
6. Georgia: 24.90 MT
7. Pennsylvania: 8.82 MT
8. New York: 28.44 MT

The hub producing the least H_2 to support aviation is in Pennsylvania (8.82 MT). As stated in the Water Consumption section of the report, the H_2 production method requiring the least water is SMR with CCS, or "blue" H_2, at 8-12 gallons of water per kg of H_2. If the Pennsylvania hub were to make all its aviation related H_2 blue, this would result in the consumption of between 70 and 105 billion gallons of water per year. As this is the smallest quantity of H_2 we expect to be produced at any of the hubs and the least water-intensive method we considered, this represents a lower bound for all other hubs in terms of water consumption.

Model Description

Based on multicriteria decision analysis (MCDA) theory, we built a network optimization model to minimize the cost and emissions of the hydrogen supply chain, given different value weights for either objective. We perform our analysis over a series of probabilistic scenarios and take the expected value of cost and emissions across all scenarios. These scenarios are informed by quantitative and qualitative research from literature reviews and interviews with various industry stakeholders, and we believe these scenarios adequately capture the uncertainty in hydrogen demand in 2050 that will have a significant impact on the size and impact of the hydrogen network in question. We ran our analysis using the Gurobi optimization software.[lxiv]

Overview of Production Sections:

As a mathematical representation of our framework, our supply chain stages include hydrogen production ***(make)***, hydrogen transportation ***(move)***, hydrogen storage near the airport ***(storage)***, and last mile hydrogen delivery ***(final mile)***.

- We consider green, blue, and gray hydrogen production alternatives within our ***(make)*** formulation.
- We consider EV trucks, diesel trucks, new pipelines, and retrofit pipelines as hydrogen transportation alternatives from hydrogen hubs to 87 airports throughout the contiguous U.S. within our ***(move)*** formulation.
- We consider tank storage of liquid hydrogen (LH_2) storage at each of our 87 airports in question for backup fuel stores within our ***(store)*** formulation.
- We consider EV truck delivery of LH_2 from storage and staging facilities (off-site but proximate initial delivery sites for hydrogen) to planes for fueling within our ***(final mile)*** formulation.

Overview of Objective Function & Expected Outcome:

- MC/E - Make cost /emissions
- MVC/E - Move cost /emissions
- SC/E - Store cost /emissions
- FIMIC/E - Final Mile cost /emissions
- r - scenarios [1-11]
- α - value weight of cost/emissions [0,1]

$$Objective = min(\alpha (MC + MVC + SC + FIMIC) + (1-\alpha)(ME + MVE + SE + FIMIE))$$

Example of expected value calculation for cost and emission:

$$E[MC] = \Sigma_r P_r (\Sigma_\alpha MC_\alpha)$$
$$E[ME] = \Sigma_r P_r (\Sigma_\alpha ME_\alpha)$$

Supplemental Information for 4 Key Questions

Question 1: Is it Realistic?

See Table 3 for the 30 airports under consideration. These are the 30 airports with the largest air traffic as measured in RPM by the Bureau of Transportation Statistics (BTS)[lxv].
To determine what percentage of rpm across these 30 airports would equate to 20% of total domestic RPM in the U.S., total U.S. domestic RPM was found by summing domestic RPM across all airports with data recorded by BTS. This was compared to domestic RPM across the 30 airports we considered to find what percentage of RPM across our 30 airports would need to be converted to H_2.

To get an estimate of how many kg of H_2 this would correspond to, we used an estimate from the Mission Possible Partnership for how much H_2 would need to be produced for the global aviation sector to convert 20% of 2050 air traffic to being powered by H_2: 107 Mt/year.[iv]

From an ICAO report, we found that 22.2% of global air traffic is currently attributed to North America[lxvi]. We estimate that the U.S. makes up between 50 and 70% of the air traffic in North America. Using the lower bound on North American air traffic attributed to the U.S. (50%), we estimate that the U.S. will then require approximately 11 MT/year of H_2. Using the upper bound (70%), we estimate that the U.S. will require approximately 16.5 MT/year of H_2.

