EVOLVED ENERGY RESEARCH

THE CLEAN HYDROGEN LADDER AND THE ANNUAL DECARBONIZATION PERSPECTIVE

APPLICATIONS FOR HYDROGEN IN A DECARBONIZED ECONOMY

Prepared with the support of Breakthrough Energy Foundation

ABOUT THIS REPORT

This report belongs to a series of whitepapers that expand on the findings of Evolved Energy Research's *2022 Annual Decarbonization Perspective (ADP)*, an annually updated technical blueprint for the transition to a net-zero economy. The aim of these whitepapers is to isolate specific parts of the energy transition and provide a fuller discussion of the insights gained from EER's modeling and analysis.

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ABOUT EVOLVED ENERGY RESEARCH

Evolved Energy Research (EER) is a research and consulting firm focused on questions posed by transformation of the energy economy. Their consulting work and insight, supported by sophisticated technical analyses of energy systems, are designed to support strategic decision-making for policymakers, stakeholders, utilities, investors, and technology companies.

KEY FINDINGS OF THIS REPORT

1. In every decarbonization pathway, hydrogen production grows dramatically, but the differences in hydrogen consumption between scenarios indicates its role is one of the least certain pieces of decarbonization. A critical factor is that hydrogen remains uncompetitive against most end-uses that can be directly electrified.

2. The results of the Annual Decarbonization Perspective are closely aligned with the hierarchy of the "Clean Hydrogen Ladder"; hydrogen applications in the top three rungs of the ladder account for over 70% of hydrogen used in ADP's Central scenario.

3. Most hydrogen is used for feedstock applications (synthetic fuels and ammonia) rather than direct uses, as the delivery costs of direct use make it uncompetitive (e.g. domestic heating).

4. The competitiveness of e-fuels derived from hydrogen is highly dependent on low-cost renewable deployment; constraints on siting renewables make other fuel strategies more competitive and shrink the role of hydrogen in the energy system.

5. Nationally, most of the hydrogen is produced using electrolysis but with greater production shares of non-electrolytic hydrogen outside of the wind belt.

6. It's important for policymakers to consider three key decision points for when hydrogen makes sense:

   a) Is electrification technically feasible?

   b) How flexible is the electrified end-use (which can lower average costs)?

   c) Does the end use need a hydrocarbon (not needing hydrocarbons lowers cost)?

