Resolving Chicken-and-Egg Challenges to Deliver Net-Zero-America Clean Hydrogen Ambitions

Anthony Y. Ku, Chris Greig, and Eric Larson
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Executive summary

Efforts to decarbonize global energy systems by mid-century are facing a tension between the desire for urgency, and pragmatic challenges posed by the disruption of current business models, constraints on supply chains, policy uncertainty due to geopolitical competition, challenges to social license, and risk-averse private capital markets. Governments around the world are rising to these challenges with policy support in the form of strategic guidance, regulatory mandates, and financial incentives with the intention of spending "billions to unlock trillions in private capital".

Clean hydrogen (H_2) efforts feature in the decarbonization plans of every major economy. H_2 can serve a range of applications, and has the potential to grow in total market size to several times current levels used in the refining and chemicals sectors. In the United States, federal support has coalesced around: (1) funding for regional H_2 hubs; and (2) generous clean H_2 production subsidies. The goal of this two-pronged approach is to usher in a period of rapid ecosystem growth. The hub model offers platforms for early-movers to prove business models, initiate the build-out of supporting infrastructure, and provide a starting point for future scale-up efforts, while subsidies are intended to stimulate enough initial production to drive down long-term costs via learning curves and maturation of the supply chain.

To deliver the desired catalytic effects, two inter-related challenges must be overcome:

- Resolving "chicken-and-egg" decision bottlenecks that currently exist, as well as those that will inevitably emerge as growth accelerates. Mechanisms for coordinated sequencing must be developed within the ecosystem to anticipate and overcome "chicken-and-egg" situations where entities are unable to act on their strategic intent due to commercial uncertainty, misallocated risk, or institutional constraints; and
- Addressing the underlying factors impeding the mobilization of private capital at scale. Private capital, particularly construction debt financing, requires an investment landscape wherein systemic risks are known and understood, especially in emerging clean energy sectors. Open questions related to technology performance, cost trajectories, business models, regulatory and policy stability, supply chains, and access to enabling infrastructure generate hesitancy among investors.

The goal of this study was to develop a deeper understanding of how to facilitate the near-term establishment of a clean H_2 ecosystem in a way that provides a foundation to catalyze rapid, large-scale, longer-term mobilization of private capital. These outcomes are dependent upon decisions undertaken by institutions and individuals. One might assume that a common interest in reaching Net Zero means different members of the ecosystem have a shared and mutual understanding of motivations, opportunities and challenges. In reality, multiple gaps in perception and understanding exist across the value chain as well as within segments.

Our approach involved mapping stakeholders across the clean H_2 ecosystem, their capital discipline processes, their situational awareness, and how their choices are influenced by their roles within the ecosystem. These factors are generally not considered by system-level

technoeconomic modelling and analyses, which tend to compute "optimal" outcomes assuming actors make rational decisions with long horizons and perfect information, and implement them immediately with flawless execution. By exploring these institutional factors, we seek to add a necessary degree of realism to how roadmaps such as those developed by Princeton's Net Zero America project might be implemented in the real world.

Our primary research was conducted in three phases. First, we reverse-engineered the 'capital discipline' process for project development from a fully operational expanded clean energy ecosystem, through the various construction, financing, development activities and investment decision sequences to identify potential decision bottlenecks. Decision bottlenecks occur when interdependent investment decisions must be taken concomitantly by differently stakeholders in the ecosystem, and each hesitates, waiting on the other to move first in a 'chicken-and-egg' situation. Second, a series of semi-structured interviews were conducted with senior-level individuals associated with organizations across the primary H_2 value chain, supporting ecosystem, and investment community. These results were used to collect data from within organizations on practices and perceptions around the challenges associated with their engagement in the clean H_2 landscape. Then, for the third phase, Princeton collaborated with Deloitte to co-host two facilitated one-day workshops with key stakeholders from across the ecosystem to collectively review the results of the interviews, and develop "consensus" views (with nuanced dissent) on near-term barriers to action and the most impactful enablers needed to spur long-term growth. Altogether, over 50 individuals from across the ecosystem were involved in the interviews and workshops. To allow participants to engage freely, all discussions were held under the Chatham House rule which allows use of content as long as it is not attributed to any individual participant.

A detailed accounting of inputs and outcomes from the interviews and both workshops, including specific examples drawn from the experiences of study participants, is included in this report.

The first workshop focused on the barriers to growth. The session opened with an exercise mapping different types of chicken-and-egg situations against the stakeholders involved in each situation. This taxonomy was used to identify and catalogue possible drivers within each theme:

- Business case and Economics – including business model incumbency, cost uncertainty, different expectations on contract terms, confusion around "co-opetition", and low "willingness to pay" for the low carbon intensity attribute;
- Supply chain and Enablers – including poor economics and scalability for equipment manufacturing, and unfavorable social license and economics for supporting infrastructure (e.g. pipelines and storage); and
- Process and Decision-making – including disconnects within incumbent capital discipline and risk management practices, challenges to established competitive and cooperative business arrangements, reluctance by first movers to share learning, uneven enthusiasm and investment in different parts of the ecosystem, and concerns about policy stability.

Workshop attendees were then asked to individually rank drivers in terms of importance and urgency from their perspective, and then reach a consensus view on the top barriers. The top three were:

(1) Willingness of off-takers to pay – focused on the underlying economics of investment decisions. This "barrier" includes not just weak demand signals and low absolute pricing levels, but also uncertainty in the evolution of cost and price trajectories over time, and market maturity and its capacity for price discovery. The consensus view was that this is true not just for primary producers of clean H_2, but also further downstream to primary users of clean H_2 who also require a willingness to pay from their end customers to justify the cost premiums for low carbon intensity;
(2) Risk management practices – as a general principle, organizations aim to push risk onto their counterparties. In uncertain environments, this can lead to impasses where neither party is willing to assume sufficient risk to allow a transaction to move forward. Participants offered examples in both capital investment decisions related to the primary production, distribution, and use of clean H_2, as well as in the broader ecosystem across the supply chain, supporting infrastructure, and financing communities; and
(3) Policy questions – government support in the US has opened a window of opportunity, not just for clean H_2 but also for other clean energy approaches. Participants noted uncertainty around the durability of policy support over the medium term (into the 2030's), its breadth across the ecosystem, and its effects on the balance of power in the ecosystem between well-established incumbent players and new entrants.

These themes are already well-recognized in general terms; however, the discussion uncovered important nuances on how these factors create sticking points in interactions between (and within) organizations at the level of the individual transactions needed to develop a robust and growing ecosystem. This level of resolution is necessary to identify targeted interventions – internal or external – to address the sequencing gaps responsible for most "chicken-and-egg" problems. For longer-term capital mobilization, a key aspect that underlies all three barriers is the effect of uncertainty over relevant decision time horizons. In stable environments, market participants have relatively mature processes to quantify and manage uncertainty in their investment and operating decisions. However, the required speed and scale of the energy transition makes the landscape more volatile, introducing systemic risk which is disrupting traditional risk assessment processes. Risk is less well-understood in environments where technologies, costs, business models, use cases, and competitive landscapes are subject to disruption over time scales much shorter than the economic life of capital investments.

The second workshop focused on identifying the critical enablers considered necessary to catalyze the required rapid, expansive, and sustainable growth of a clean H_2 ecosystem.
To facilitate this exercised, an S-curve framework for growth was introduced, wherein periods of rapid expansion are preceded by an induction period during which the underlying foundations needed to sustain growth are established. Participants were divided into groups tasked with identifying the foundational elements needed to support a period of clean H_2 ecosystem growth at the required speed and scale (x10 in 10-15 years and x100 in 25-30 years); responses were grouped into two categories:

- Elements currently in place – responses centered around early stage projects, including hubs, with an emphasis on exploratory learning from first-of-a-kind projects. The DOE hubs initiative was recognized as a valuable platform to stimulate validation of technologies, clarification of business models, definition of regulatory frameworks,

development of supply chains, and construction of shared infrastructure. All of these elements have already been recognized as necessary for "commercial liftoff".

- Elements needing increased attention – sorting out competitive applications, market-formation enablers, supporting infrastructure, supply chains, project financing models, as well as additional factors such as consistent terminology, convergence on standardized engineering packages, synchronization of growth in supply and demand, increased public acceptance (user education), workforce development, expedited permitting, and evidence of progress in cost reductions through scale and learning curves.

Through the facilitation process, participants converged on three priority outcomes in the current decade that are needed in order to catalyze expansion of clean H_2 production and use by at least an order of magnitude over each of the next two decades: use case clarity; a threshold level of clean hydrogen producers and users transacting in transparent markets; and a sufficient network of supporting infrastructure and equipment supply chains to Important points from the discussion in each area include:

- Use case clarity – the landscape continues to evolve, so the most important outcome needed is to identify markers that indicate whether use cases are "winning" or "losing" rather than focusing on a static assessment by any given group. Expectations from workshop participants, along with indicators for each sector, are included in the report;
- Market formation – there was debate as to whether clean H_2 markets need to reach "merchant" or "spot" market status, or whether alternate models such as well-organized bilateral contracts are sufficient. Participants also flagged a need to establish clarity on clean hydrogen terminology, the validation and valuation of carbon intensity, and whether it is coupled directly to the H_2 molecule or can be traded as a decoupled attribute (akin to the trading of Renewable Electricity Credits in renewable power generation).
- Infrastructure and supply chains – the routing and expansion of pipeline networks for H_2 and CO_2, and whether they would be operated as open-access or private facilities was a key topic. The effect of regional differences in pipeline receptivity, and geology for H_2 and CO_2 storage were flagged as potential drivers for heterogeneity in how clean H_2 markets across the US might develop. Evolution of electricity transmission and allocation of "clean" electrons to support electrolysis facilities were also cited as a foundational piece to support large-scale ecosystem development.