Question 2: Fuel Cost

To determine how much purchasing H_2 would cost for the "average" airport in our list, we first found the average quantity of H_2 needed for our 20% H_2 RPM scenario across the 30 airports we considered: 232,182,768 kg. This quantity was then multiplied by the levelized cost of producing hydrogen (similar to the idea of levelized cost of energy) for steam methane reformation (Gray), steam methane reformation with carbon capture (Blue), and renewable-powered electrolysis (Green).

These cost numbers were generated by NREL, notably for 2018 rather than 2050, and are listed below[lxvii]:

- Steam methane reformation without carbon capture (Gray): \$1.08/kg
- Steam methane reformation with carbon capture (Blue): \$1.86/kg
- Electrolysis with Solid Oxide electrolyzers (Green): \$4.66/kg

Subsidies from the IRA were estimated to apply as follows[lxviii]:

- Gray: \$1.08/kg - applied IRA subsidy = \$1.08/kg - \$0.00/kg = \$1.08/kg
- Blue: \$1.86/kg - applied IRA subsidy = \$1.86/kg - \$0.86/kg = \$1.00/kg
- Green: \$4.66/kg- applied IRA subsidy = \$4.66/kg - \$3.00/kg = \$1.66/kg

To determine the cost of an equivalent quantity of Jet A fuel (JAF), the quantity of H_2 being considered was converted to JAF on an equivalent-energy basis:

$$Equivalent\ JA = \frac{232{,}182{,}768\ [kg\ H_2]}{1} * \frac{1\ [Liter\ H_2]}{14.13\ [kg\ H_2]} * \frac{8\ [MJ]}{1\ [Liter\ H_2]} * \frac{1\ [L\ JAF]}{34.69\ [MJ]} * \frac{1\ [gal\ JAF]}{3.7854\ [Liter\ JAF]} = 199{,}868{,}755\ gal\ JAF$$

From here, both a low- and high-cost scenario were considered for the price of JAF[lxix]:

- Low-cost scenario: \$1.45/gal
- High-cost scenario: \$3.17/gal

Question 3: Transport Cost

To calculate the CapEx costs associated with delivering H_2 via trucks (electric or diesel), the number of trucks required for delivery for each airport was calculated by rounding up the following equation to the nearest integer:

$$n_{trucks} = \frac{H_2\ Demand\ [kg]}{Truck\ capacity\ [kg]} * \frac{Round - trip\ distance\ [miles]}{Annual\ truck\ mileage\ [miles]}$$

where H_2 demand is the demand of the individual airport under the 20% hydrogen RPM scenario (see Table 3), truck capacity is 3610 kg[lxx], round-trip distance is two times the distance from an airport to its nearest H_2 hub (see Table 3), and annual truck mileage was calculated as follows:

$$\begin{aligned} annual\ mileage\ &= \frac{avg. speed\ [miles]}{[hour]} * \frac{shift\ length\ [hours]}{[day]} * \frac{annual\ days\ worked\ [days]}{[year]} \\ &= \ miles/yr \end{aligned}$$

where average truck speed is 43.5 mph[18], shift length is 8 hrs/day, and annual days worked is 145, resulting in an annual mileage of 50,460 miles/year.

Capital costs for electric diesel trucks were found as follows:

- Class 8 diesel truck cab[18]: \$115,000
- Class 8 electric truck cab[lxxi]: \$350,000
- Liquid H_2 tank trailer[18]: \$950,000

Specifications for pipeline cost and operating characteristics used in calculations are as follows[lxxii]:

- CapEx cost: 1.38 M\$/mile
- Annual H_2 delivered: $\frac{6.6*10^7\ [m^3\ H_2]}{1\ [day]} * \frac{365\ [days]}{1\ [year]} * \frac{1\ [kg\ H_2]}{11.126\ [m^3\ H_2]} = 216{,}5198{,}634\ kg/yr$

Question 4: Storage Cost

Operating and cost characteristics of liquid H_2 (LH_2) storage sphere used in analysis:

- Cost of single storage sphere[18]: \$7,378,429 (lower bound)
- Cost of LH_2 pump[18]: \$32,039
- Cost of piping mains, headers, and valves (including fittings)[18]: \$299,944
- Total cost per sphere (sphere itself, pump, piping equipment): \$7,710,412
- Capacity of single storage sphere[lxxiii]: 3218 m^3 LH_2

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