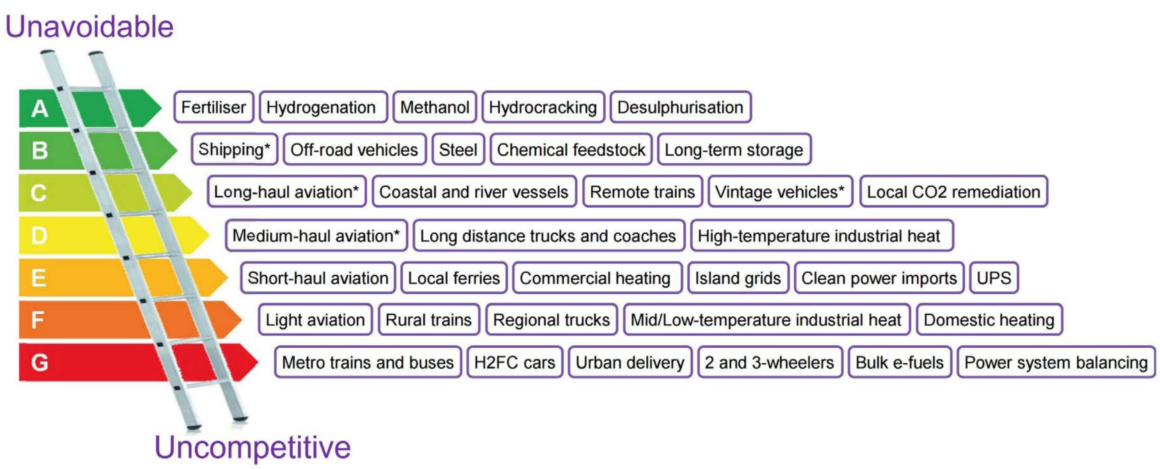
BACKGROUND

The optimal role of hydrogen in a decarbonized economy has been debated for decades. With the passage of the Inflation Reduction Act in the U.S. and the introduction of robust tax credits to produce clean hydrogen, questions about the appropriate scope of hydrogen's demand-side applications are even more relevant today. It is essential that investments in hydrogen infrastructure are targeted at applications that are economically competitive and technologically sensible to minimize the cost of the energy transition. While hydrogen and hydrogen-derived fuels will undoubtedly play some role in the energy transition, there are many sectors in which hydrogen is a poor decarbonization solution because it is more expensive or logistically complex than direct electrification, or other competing technologies such as biofuels or fossil fuels with CCUS. Evolved Energy Research's ***Annual Decarbonization Perspective 2022 (ADP)*** serves as a detailed technical blueprint for the transition to a net-zero economy in the U.S., including least-cost pathways for sectors where electrification is an incomplete or infeasible decarbonization solution (such as chemicals, heavy industry, and heavy transport) and where hydrogen is most competitive.

The "Clean Hydrogen Ladder" developed by Michael Liebreich/Liebreich Associates (henceforth "Liebreich's Ladder") is one notable framework for assessing hydrogen's competitiveness across various end uses. Widely circulated among energy professionals and industry stakeholders, Liebreich's Ladder ranks the relative likelihood that hydrogen will outcompete other decarbonization solutions and achieve widespread adoption for a given end-use. This paper applies the ranking system devised in Liebreich's Ladder to our ADP findings regarding hydrogen production and applications to assess the extent to which our results confirm or challenge the Liebreich's Ladder hierarchy of end-uses, and to offer a sense of scale regarding the volume of hydrogen required for each end-use. Comparing hydrogen use across different ADP decarbonization scenarios also provides insight into how real-world variables like land constraints or slow consumer uptake of electrification may impact the ultimate competitiveness of hydrogen.

FIGURE 1

The Clean Hydrogen Ladder



** Via ammonia or e-fuel rather than H2 gas or liquid*

Source: Liebreich Associates (concept credit: Adrian Hiel/Energy Cities)

METHODOLOGY

The findings discussed in this report, originally published in the Annual Decarbonization Perspective (ADP), are based on our EnergyPATHWAYS and RIO modeling platforms, widely recognized as best-in-class, in combination with the most current data on technology cost and performance. We model a diverse set of fuel production technologies derived from clean electricity, sustainable biomass feedstocks, and fossil fuels with carbon capture, as well as storage and transport technologies, across 27 distinct geographic regions in the U.S. We also model many distinct technologies for storing energy in different forms to balance supply and demand across a variety of energy carriers, including hydrogen and ammonia. This enables us to represent the integration of the fuels sector with the electricity sector—an essential characteristic for the economics of high-renewable energy systems, and particularly important for accurately assessing the economic uses of hydrogen and its competitors.

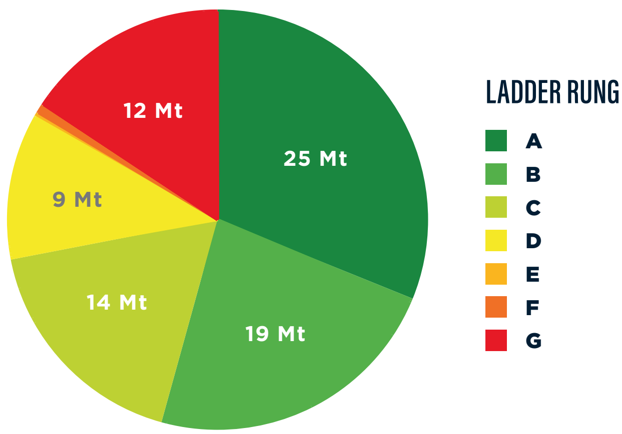
ADP models seven distinct decarbonization scenarios and fourteen sensitivities that achieve economy-wide net-zero GHG emissions (in addition to a business-as-usual “baseline” scenario). This white paper focuses primarily on differences in the use of hydrogen in the seven core ADP scenarios. The Central scenario represents the least-cost pathway to reach net-zero by 2050.