The mobilization of sufficient development and construction capital to sustain a full and growing pipeline of projects at varying levels of maturity across the ecosystem was also identified as a pressing need. The second workshop included increased participation from capital providers, including representative input from venture capital, private equity, industrial balance sheet funding, and institutional and infrastructure finance. Segmentation across investors is important due to differences in motivations, risk appetite and patience, and capacity for large debt financing deals. An important finding from discussions between industrial players and institutional investors is the need to resolve systemic risk in the ecosystem to truly unlock large-scale participation.

Looking across the full range of stakeholder inputs from the study, there was general agreement on many aspects of the current technical and commercial state of the clean H_2 ecosystem, and the immediate and long-term challenges that must be overcome to achieve scale. However, responses from the interviews and discussions during the workshops revealed areas where some stakeholders held divergent views and also had limited situational awareness about the constraints of other stakeholders. While players generally have a clear understanding of their immediate situation and competitors, broader situational awareness is uneven. Even large, connected players do not have a complete picture. Conversely, new entrants were motivated to engage larger and incumbent players, but did not necessarily appreciate the complexity of internal decision-making within the larger companies. Finally, there was evidence of a gap in appreciation of the specific transactional requirements between some industry players and the different types of investors; those directly involved in financing deals were generally aligned, but a common understanding of what it takes to truly "unlock trillions" in private capital is still evolving.

To this end, mechanisms for improving coordination across the ecosystem will be important for addressing both near-term sequencing, and longer-term capital mobilization challenges. Models from other fields may be applicable to clean H_2. For example, quarterbacking organizations within the pharmaceutical industry have played roles in assisting market formation (e.g., by organizing buyer's clubs), engaging in shuttle diplomacy to bridge divides between key players in the ecosystem or the general public, and coordinating supply and demand growth; a similar model is worth considering for clean H_2.

The study initially focused on the chemicals industry in the US, given its dominant role in the production and domestic use of H_2, before expanding the scope to consider other sectors in order to better understand the prospective growth of a broader ecosystem. The US chemicals sector is currently one of the largest domestic consumers of H_2, over 90% of it produced by steam methane reforming. It was well-represented in this study, in both interviews and workshops. On paper, it is well-positioned to lead the adoption of clean H_2 due to its historical experience with producing and using H_2 safely, established business models for both captive and merchant H_2 to mitigate offtake risk, and strong balance sheets and track records of success to ensure adequate capital for projects. With recent government subsidies greatly strengthening the economic case for action, the sector is poised to move in the near-term.

A case study of the chemicals sector is included to illustrate the practical implications of the findings of this study. The case study reviews opportunities for the use of clean H_2 to support decarbonization, including replacement of high carbon intensity H_2 feedstock, but also as a source of industrial heat and power. There is the opportunity for both evolutionary (incremental) change and revolutionary (disruptive) change, and stakeholder perspectives on the barriers to action are presented in the context of chemical sector use cases. Different corporate approaches to prioritizing clean H_2 projects are surveyed, drawing on content from the study and public announcements from the broader chemicals industry. Sector specific "chicken-and-egg" problems are discussed, along with possible targeted interventions drawn from a detailed look at the underlying drivers. Capital allocation is also discussed, with a particular focus on the transition period where legacy assets face a decision for stranding versus upgrading.

Although the primary focus of this study was on the clean H_2 market in the US, our findings could also have relevance to clean energy development beyond H_2 and beyond the US. Acting on the key lesson from this work – the need for a high-resolution appreciation for institutional decision-making, as a complement to efforts in the technical, commercial and policy arenas – will be essential to unlock the capital needed to advance the energy transition at the speed and scale anticipated in mid-century net-zero scenarios.

Acknowledgments

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Acronyms

CCS	CO_2 Capture and Storage
CCUS	CO_2 Capture, Utilization, and Storage
CI	Carbon intensity
DOE	US Department of Energy
EFI	Energy Futures Initiative
FEED	Front-End Engineering Design
FID	Final Investment Decision
HDV	Heavy duty vehicle
IGC	Industrial gas company
IIJA	Infrastructure Investment and Jobs Act
IRA	Inflation Reduction Act
ITC	Investment Tax Credit
MDV	Medium duty vehicle
O&G	Oil and gas
OEM	Original equipment manufacturer
PPA	Power Production Agreement
PTC	Production Tax Credit
REC	Renewable Energy Credit
NGO	Non-government organization
NZA	Net Zero America
45Q	US PTC for CCS and CCUS
45V	US PTC for clean H_2
45Y	US PTC for clean electricity generation
48	US ITC for clean energy equipment

1. Introduction

Princeton University's Net Zero America (NZA) study used high-resolution technoeconomic and social impacts analyses to show pathways for fully decarbonizing the United States economy by 2050 [1]. Several possible paths were identified, all of which require an unprecedented pace and scale of commitment of infrastructure deployment, capital allocation, and political will across government, industry, and the financial sector.

In practical terms, a tension exists between the desire for urgency and the pragmatic challenges posed by the disruption of current business models, constraints on supply chains, policy uncertainty due to geopolitical competition, challenges to social license, and risk-averse private capital markets [2-5]. These challenges are especially acute for nascent yet-to-scale technologies like clean fuels, CO_2 capture and storage (CCS), and decarbonized heavy industry. One might assume that a common interest in reaching Net Zero means different members of the ecosystem have a shared and mutual understanding of motivations, opportunities and challenges. In reality there are multiple gaps in perception and understanding within and across value chains. Governments around the world are rising to these challenges with policy support in the form of strategic guidance, regulatory mandates, and financial incentives with the intention of spending "billions to unlock trillions in private capital" [6].

A significant clean hydrogen (H_2) economy features in the decarbonization plans of every major economy. H_2 can serve a range of applications, and has the potential to grow in total market size by several times the current levels used in the refining and chemicals sectors [1,7]. In the United States, federal support has coalesced around: (1) funding for regional H_2 hubs and (2) generous clean H_2 production subsidies [8]. The hub model offers platforms for early-movers to prove business models, initiate the build-out of supporting infrastructure, and provide a starting point for future scale-up efforts [9]. Production subsidies can offset the near-term marginal costs of producing clean H_2, to help stimulate market growth to the scales needed to deliver the cost reductions necessary for long-term affordability. These measures are generating a significant pipeline of project announcements, but it remains to be seen how many announcements will reach final investment decisions (FID) and become successful completed projects. Furthermore, it is unclear whether the measures will fully unlock the required private capital and capabilities needed to catalyze the rapid expansion of a clean H_2 ecosystem in the 2030s and beyond.

To deliver the desired catalytic effects, two inter-related challenges must be overcome:

- Resolving "chicken-and-egg" issues that currently exist, as well as those that will emerge as growth accelerates. Mechanisms for coordinated sequencing must be developed within the ecosystem to overcome standoffs where independent entities are unable to act on their strategic intent due to commercial uncertainty, misallocated risk, or institutional constraints; and
- Addressing the underlying factors impeding the mobilization of private capital at scale. Private capital, particularly construction (debt) financing, requires an investment landscape wherein systemic risks are known and understood. In emerging areas of clean energy, open questions related to the technology performance, future cost trajectories,

business models, regulatory and policy stability, supply chains, and access to enabling infrastructure can cause investors to hesitate.

Financial incentives offered by the government can tip the economics of clean H_2, and have stimulated a wave of project announcements. This is a positive development, but many of these projects have not taken final investment decisions (FID) that signal the commitment to build. Continued progress ultimately depends on choices by decision-makers within organizations across the ecosystem. As such, it is necessary to understand both the motivations of, and constraints on, individual players across the ecosystem, and how decision processes can interact, at a deeper level, to devise effective mechanisms to overcome "chicken-and-egg" bottlenecks, and unlock capital.

Thus, the goal of this study was to develop a deeper understanding of how to accelerate growth of a clean H_2 ecosystem in the near-term through debottlenecking of "chicken-and-egg" challenges, and over the longer-term through the effective mobilization of private capital.

Our approach involved mapping stakeholders across the clean H_2 ecosystem, their capital discipline processes, their situational awareness, and how their choices are influenced by their roles within the ecosystem. These factors are generally not considered by system-level technoeconomic analyses, which tend to compute "optimal" outcomes assuming actors make rational decisions with long horizons and perfect information, and implement them immediately with flawless execution. While previous studies have touched upon various aspects of institutional decision-making and collaboration in achieving commercial liftoff, stimulating, and advancing the clean H_2 ecosystem [7,9,10], there has not been a systematic look at how *interactions* between ecosystem stakeholders (pairwise and collectively) can hinder or accelerate progress in project execution or impact the retirement of systemic risk to mobilize private capital mobilization. By exploring these institutional factors, we seek to add a necessary degree of realism to how roadmaps such as those developed by the NZA study might be implemented in the real world.

Our primary research was conducted in three phases. First, we reverse-engineered the 'capital discipline' process for project development from a fully operational expanded clean energy ecosystem, through the various construction, financing, development activities and investment decision sequences to identify potential decision bottlenecks. Decision bottlenecks occur when interdependent investment decisions must be taken concomitantly by differently stakeholders in the ecosystem, and each hesitates, waiting on the other to move first in a 'chicken-and-egg' situation. Second, a series of semi-structured interviews were conducted with senior-level individuals associated with organizations across the primary H_2 value chain, supporting ecosystem, and investment community. These results were used to collect data from within organizations on practices and perceptions around the challenges associated with their engagement in the clean H_2 landscape. During the third phase, Princeton collaborated with Deloitte to co-host two facilitated one-day workshops with key stakeholders from across the ecosystem to collectively review the results of the interviews, and develop "consensus" views (with nuanced dissent) on near-term barriers to action and the most impactful enablers needed to spur long-term growth. Altogether, over 50 individuals from across the ecosystem were

involved in the interviews and workshops. To allow participants to engage freely, all discussions were held under Chatham House rule which allows use of content as long as it is not attributed to any individual participant.

The study initially focused on the chemicals industry in the US, given its dominant role in the production and domestic use of H_2. The scope was expanded during the study to consider other sectors in order to better understand the prospective growth of a broader ecosystem.

This report is organized as follows:

- *Background and context* provides information concerning the clean H2 ecosystem, technology adoption trajectories, capital discipline processes, and federal incentives for clean H2 in the US.
- *Barriers* reports the findings from the reverse engineering exercise, stakeholder interviews and Workshop 1 around barriers to growth. This includes a discussion of different types of "chicken-and-egg" problems in clean H_2, the underlying drivers, and consensus views that emerged during Workshop discussions on the impediments to action.
- *Enablers* reports findings from the interviews and Workshop 2 around enablers to unlock rapid, expansive, and sustainable growth of a clean H_2 ecosystem, with an emphasis on elements that need to be put in place in the near-term to sustain long-term growth. The section reports consensus views that emerged during the Workshop discussions. It also includes independent analysis by the authors on how to leverage clean H_2 hubs to accelerate the development of several foundational elements.
- *Case study* illustrates the practical implications of the findings of this study by reviewing opportunities for the use of clean H_2 to support decarbonization in the US domestic chemical sector, stakeholder perspectives on barriers to action specific to the sector, and special considerations related to capital assets.
- *Conclusions*
- *Appendices* that summarize interviews with hydrogen ecosystem and private capital stakeholders and provide supporting data and analysis for use cases and examples used during the study.

2. Background and context

2.1. Expectations on the scale and breadth of a future clean H_2 ecosystem

Clean H_2 has the potential to play a role in several sectors of a decarbonized economy. The complexity of the energy transition means that it is not possible to know with certainty at this point, the exact path that a clean H_2 ecosystem will take, but there are a number of studies that provide guidance on possible trajectories consistent with a 2050 Net Zero target. The results of these studies can be used to calibrate expectations on the type, number, and scale of projects at various points in time, and also serve as a reference point to inform efforts to develop policy and interventions consistent with long-term decarbonization goals.

Figure 1 shows possible growth curves for clean H_2 production and consumption under the NZA "E+" scenario.* In this pathway, production shifts from primarily high carbon intensity (CI) "grey H_2" in 2020, towards a mix of low CI H_2 produced by either reforming of natural gas with CCS ("blue H_2"), electrolysis powered by zero-carbon electricity ("green H_2"), or gasification of biomass with CCS ("emerald H_2). On the use side, demand is initially dominated by the bulk chemicals sector, with the emergence of H_2 use in transportation (for medium-, and heavy-duty vehicles) in the mid-term, and a host of end uses by 2050. In the E+ scenario, the total market grows from about 1 EJ (10 Mtpa) in 2020 to over 8 EJ (80 Mtpa) in 2050.

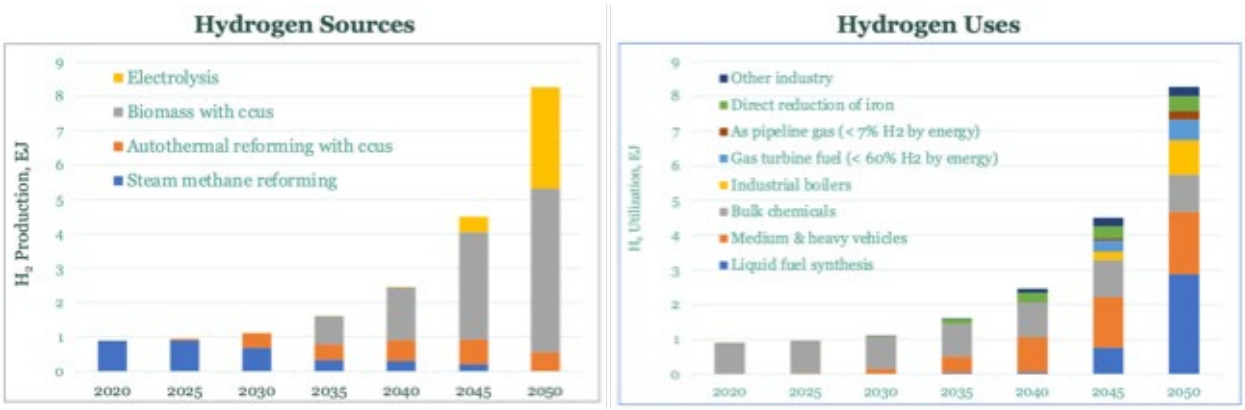

Figure 1. Growth of H_2 production and consumption under the NZA E+ scenario. Expansion in quantity and modes of H_2 production (left) and use (right) consistent with Net Zero by 2050 E+ pathway. There is a ramp-up of CCUS based production through the 2030's (including negative emissions production associated with biomass feedstock combined with CCUS) and rapid growth of electrolysis-based production in the late 2040s. Demand for H_2 for medium and heavy duty ground transport emerges starting in the 2030s, with additional applications entering in the 2040s. Source: [1].

* The NZA E+ scenario assumes aggressive end-use electrification, but energy-supply options for minimizing total energy system cost while meeting the goal of net-zero emissions in 2050 are relatively unconstrained. See [1].

2.2. Taxonomy of a clean H_2 ecosystem

A core hypothesis of this study is that interactions between stakeholders – both across and within organizations - is an important factor in enabling and sustaining growth of the clean H_2 ecosystem. As such, it is valuable to begin with a taxonomy of the overall landscape.

Figure 2 is a graphical representation of different "lanes" that exist across the H_2 landscape, with an emphasis on the chemical and industrial sectors. The horizonal arrows represent different niches in the primary value chain, with each lane depicting a particular sub-segment along production, distribution, and use of H_2 and its derivative products. The vertical bars on the left show the extended ecosystem. This includes supporting elements such as the supply chains for equipment, engineering, and construction) and finance providers. The left-most lane represents government (at multiple levels) and non-profit entities, including academia and non-government organizations (NGOs).

Within each lane, there exist multiple organizations, with specific motivations and constraints. Moreover, individual organizations are rarely monolithic, and different functions within an organization can have competing objectives.

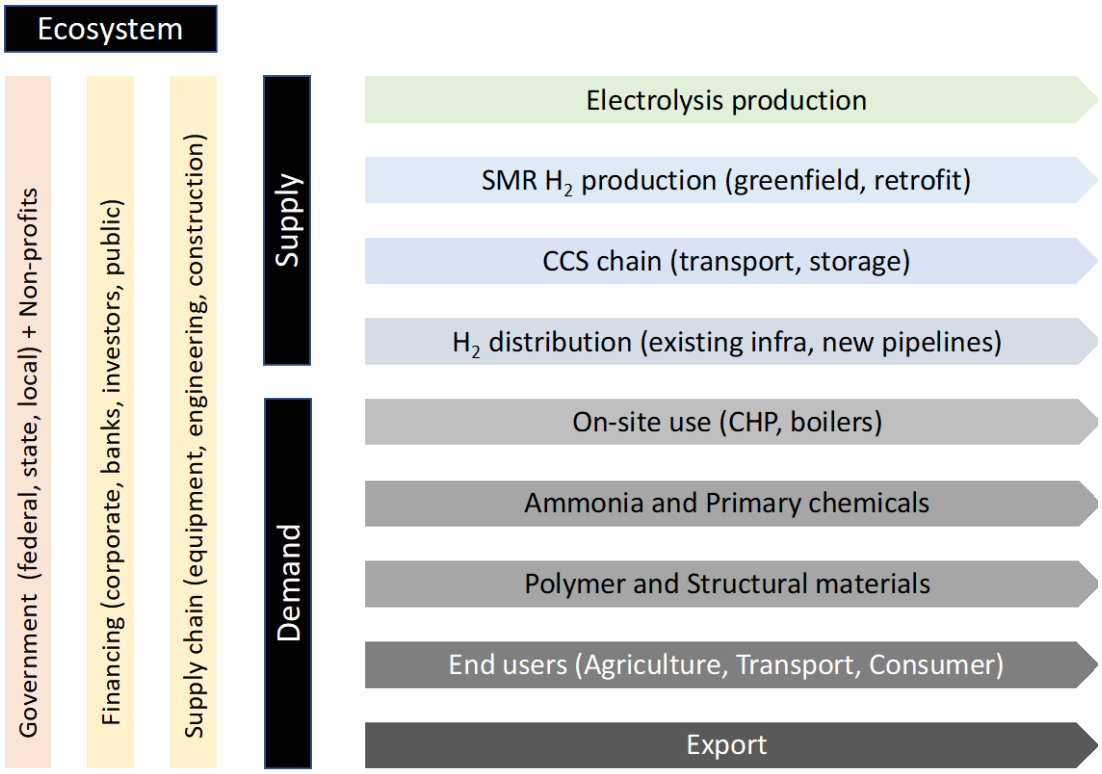

Figure 2. Taxonomy of a clean H_2 ecosystem. Different lanes exist across the value chain and supporting ecosystem. Each lane includes multiple organizations, and their interactions are an important factor determining the pace of progress.