CENTRAL SCENARIO

In the ADP Central scenario, U.S. hydrogen consumption in 2050 is approximately 80 million tonnes (Mt), over 70% of which satisfies end-uses on the top three rungs of Liebreich's Ladder. This represents general agreement between the results of our economy-wide decarbonization modeling and the Liebreich's Ladder ranking framework.

Where ADP end-uses do not correspond exactly to those end-uses identified on Liebreich's Ladder, we have distributed them on the rung with their closest analogue. The results of this exercise are meant to provide a general picture of the share of hydrogen production that can be expected to flow to distinct sectors of the economy.

FIGURE 2.
Hydrogen End-Use in ADP Central Scenario, 2050



Use as a feedstock for ammonia, methanol, and other bulk chemicals accounts for roughly 40% of demand, or over 30 Mt. Rung B is constituted largely by iron and steel (9 Mt) and shipping (7 Mt). Aviation (10 Mt) makes up the overwhelming share of rung C, followed by freight rail (2 Mt). In aviation, hydrogen is a feedstock to produce synthetic hydrocarbons (e-fuels) via Fischer-Tropsch.

The demand in groups D through G is attributable largely to the transportation sector: predominately, heavy-duty trucks in group D and light and medium-duty trucks in Group G. Busses, rail, and recreational boats also account for small shares in these rungs. While Liebreich's Ladder indicates hydrogen is generally uncompetitive with battery electric vehicles for these end-uses, our results reflect assumptions about a wide diversity in users' vehicle preferences. Across trucking applications, there is significant uncertainty around the ultimate competitiveness of battery electric vs fuel cell trucks; variation in the duty-cycles, flexibility of re-fueling, and other logistical practices in trucking subsectors suggests that decarbonization solutions could be mixed across the trucking industry. Our assumptions are derived from independent research and reviews of the latest literature. The central scenario does not indicate that hydrogen will dominate these transport sectors, merely our assumption that some users will turn to hydrogen based on duty cycle (vehicle use patterns). As a result, transport applications spread across the bottom half of Liebreich's Ladder make up approximately a quarter of U.S. hydrogen demand in our central scenario. Hydrogen applications in space heating, whether residential or commercial, make up less than 1% of hydrogen use, supporting the view that this space heating is a highly uncompetitive application. This is true across every decarbonization scenario modeled in ADP.