The following are notable observations concerning the different lanes:

- Electrolysis
  - This is an emerging niche. There are a range of players developing electrolysis projects, from established energy companies to new entrants that focus both on equipment manufacturing and deployment of (modular) systems for production.
- SMR H_2 production
  - This represents the incumbent mode of H_2 production, with low CI possible through retrofitting of CCS. This lane includes large energy or industrial companies with the capacity to build and operate SMR facilities. In these organizations, operations groups have incumbent experience and expectations in H_2 production, while CCS teams may be tasked with retrofitting or designing greenfield installations with different parameters.
- CCS chain
  - For production with CCS, it is necessary to transport and store the captured CO_2. Players in this lane include oil and gas (O&G), midstream, specialist companies that operate pipelines, and injection operators that geologically sequester CO_2. Various companies in this lane have the capacity for vertical integration, but the actual decision to do so can vary on the circumstances around specific projects.
- H_2 distribution
  - Distribution involves storage and delivery of H_2 product. This includes delivery by pipeline, as well as by gas and liquid trucking. On-site production and storage is also an option. Industrial gas companies (IGCs) are key players, as well as O&G companies.
- On-site use for energy
  - This lane is highlighted separately because it includes emerging uses, such as the repowering of industrial boilers or combined heat and power (CHP) units to burn H_2. This represents an important option in decarbonizing the chemical sector, since about a third of chemical sector CO_2 emissions are associated with cogeneration.
- Ammonia and Primary chemicals
  - Low CI H_2 could allow decarbonization of ammonia production. In addition, there are opportunities in methanol production and other feedstocks. Large chemical companies are the primary players in this lane.
- Polymers and Structural materials
  - Within the chemicals sector, low CI H_2 feedstocks may offer paths to reducing the CI of polymer supply chains.
  - More broadly, low CI H_2 is considered a candidate for decarbonization of steel and other metals production.
- End users
  - End users may not directly recognize the role of low CI H_2 in the final products they buy. This introduces questions about the possibility of disconnects in the "willingness to pay" that are explored in this study.
    - Agricultural uses refer to ammonia-derived fertilizers, and the companies that produce and use them.

        - H_2 for transportation is a use case receiving considerable attention, particularly for MDV and HDV applications It also includes the use of H_2 as a fuel for transportation, although participation from vehicle OEMs and the fuel cell vehicle value chain was limited in this study due to a primary focus on the chemical and industrial sectors.
        - Consumer products include downstream chemical products that utilize primary chemicals, polymers, and structural materials.
- Export
    - Energy trade via H_2 or H_2 carriers, including ammonia. Coupling of the US market to international markets seeking to import energy is a component of the growth strategy for some multinational energy companies.
- Supply chain
    - Equipment suppliers, including but not limited to electrolyzers, fuel cells, H_2 capable burners, safety components and other equipment needed to implement the various applications. In situations where demand for equipment is growing strongly, the ability to stand up manufacturing capacity can be limiting.
    - Engineering and construction companies provide services necessary for the construction of facilities across the ecosystem. For large and/or large numbers of projects, the capacity of engineering, procurement, and construction (EPC) companies may be limiting due to availability of human capacity.
- Financing
    - Capital is needed to finance the construction of assets for production, distribution and use. There are different types of capital investors, as discussed in Section 2.4.
- Government and Non-profits
    - Government stakeholders exist at the federal, state, and local level with differing and interlocking areas of jurisdiction. Oft-cited concerns about permitting and regulatory oversight can include stakeholders at all three levels.
    - Non-profits such as universities and NGOs can work on issues such as strategic road-mapping, market development, community engagement and societal impacts, and stakeholder coordination.

2.3. Technology adoption trajectories

The evolution of systems is often described by an “S-curve”, wherein periods of rapid expansion are preceded by an induction period during which the underlying foundations needed to sustain growth are established [11]. Figure 3 is a potential S-curve trajectory for expansion of a clean H_2 ecosystem in the US. This framework was used to support a discussion of Enablers during the second workshop.

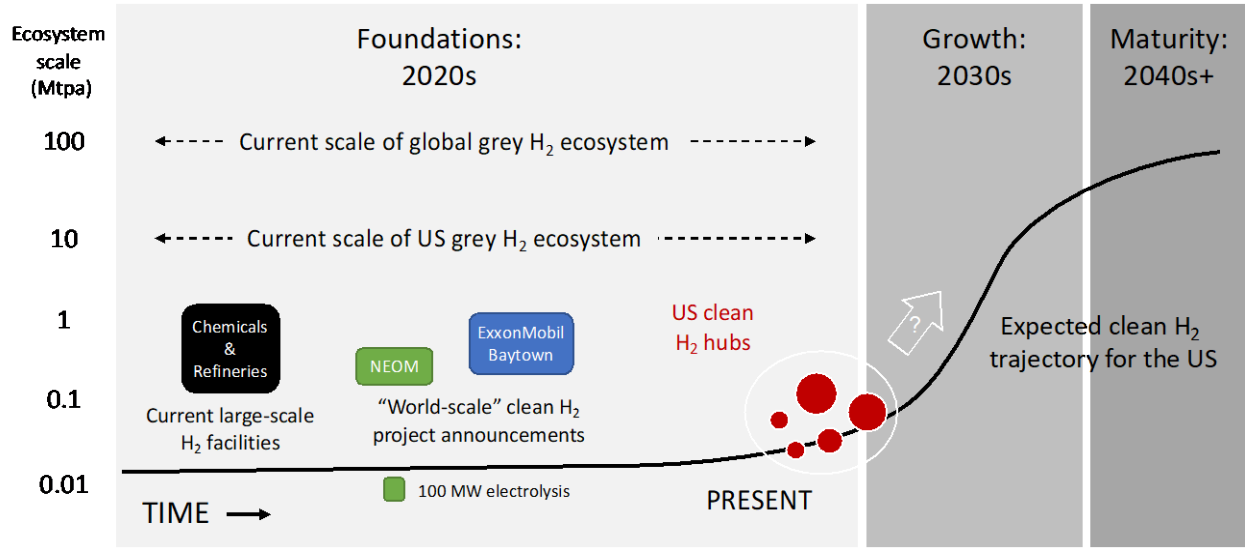

Figure 3. Potential S-curve trajectory for establishing a clean H_2 ecosystem in the US by 2050. Note: The that the vertical and horizontal scales in the above graphic are logarithmic. development of the clean H_2 ecosystem is expected to follow an S-curve trajectory and progress through three stages: a Foundations stage, during which key elements to support the ecosystem are established; a Growth stage with rapid scale-up; a Maturity stage where ecosystem size stabilizes. The current scales of the US and global grey H_2 ecosystems are shown (black dotted lines), along with the representative size ranges for projects and facilities. Conventional high-CI SMR facilities (400 to 2400 tpd; 0.15 to 0.88 Mtpa) are shown in black, and an announced "world-scale" SMR with CCS project for "blue H_2" in blue. The green boxes represent the approximate production for a 100 MW electrolysis ("green H_2") facility at utilization factors ranging from 30 to 100% (15 to 45 tpd; 5 to 16 kpta) and an announced "world scale" (NEOM) project [12,13]. The red bubbles show the potential sizes of clean H_2 hubs within the US DOE IIJA portfolio, ranging from a minimum of 50 to 100 tpd (19 to 37 ktpa). US DOE targets for clean H_2 market size are 10 Mtpa and 50 Mtpa by 2030 and 2050, respectively.

2.4. Capital discipline

Capital discipline processes exist to support capital investment decisions to ensure risks are understood and mitigated to an acceptable level. In organizations that routinely deploy capital for infrastructure assets, the process includes multiple steps beginning with a definition and evaluation process and progressing through approval, construction, operation, and decommissioning (Figure 4). Capital discipline ensures there is a progression wherein capital allocation and risk are matched throughout the development lifecycle of an asset, and specific gates are used to ensure a rigorous decision process. The different classes of capital – development, project finance, institutional equity, corporate debt, and public – have different objectives, expectations on returns, risk appetites, and time horizons. Specific investors may also exhibit variations within a range in each class.

Each step in the process serves a specific purpose in managing risk:

- Definition and Evaluation
    - During this period, relatively small amounts of capital are progressively deployed in increasing amounts to quantify and reduce risk. This includes a staged process for project design (e.g., scoping, pre-FEED, and FEED), building the business case (e.g., prefeasibility and feasibility studies), and gaining stakeholder acceptance (e.g. through initial engagement, impact assessments and establishing conditions for contracts with counterparties and permits).
    - In an emerging landscape, systemic risk factors related to technology validation, clarification of business models, and regulatory uncertainty can also exist.
    - This stage is almost exclusively supported by development capital, typically developer balance sheet equity, but can also attract support from venture capital, private equity, and government grants in emerging sectors.
    - Projects can spend variable amounts of time during this stage before a decision is made to advance or discontinue the effort.
- Approval and Funding
    - During this stage, the project secures binding contractual agreements and other requirements to support operations (e.g., site control, infrastructure access, offtake agreements, and permitting).
    - This stage is also typically supported by development capital, with the time frames having more urgency as the risk decreases. Project (debt) finance, and potentially institutional equity will typically be secured at this stage to complement the developer's equity in closing the required total investment capital and thereby reach FID.
    - FID marks the point at which construction capital is committed.
- Construction and Start-up
    - This stage marks the deployment of significant sums of capital to support construction of the project.
    - The quantum and timeline and for the allocation of capital are well defined to support execution but nonetheless retain a level of uncertainty and are at risk until completion.
- Commercial Operations
    - During commercial operation, the asset generates revenue to cover operational expenses, pay back debt and generate financial return on the project.
- Closure and Remediation
    - At the end of life, the project Is decommissioned and debt is fully retired.

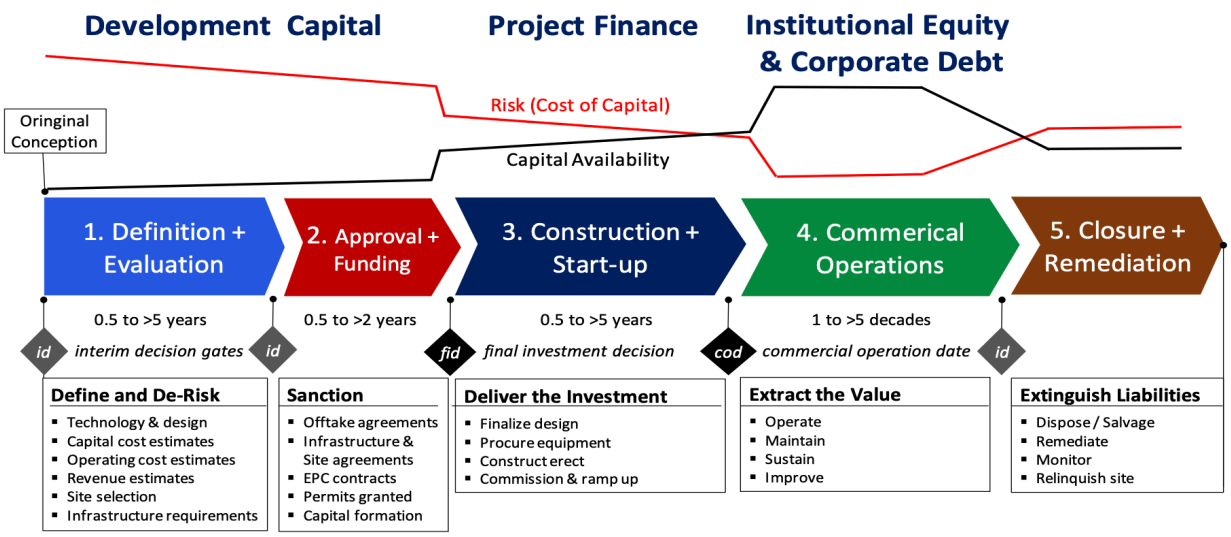

Figure 4. Capital discipline for physical assets. The deployment of capital for infrastructure assets follows a process to align resources to risk. Source: [5].

2.5. Federal incentives for clean H_2 in the US

The clean H_2 ecosystem is enabled by technology, but the current wave of activity is driven primarily by policy. Figure 5 summarizes the financial incentives available to clean H_2 projects in the US via tax credits (for any qualifying project, from the Inflation Reduction Act, IRA), and direct financial support on a competitive basis (with $8B authorized by the IIJA for up to 50% cost sharing for winning clean H_2 hub bids) [6,8]. Incentive strategies can target tax credits at various points in the value chain, with some statutory restrictions on stacking [6]. Most of these credits can be claimed for 10 years, and qualifying projects must commence operation by the end of 2032 to begin receiving credits. The 45V production tax credit (PTC), requires a lifecycle carbon intensity (CI) of the H_2 product of <0.4 $CO_{2,eq}$/kg H_2 to qualify for the full $3/kg credit. Projects not able to meet this standard can claim a partial credit or pursue other incentives. Projects that are part of hubs selected for IIJA funding are also eligible for IRA incentives, significantly lowering the economic barrier to early action.

The cumulative total of IRA tax credits earned is not capped, and if the clean H_2 markets grow at the rate envisioned by the DOE, the cost of these subsidies may become very significant within the eligibility period established by the IRA. Figure 4 shows the annual production of clean H_2 implied by the budget assumptions used during debate of the IRA. The projected annual claims for 45V, developed by the Congressional Research Service [14], are listed at the top of the figure. The bars represent the annual production consistent with the estimated budget costs, assuming a $3/kg rate. Over the full 2023-2031 period covered by the projection, the estimated total cost of $13.2B would cover a total of 4.4M tH_2, with production of 1.2M tpa in 2031. Since the 45V is a tax credit available to all qualified claimants, the true budget impact will depend on how fast the clean H_2 market actually grows. If the market takes off and, for example, achieves the US Department of Energy (DOE) target of 10 Mtpa by 2030, the budget impacts could be an order of magnitude, or more, larger than expected upon passage of the IRA. Conversely, a dearth of

eligible projects or legislative updates curtailing the credit would reduce the cumulative cost of the incentive, and while some early adopters may make money from demonstrations, the market could fail to catalyze the required flows of private capital.

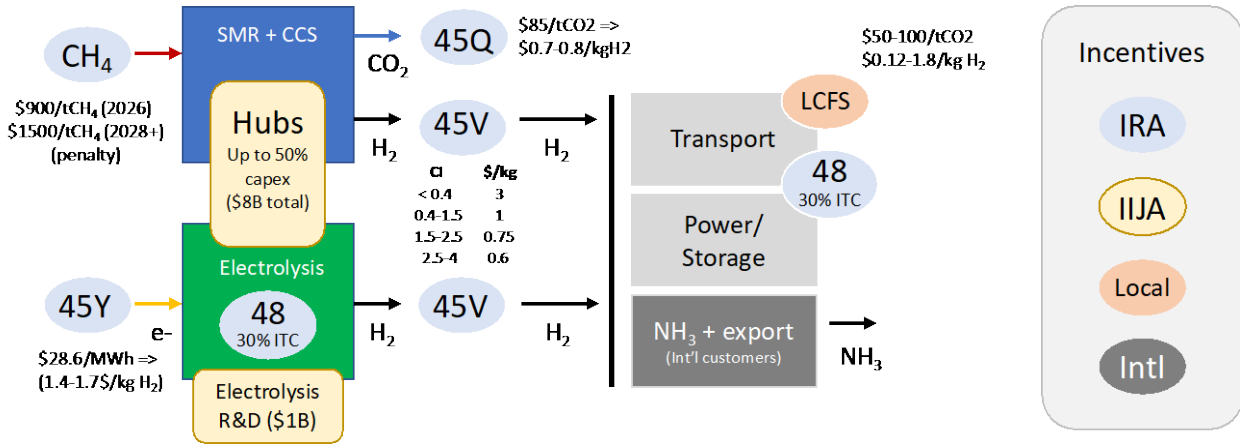

Figure 5. US incentives around the H_2 value chain. Map of the clean H_2 value chain showing incentives available for methane abatement (avoidance of penalty), clean electricity (45Y PTC, 10 yrs), CCS (45Q PTC, 12 yrs), clean H_2 (45V PTC, 10 yrs, indexed to CI), investment tax credits (ITC) for clean energy equipment including electrolyzers and energy storage (48), grant money for clean H_2 hubs and electrolyzer research and development (IIJA), local incentives for clean transportation fuels (LCFS markets in California and other states), and international incentives for clean energy trade (such as price premiums offered by European or Japanese end users).

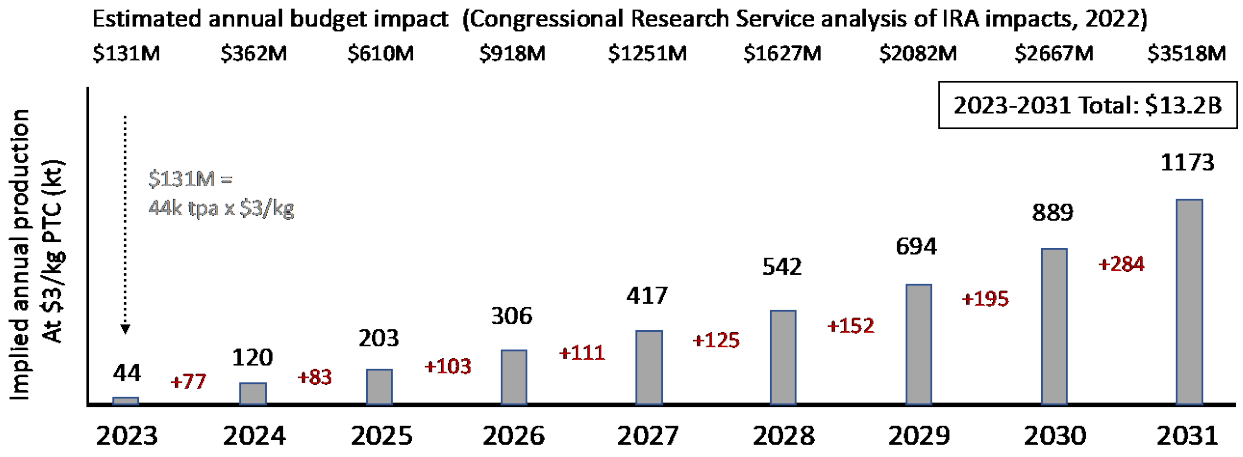

Figure 6. Implied annual clean H_2 production covered by 45V under IRA budgetary assumptions. The annual production of clean H_2 that can be covered each year was computed by dividing the annual budget impact (as estimated by the Congressional Research Service in its 2022 analysis of the IRA [6]) by a 45V PTC rate of $3/kg. The annual increase in production is shown in red. Note: There is no cap on the budget impact of 45V.

2.6. Global perspective

The primary focus of this study is on the US market, but clean H_2 ecosystems are developing in China, Europe, and other parts of the world [15-17]. There are two notable connections to the global landscape that warrant attention:

- Generous incentives in the US have been a gamechanger in stimulating project interest, as well as prompting discussion within the European Union, China and elsewhere, about how to level the playing field. There are concerns that the US IRA incentives have sparked a 'race to the bottom' in protectionist subsidies with the EU and China that could ultimately result in market distortions, fragmented supply chains, and long-term unaffordability. The trajectory over the next decade remains unclear, with governments trying to balance growth of clean H_2 markets against geostrategic interests.
- Integration of these ecosystems through energy trading using some form of H_2 as a carrier (for which there is already a pipeline of projects under development), the development of global supply chains for equipment, and private capital flows seeking attractive returns could provide benefits across borders.

3. Barriers to growing at scale and speed

Sustained, rapid growth at the ecosystem level depends not only on the cumulative successful execution of projects across the value chain, but also the creation of supporting capabilities and removal of technical, commercial, regulatory, and institutional barriers. This section reports our findings concerning these barriers, including underlying drivers of "chicken-and-egg" problems and other sequencing challenges identified during Workshop discussions and consensus views from the discussions on the major impediments to action.

3.1. Workshop structure

The project team collaborated with Deloitte to host a one-day facilitated Workshop on November 26, 2022 in Houston, TX. The event featured a series of interactive discussions around the theme: "*How can we rapidly evolve a large clean H_2 economy?*" Participants were exposed to various aspects of this question and encouraged to share and debate their various perspectives on the factors that make progress difficult in their specific roles and organizations, as well as at the level of the overall ecosystem. Where possible, the participants were also asked to reach consensus views on priorities, with an emphasis on identifying gaps within and between their organizations.