VARIABILITY ACROSS DECARBONIZATION SCENARIOS

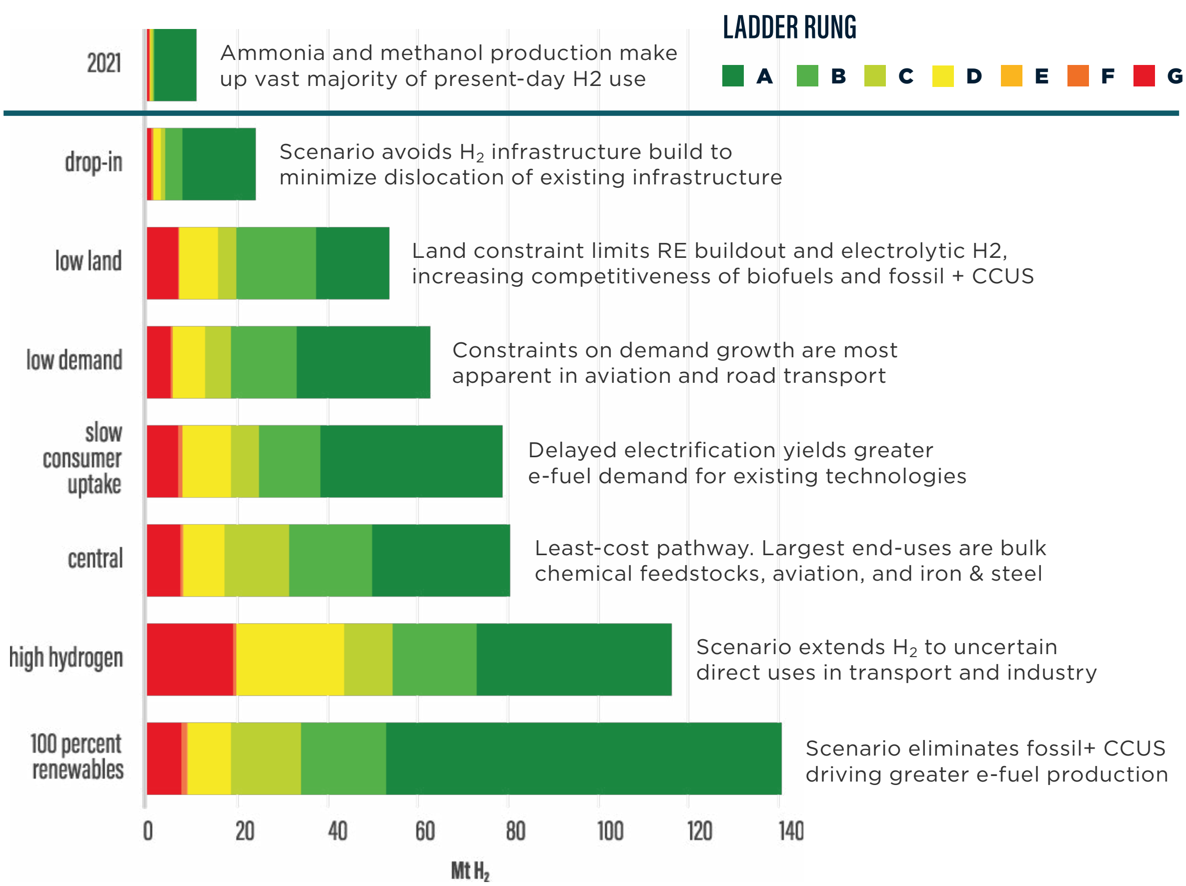
Comparing hydrogen production and end-use applications across different decarbonization pathways reveals how several key variables—for example, land availability, the scale of renewable buildout, and end-user technology preferences—can increase or constrain hydrogen use in specific sectors of the economy. Figure 3 shows the volume of hydrogen production across all seven ADP scenarios, and the share of hydrogen application distributed among each rung of Liebreich's Ladder.

In the 100 Percent Renewables scenario, all fossil fuels and nuclear energy must be replaced by renewable electricity along with alternative fuels and feedstocks, many of which are derived from electrolytic hydrogen. This accounts for the more than tripling of hydrogen demand in rung A of Liebreich's Ladder. Hydrogen is used to create the hydrocarbon substitutes (via Fischer-Tropsch) for natural gas, LPG, and other feedstocks of the bulk chemicals industry.

In the Low Land scenario, a land constraint is imposed to reflect societal preferences for conservation or other competing land uses over wind and solar deployment. The result is far less renewable energy available for electrolysis, and a greater share of hydrogen produced from steam reforming (25%) and BECCS (35%). In this scenario, total hydrogen production is 54 Mt in 2050, reflecting a >30% reduction relative to the Central scenario. Because electrolytic hydrogen production is constrained, other fuels pathways become more competitive than hydrogen-derived e-fuels for replacing fossil fuels in aviation and bulk chemicals. The volume of hydrogen going to produce sustainable aviation fuel is reduced by almost 90% relative to the central scenario, and hydrogen for bulk chemicals is reduced by over 40% relative to the central scenario.