Content for the Workshop was developed from over 40 one-hour private interviews conducted by the authors with senior-level personnel in organizations up and down clean H2 value chains. These were supplemented by independent analysis of the public literature and calculations by the authors. Discussions were framed around "reverse-engineering 'capital discipline' process for project development to understand the various construction, financing, development activities and investment decision sequences to identify potential decision bottlenecks to reach a fully operational expanded clean energy ecosystem. The Workshop had a total of 29 participants, including 13 people who had participated in the stakeholder interviews and 4 facilitators.

This section presents a synthesis of the Workshop outcomes. Additional content generated by the Workshop is included in Appendix A.

3.2. Summary of "Chicken-and-egg" problems and other sequencing challenges

A range of "chicken-and-egg" problems and sequencing challenges (e.g., incentive to delay) were identified during the course of this research (Figure 7). These can not only delay the FID milestone, but can even cause investors to hesitate allocating capital to pre-FID studies and associated activities:

- **Offtake contracts.** Producers need offtake agreements to support expansion of capacity, while consumers require surety of supply at competitive prices from a reasonable term to commit to offtake.
- **Cost trajectory uncertainty.** The relative cost competitiveness of H_2 generated from "blue" vs "green" projects is expected to change over time as technologies evolve, but uncertainty in cost evolution, especially for electrolysis, creates an incentive for offtakers to wait to see how fast costs decrease.

- **Uncertainty related to government policy.** Government subsidies are essential to the business case of many announced projects. Eligibility rules for some subsidies are still to be finalized, creating uncertainty as to whether a specific project will qualify.

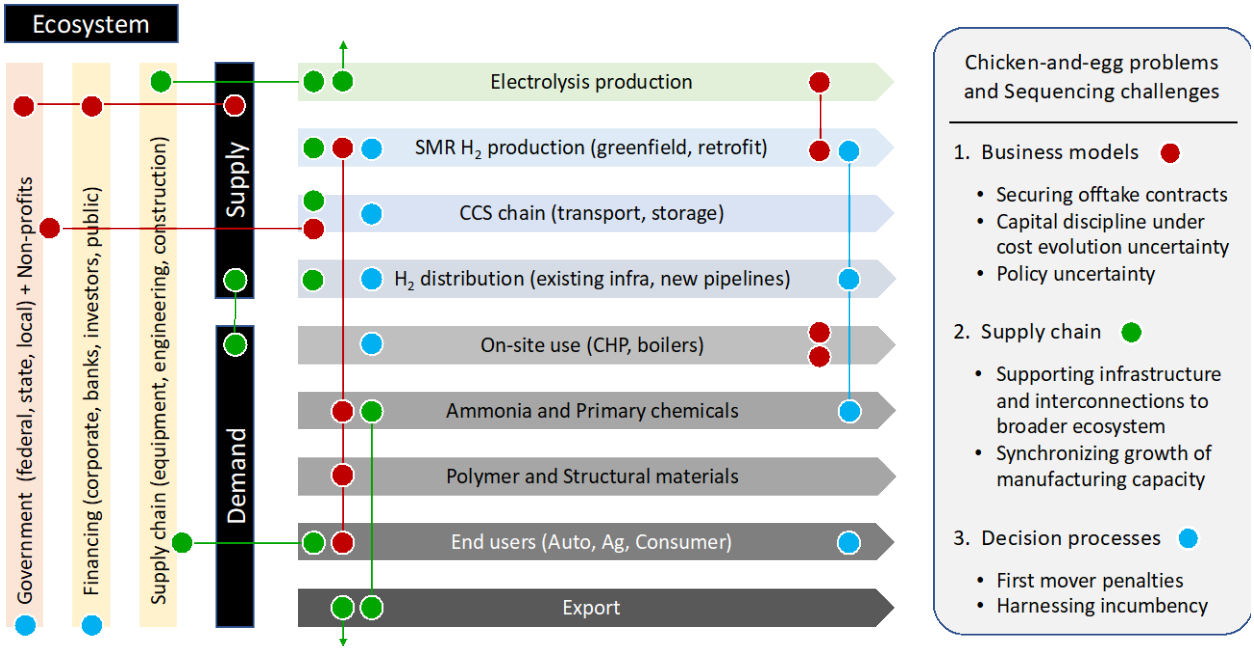

Figure 7. "Chicken-and-egg" problems and other sequencing challenges across the emerging clean H_2 ecosystem.

- **Connectivity to broader ecosystem.** Competition for "clean electrons" for electrolysis versus other uses across the broader ecosystem has raised questions of "additionality" requirements that add technical and financial complexity to "green" H_2 projects. Export of energy (as H_2 or NH_3) would impose importer requirements on carbon intensity that would need to be considered.
- **Distribution infrastructure.** CO_2 pipeline projects require sufficient commitment from producers, and CO_2 capture projects require pipelines for offtake. CO_2 pipeline capacity is often sized to accommodate offtake from multiple capture projects, so midstream developers will need to coordinate commitments from multiple CO_2 (capture) sources.
- **Manufacturing capacity.** Equipment manufacturers need assurance of demand to invest in manufacturing capacity, but demand for equipment depends on availability of equipment in the market. Electrolysis project announcements exceed electrolyzer manufacturing capacity announcements. New entrant manufacturers have greater counterparty risk due to less mature businesses and weaker balance sheets, and this can slow progress on individual projects as some developers choose to wait for established manufacturers.
- **First mover penalty.** Early adopters bear the risk of defining workable business models and creating supporting infrastructure, in addition to technology cost premiums. Since later adopters get to benefit from this learning and activity, there is an incentive to wait and allow others to go first.

- **Incumbency.** Established players have a base of experience and financial strength to draw upon, but may be constrained by traditional processes or existing business models. New entrants can be more disruptive, but could have less resources to support their execution. Established players have existing commercial relationships and this may impede the ability of new entrants to gain traction.

3.3. Workshop results: Barriers and Underlying drivers

At their root, "chicken-and-egg" issues are a problem of sequencing and coordination. However, the details concerning the players, their motivations, and the contexts are relevant when trying to understand how the stand-offs developed, and, even more importantly, how to unlock them. The Workshop began with an activity to gain insight into the barriers and their underlying drivers. Participants were asked to identify specific impediments to progress in three areas:

- Business case and Economics
- Supply chain and Enablers
- Process and Decision-making

These themes emerged during stakeholder interviews. The first two have been the subject of other studies and reports on "commercial liftoff", "demand" and market formation [7,9,10,18,19]. Aspects of the third have been discussed in the context of the other themes, but we considered institutional factors a separate topic worthy of specific attention in this Workshop.

Figures 8 to 10 show raw inputs generated by workshop participants across the above three themes. These included challenges related to technical, market, commercial, and regulatory issues; some of these issues have been recognized in previous studies and reports, but are elaborated upon here because they provide detail on how these issues manifest at the level of individual decision-makers or organizations. Some topics, such as uncertainty around how markets will form and how common supporting infrastructure will develop, surfaced across multiple participants. Participants addressing the process and decision-making themes identified concerns stemming from risk management processes (e.g., whether traditional assumptions in risk assessment are appropriate, the tendency of companies to "push" risk to counterparties, lack of insurance mechanisms), and connectivity to the broader clean energy system (e.g., electricity and water for electrolysis, carbon accounting).

By way of synthesis of the learnings reflected in Figures 8-10, here we explicate six topics that reflect the challenges facing stakeholders trying to balance the interests of their organizations with a desire to expand the broader ecosystems.

BUSINESS CASE AND ECONOMICS						
INCUMBENCY	UNCLEAR STANDARDS	UNCERTAINITY AND ECONOMICS	TERMS AND CONTRACTS	CO-OPETITION	WILLINGNESS TO PAY	MIDSTREAM
• Grey H2 is so deep that we aren't doing cost learning on low-CI H2 regulation required • Scale mismatch Ethylen3 = 3MT p.a Total clean H2 Today < C 1MT p.a • SMR is integrated into existing uses NH3 + MeOH • Path to break-even with incumbent tech needs to be very clear, but this requires coordination that isn't happening especially in OU+OI	• Unclear standards and verification processes	• Uncertainty of international competitive landscape introduces investment risk • Relative economics can shift due to relatability of inputs (e.g. NG, electricity) • Incentives (IRA) will need to be split across project; limited duration; erodes business case, could be showstopper / intensify competition • Lack offtake pricing driving project risks and increased cost	• Different owners, production, transport, use; Cost of capitol, timeline, assumptions, challenges • Contract terms: - Length of agreement - Tri-lateral parties • 3D → 4D Agreements • IP/Proprietary technology (rights/terms)	• Competition with other land use • Competition with other clean energy use • Clean electricity is needed for the entire electrolysis path. Broader sustainability • Coopetition for green electrons and water	• Unclear demand signals and lack of utilization projects • Willingness to pay by end users • Unclear demand for H2 suppliers • Unclear "willingness to pay" for a green premium...efficient uses and markets	• Green electricity production and transmission and water access is needed for electrolytic H2-permitting is too slow • Permitting challenges (external factor) • Midstream limitations delaying contract agreements • Insufficient distribution to meet demand in right timeframe

Figure 8. Barriers to progress – Business case and economics.

SUPPLY CHAIN AND ENABLERS			
SCALE	ECONOMICS	EQUIPMENT	SUPPORT
• Scale of electrolysis production mismatched to key end uses • Supply chain to support blue H2 production is not sufficient	• Financing of H2 transport and distribution • Economics of clean H2 not favorable to reach scale • Lack of focus and investment in distribution infrastructure...Who owns and operates?	• Lack of H2 CHP/boilers suppliers. Lack of guarantees of performance eon H2 blends • H2 vehicle supply chain not available • Transportation refueling infrastructure needed to enable transport H2 demands	• Government and community support for H2 transport and distribution • Government and social license to support need for CCS to enable faster CCS development serving blue H2

Figure 9. Barriers to progress – Supply chain and Enablers.