FIGURE 3

Hydrogen End-Uses Across ADP Scenarios



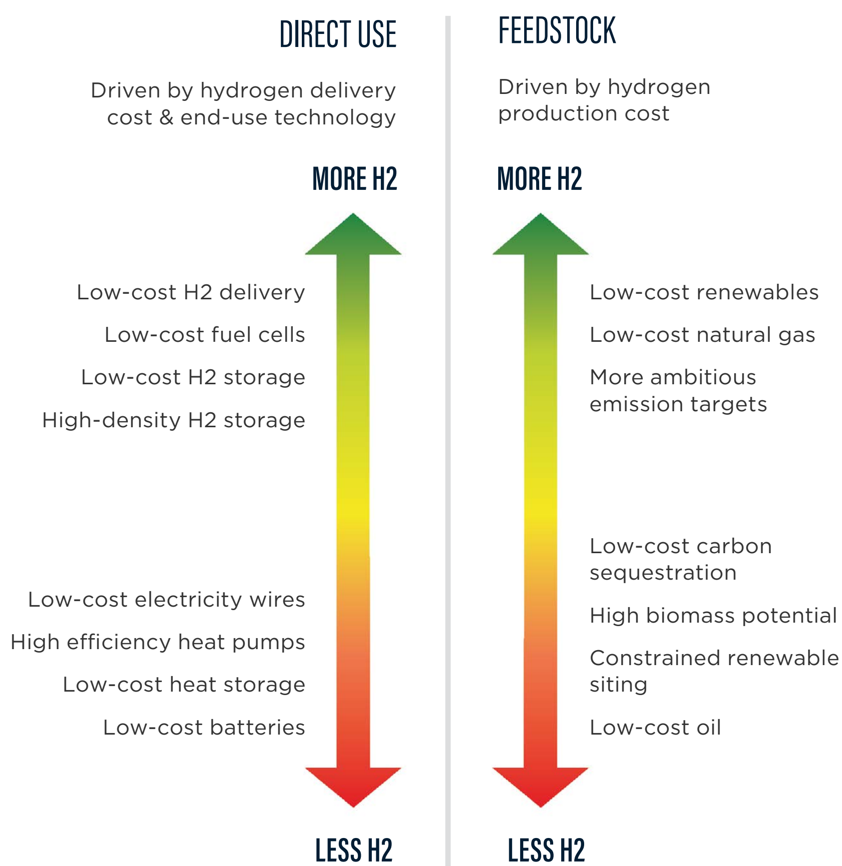
The High Hydrogen scenario is explicitly designed to explore the effects of a hydrogen economy that extends the direct use of hydrogen into applications in which the potential for electrification is uncertain, specifically in industry and heavier transport. Naturally, this scenario sees higher volumes of hydrogen in those applications deemed less competitive by Liebreich's Ladder (rungs D-G). The result is a 33% increase in the net cost of decarbonization relative to the central scenario. This scenario doesn't push hydrogen as far as has been considered in some sectors, like heating in buildings, but still reveals the negative economic impacts of pursuing hydrogen deployment in sectors in which there may be other alternatives (specifically direct electrification). This speaks to the value of direct electrification approaches being developed for areas like industrial high-temperature heating and long-haul trucking.

FEEDSTOCK VS. DIRECT USE

Dividing hydrogen applications between feedstocks and direct-uses is also helpful for understanding hydrogen's likely role in the energy system, as the variables driving the cost of hydrogen are distinct for feedstocks and direct-uses. Direct-use of hydrogen is when hydrogen is consumed in the provision of a final energy service—for example, as a vehicle fuel. Feedstock use is when hydrogen is used to produce an alternative fuel in an additional synthesis process—for example, hydrogen used to produce an e-fuel in a Fischer-Tropsch process or ammonia in a Haber-Bosch process.

For direct-use hydrogen applications, delivery costs are anticipated to be much higher than in feedstock applications. This is because delivery cost depends on both volume and distance. Lower volumes over greater distances means higher cost, the prime example being direct use of hydrogen within buildings. On the other hand, feedstock applications are comparatively high volume and the infrastructure often does not exist today, which means they can be developed close to hydrogen production.

FIGURE 4
Cost Drivers of Hydrogen Feedstocks vs. Direct Uses

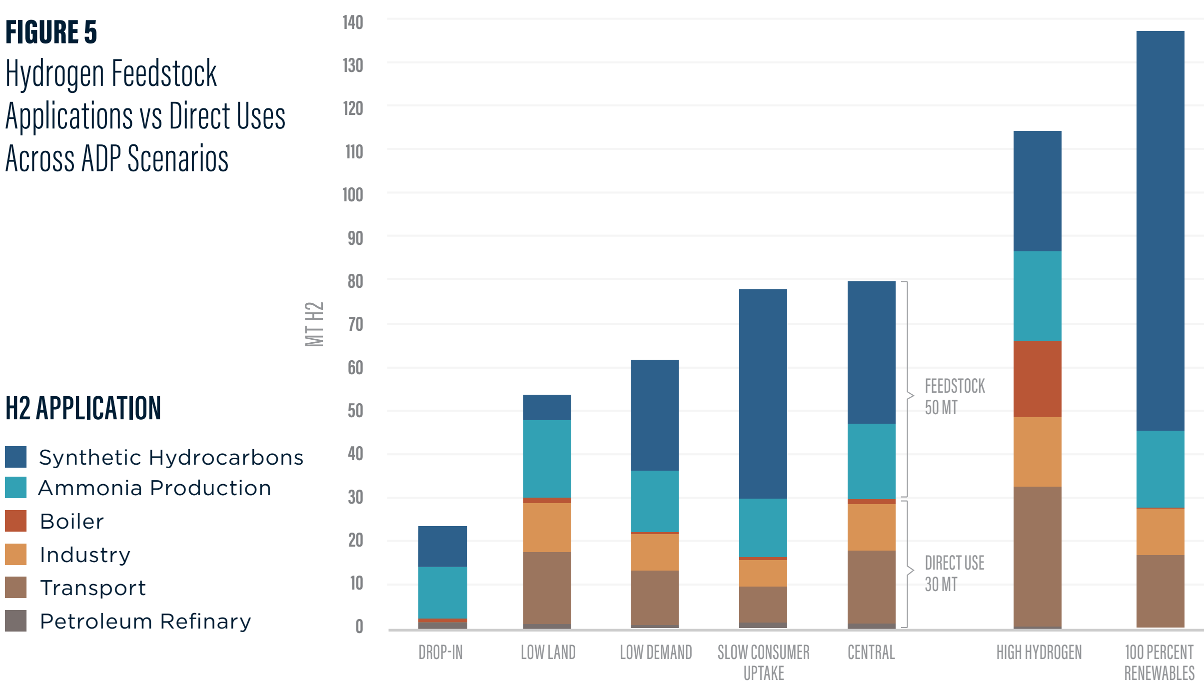


Given these dynamics, the most competitive direct uses are applications that are large-scale, require the precision application of high heat, or do not have a mature electrification competitor. For example, in the direct reduction of iron ore, hydrogen is the reducing agent and cannot be substituted by electricity; iron-ore reduction is also an industrial process done at large scale. (Although there are some potential emerging technologies for processing iron ore without the use of hydrogen, they are not within the scope of this analysis.) Similarly, some trucking fleets benefit from operating around a central hub where hydrogen delivery and storage infrastructure can be concentrated much more effectively than for passenger vehicles, which would require a more distributed (and therefore costly) delivery network.

Across all decarbonization scenarios, feedstock applications account for the majority of hydrogen use, reaching a volume of 50 Mt by 2050 in the Central scenario (65% of hydrogen production). The cost of feedstock applications is driven primarily by hydrogen production costs. Synthetic hydrocarbons used in the production of bulk chemicals and sustainable aviation fuel, and ammonia used in the production of fertilizer and shipping fuel, constitute the largest shares of hydrogen feedstock applications. These applications can have significantly lower overall energy efficiencies than direct hydrogen use (and even lower efficiency as compared to direct electrification) but also represent lower-cost opportunities for storage and delivery of energy (especially considering the highest quality renewables in the U.S. tend to be located far away from the final consumer of electricity or direct hydrogen) and can be competitive in niche applications.