PROCESS AND DECISION-MAKING				
RISK MANAGMENT	FEEDSTOCK	DEMAND CONDITIONS	POLICY QUESTIONS	ENABLING INFRASTRUCTURE
• Risk is being treated as dogma...addressing with traditional methods • SMR + CCS...Who handles storage? How to handle risk? • Everyone is trying to push the risk out to someone else • Lack of insurers for H2 an CCS projects	• Access to clean electrons and water • Lack of land for RE gas	• Balancing investment in demand and supply	• Early emphasis and attractiveness of exports detract from US decarbonization goals • Insufficient government support for demand application • Role of government? Political uncertainty • Emissions accounting unclear scope 1,2,3	• Lack of regulation framework for distribution and storage

Figure 10. Barriers to progress – Process and Decision-making.

1. *Offtake agreements and Willingness to pay: Who pays and how much?*
   Clean H_2 is more expensive than H_2 produced using traditional methods, so producers need assurance of demand to justify capital investments in production facilities. Conversely, consumers throughout the supply chain can find it difficult to commit to capital projects using clean H_2 without some confidence that producers are committed to production.

   Offtake agreements are an important mechanism to provide confidence to both producers and consumers, but the evolving cost landscape creates challenges in determining suitable terms and pricing. The preferred arrangement in the industrial gas sector is for "long-term certainty of market volumes, but short-term offtake contracts" to allow flexibility to monetize price volatility. Given the higher degree of uncertainty around the market for clean H_2, both producers and users are interested in longer term agreements to offset the systemic risk. However, long-term offtakers are exposed to being locked in to uncompetitive prices, since the cost basis for clean H_2 could change considerably if efforts to mature technology and reach scale are successful.

   Offtake contract negotiations are not new, but the uncertainty around future costs and differences in risk appetite, time horizon, and processes in assigning value to low CI can make it difficult for parties to reach mutually agreeable terms. Additional friction arises from the entry of new players who will need time to discover how to work with incumbents and each other. This is not an insurmountable problem, but workshop participants noted that the time needed to "figure out" how players in the ecosystem can work together should not be underestimated.

   In the near term, PTC subsidies available through the IRA can substitute for a direct willingness to pay on the part of the end user. By levelizing the cost of low CI H_2 relative to incumbent production, these incentives can allow players to apply existing contract structures and arrangements. This is a good starting point, because it can stimulate the learning needed to reduce costs and generate the public acceptance needed for the market to discover suitable prices for low CI H_2. However, it can be a problem if it delays solving questions such as how to properly value and transact low CI H_2.

   Practically, companies will be tracking actual progress on costs and the consumer's willingness to pay to ensure capital and operating decisions around low CI H_2 are justifiable business decisions. Continued difficulties in establishing offtake agreements, particularly in the latter part of the 2020's could be an indication that additional intervention may be necessary.

2. *Uncertainty on cost trajectories: How fast will electrolytic H_2 costs decline?*
   Electrolytic "green" H_2 is expensive, but significant cost reductions are "expected" by the 2030's due to aggressive R&D efforts, learning curve savings associated with large scale deployments, manufacturing innovation and scale, and continued addition of low-cost renewable power generation [7].

Reduction in costs are desirable, but the unknown trajectory, particularly in relation to alternatives such as "blue" H_2 produced with CCS equipped facilities, can create complications for end users looking at long-term sourcing arrangements. This is illustrated in Figure 11, which shows cost projections under four scenarios of optimistic and pessimistic trajectories for blue and green H_2 (see Appendix for details of the calculations). The solid lines indicate cost projections for hypothetical "reference production facilities" and the shaded regions reflect the ranges in cost that arise from differences at the project level.

The projected crossover where green H_2 becomes less expensive than blue could occur as early as 2024 or after 2040. This wide range means consumers would need to carefully consider offtake contracts to avoid getting locked into higher cost sources of clean H_2. Fortunately, there is room for flexibility – customers can include options or other creative terms to hedge their price risk. Moreover, it is possible (and necessary) to continually update these forecast curves (e.g., with actual learning curve data) to narrow the window of uncertainty to provide accurate information to market participants as they contemplate commercial contracts.

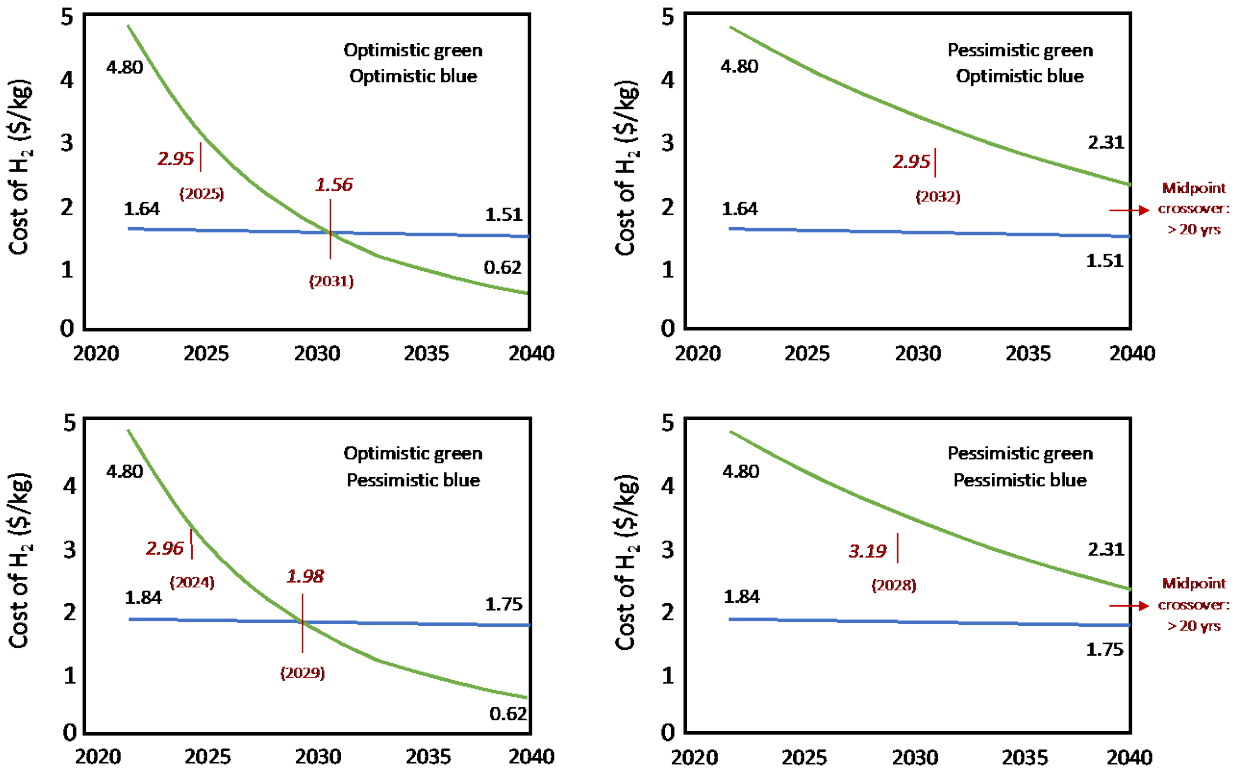

Figure 11. Projections of green vs blue cost trajectories under different learning scenarios. The solid lines represent cost forecasts based on "reference production facilities", and the shaded regions represent ranges of variation within the production class. The cross-over points, indicated by red arrows and text, reflect the estimated year in which price parity would be achieved.

3. *Manufacturing capacity: How will the electrolyzer supplier base evolve?*
   The electrolyzer manufacturing landscape is evolving quickly, with the top 20 global manufacturers almost doubling their cumulative production capacity from 14.4GW in 2022 to 25.8 GW in 2023 [20]. There are also a host of new entrants with new technologies with the potential to improve efficiency and reliability, or reduce cost and exposure to critical materials such as iridium. There are expectations that the demand will continue to exceed supply over the next decade, but also that the first wave of successful projects could drive the industry towards standardization and consolidation. In this case, dominant players could benefit from their early commercial traction into economies of scale for production in a manner that parallels the growth and evolution of battery manufacturing.

   An additional unknown concerning the electrolyzer supply chain is its global footprint and geopolitical competition between the West and China. These uncertainties could distort supply chains and slow green H_2 projects if domestic manufacturing requirements are stipulated for subsidy eligibility.

4. *Synchronizing supply and demand growth: Will facility size mismatches be a problem?*
   Operational facilities for H_2 can vary in size by over an order of magnitude. Incumbent processes such as SMRs or ammonia production operate at large-scale. In contrast, electrolyzer systems are expected to be deployed in a modular fashion with step-sizes of 50 MW or less. Figure 10 shows these differences graphically, with the area of the boxes representing the notional size of a "typical" facility. Large scale production facilities with captive end use arrangements in chemicals production represent important steps forward, but the growth of the larger clean H_2 market also requires integration with users that may be operating at different scales. For example, the potential demand for H_2 in medium and heavy-duty vehicle transportation applications may be large in aggregate, but individual refueling stations are small relative to large blue H_2 production facilities.

   Early in the growth process, mismatches in facility sizes, contract terms, trading volumes, and project schedules can create sequencing challenges that manifest as chicken-and-egg problems, delays, and unintended consequences that may hold back progress. "Large" facilities, on both the supply and demand side, can be up to two orders of magnitude larger than "smaller" facilities, creating lumpiness in the growth process. In the early stages of an evolving transition, (equity and debt) investors generally require offtake agreements that cover some or all of the production during this entire period. Small customers will only be able to absorb part of these volumes, and for shorter periods of time, putting the onus on the larger partner to coordinate across multiple counterparties. Conversely, smaller players may lack leverage in negotiations, face questions about credit-worthiness, and find themselves deprioritized in favor of deals within and between larger players. These dynamics also apply to the manufacturing supply chain, and efforts to develop shared enabling infrastructure such as pipelines, transmission, and storage capacity.
   Growth of clean H_2 supply and demand must be coordinated, particularly early on when the market size is small relative to the incremental contribution of new facilities. While

the coordination of "lumpy" growth is not a new problem for industry, workshop participants warned against underestimating the importance of logistics, particularly in a rapidly expanding environment with new players figuring out how to work with each other.