FIGURE 5

Hydrogen Feedstock Applications vs Direct Uses Across ADP Scenarios

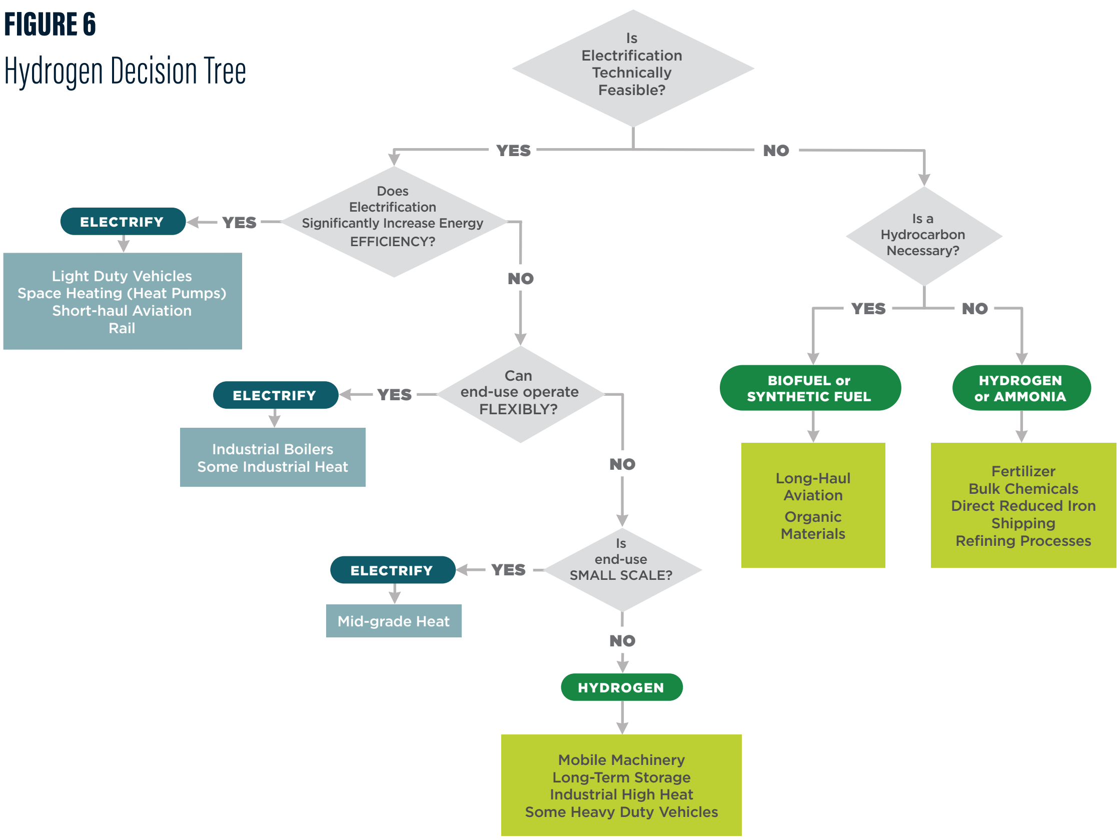


HYDROGEN DECISION TREE

While hydrogen plays an important role in every decarbonization scenario, its competitiveness against other fuels strategies or direct electrification varies significantly across applications and is highly dependent on several uncertain variables. It is essential for policymakers, regulators, and private companies to assess proposed hydrogen use-cases carefully as the competitive landscape changes in the coming years to ensure the energy transition proceeds in a cost-effective and sensible manner. We have distilled the results of our modeling into a decision-making framework to support the conceptual understanding of where hydrogen should be utilized in a decarbonized economy.

FIGURE 6

Hydrogen Decision Tree



These are not absolute edicts but represent a general guide within the context of a decarbonization pathway and support intuition around the logic behind hydrogen's deployment. The following questions represent major branches in the hydrogen decision tree:

- Technical feasibility of electrification — where electrification is possible, it is more than likely preferable. Some end-uses, due to their technical requirements, do not have currently feasible electrification solutions.
- End-use flexibility — In areas where electrification is technically feasible, flexibility can increase its economic preferability. The ability to operate an end-use flexibly can help lower the average cost of delivered energy if time differentiated rates for electricity are seen by the customer.
- Need for a hydrocarbon — Where electrification isn't technically feasible, the key question is whether a hydrocarbon is necessary. Where it is, the production of cost of the synthetic fuel goes up significantly (due to the cost of captured carbon or the opportunity cost of otherwise injecting it underground).

Hydrogen's role is often debated between unrestrained advocates and intransigent detractors. In our view, hydrogen has a critical role in a decarbonized economy, but uncertainty still remains in the breadth and scale of hydrogen use. The scale of that role will ultimately be determined by three key factors:

- technological progress in direct electrification of marginal end-uses (aviation, high-temperature industrial heat, domestic shipping, etc.), which may decrease the need for hydrogen for direct-use or as a feedstock;
- the availability and social acceptance of renewable siting, which, if limited, places even more importance on the superior efficiency of electrification approaches over hydrogen direct-use;
- and the success of the electrification transformation generally, which will require significant consumer participation.

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