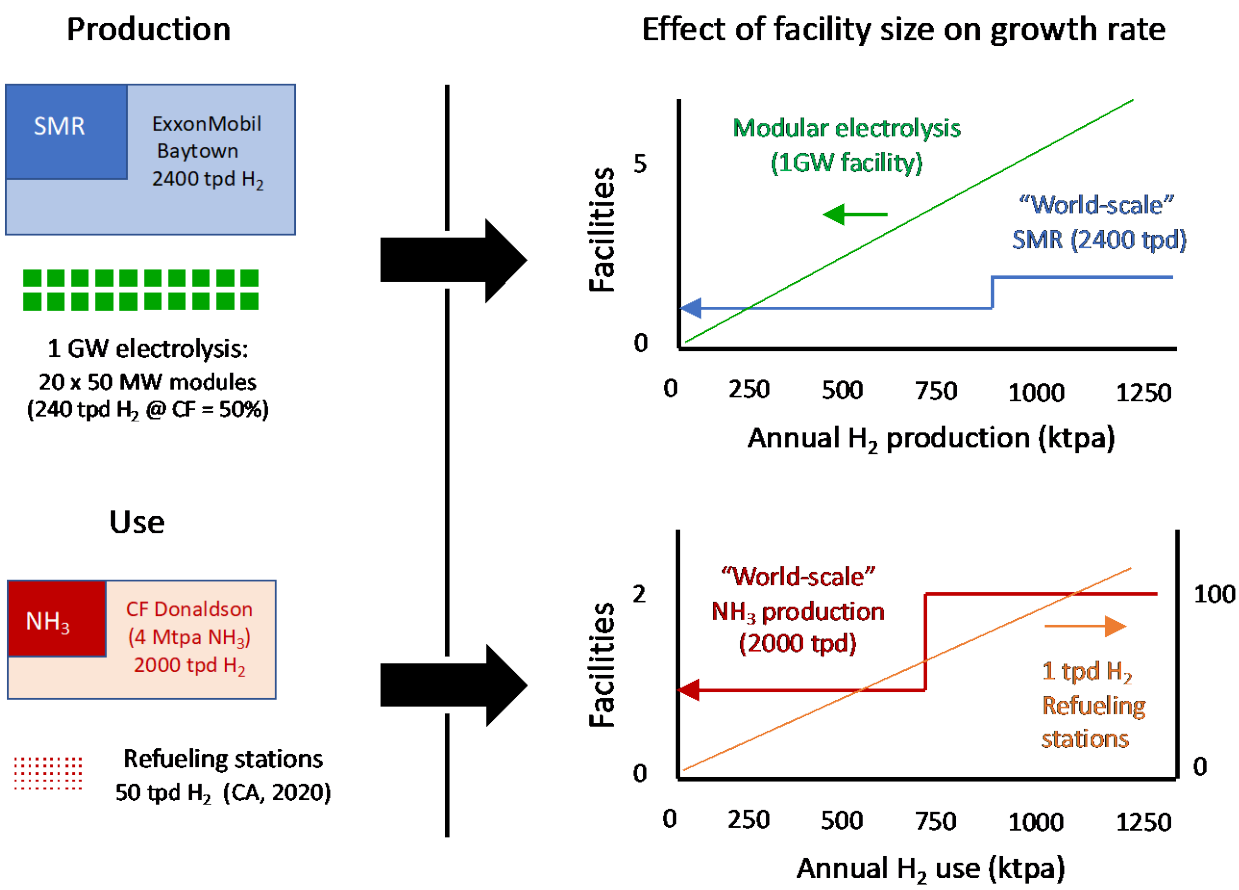

Figure 12. Facility sizes and potential supply and demand mismatches. (left) Representative and "world-class" facility sizes for steam methane reforming production (SMR), 1 GW electrolysis using 50 MW modules (operated at 50% capacity factor), ammonia (NH_3) production, and H_2 vehicle refueling stations (1 tpd each). (right) Implied step sizes associated with adding additional facilities.

5. *How do we reduce the first mover penalty?*
   First movers take on risk for the chance to capture early market share and develop learnings that offer competitive advantage. Participants noted two types of penalties that can arise in the rapidly evolving clean H_2 landscape that might deter early movers.

   First, early adopters bear the risk of defining workable business models and creating supporting infrastructure. Since later adopters get to benefit from this learning and activity, there is an incentive to wait and allow someone else to go first. There are strong competitive approaches based on direct electrification for potential use cases for clean H_2 in the areas of transportation and heating. In these areas, a first mover might develop a viable technical solution, but still lose if the market later moves *en masse* towards the

electrification option. This risk is new relative to a more "stable" landscape where competitors compete to innovate on a more certain use case.

Second, public funding to support early movers is a boon, but data sharing obligations could undermine the benefits of moving early. Investment by a company in a riskier and more expensive "first-of-a-kind" asset becomes more difficult (even if subsidized) when the company loses some or all of this benefit. If enough companies defer, this can slow overall growth of the market. Setting the proper level of disclosure in exchange for public funding support is particularly relevant for the DOE hubs programs established by IIJA, which represents a significant opportunity to accelerate development of a clean H_2 ecosystem in the US.

6. *Mobilizing private capital: Do we understand what is needed?*
   Different types of investors and the process of capital discipline were briefly explained in the Introduction. During the Workshop, participant responses reflected a wide range of opinions on how to engage private capital more effectively.

   There is the need for different pools of capital to "find their lanes" effectively. Whereas traditional corporate, infrastructure, and institutional investors are clear on their appetite for risk, newer entrants are still "figuring out" where they fit into the overall process. For example, while Silicon Valley-style financing models do not align well with the needs of infrastructure projects, there might be windows for venture capital to participate in early project scoping using an "at-risk" funding model that might be more aligned with their risk appetite, time horizons, and expectations for return.

   Participants also observed that there was uneven enthusiasm and investment in different parts of the ecosystem. Specifically, there is a lot of interest in projects directly involved in the production of clean H_2, particularly green projects. They noted a need for more activity for end-use facilities and supporting infrastructure.

3.4. Workshop results: Consensus views

Workshop attendees were then asked to individually rank drivers in terms of importance and urgency from their perspective, and then reach a consensus view on the top barriers. Participants were asked to "vote" for different barriers. Results are shown in Figure 13.

Group	Barrier	Votes
1	Desirability/willingness to pay	24
3	Risk management	19
3	Policy questions	13
2	Economics	7
1	Uncertainty and economics	6
1	Terms / contracts	6
2	Equipment	6
1	Co-optition	4
2	Scale	4
1	Incumbency	3
1	Unclear standards and verification process	2
3	Demand conditions	2
3	Enabling infrastructure	1
1	Mid-stream	0
1	H2 Midstream	0
2	Support	0
3	Feedstock	0

Figure 13. Ranking of barriers. Workshop participants were each given five units of "currency", each representing $10 and asked to vote by distributing the currency across what they considered to be the most important barriers towards future growth of a clean H_2 ecosystem. Votes could be "weighted" through higher allocations to higher priority issues.

The top three issues, with clear separation from others, were:

(1) Willingness of off-takers to pay.
There was broad agreement amongst participants of the importance of offtake to the underlying economics of investment decisions. This "barrier" includes not just weak demand signals and low absolute pricing levels, but also uncertainty in the evolution of cost and price trajectories over time, and market maturity and its capacity for price discovery. The consensus view was that this is true not just for primary producers of clean H_2, but also further downstream to primary users of clean H_2 who also require a willingness to pay from their end customers to justify the cost of a low-CI product;

(2) Risk management practices.
As a general principle, organizations tend to "push risk" onto counterparties. In uncertain environments, this can lead to impasses where neither party is willing to assume sufficient risk to allow a transaction to move forward. Participants offered examples in both capital investment decisions related to the primary production, distribution, and use of clean H_2, as well as in the broader ecosystem across the supply chain, supporting infrastructure, and financing communities; and

(3) Policy questions.

Government support in the US has opened a window of opportunity, not just for clean H_2 but also for other clean energy approaches. Participants noted uncertainty around the durability of policy support over the medium term (into the 2030's), its breadth across the ecosystem, and its effects on the balance of power in the ecosystem between well-established incumbent players and new entrants.

It is not surprising that these themes emerged as high priority barriers. However, the discussion uncovered important nuances on how these factors create sticking points in interactions between (and within) organizations at the level of the individual transactions needed to develop a robust and growing ecosystem.

This level of resolution is necessary to identify targeted interventions – internal or external – to address the sequencing gaps responsible for most "chicken-and-egg" problems. For longer-term capital mobilization, a key aspect that underlies all three barriers is the effect of uncertainty over relevant decision time horizons. In stable environments, market participants have relatively mature processes to quantify and manage uncertainty in their investment and operating decisions. However, the energy transition makes the landscape more volatile, introducing systemic risk which has is disrupting traditional risk assessment processes. Risk is less well-understood in environments where technologies, costs, business models, use cases, and competitive landscapes are subject to disruption over time scales significantly shorter than the typical economic life of projects

4. Enablers for growth at scale and speed

To enable long-term growth of clean H_2 ecosystem, steps must be taken to address the technical, commercial, regulatory, and institutional aspects of systemic risk. This section reports our findings on this topic and their implications for mobilizing private capital to unlock rapid, sustained growth of the ecosystem. Our findings are drawn largely from discussion at the second Workshop.

4.1. Workshop structure

The project team collaborated with Deloitte to host a second one-day Workshop on January 26, 2023 in Houston, TX. The event featured a series of interactive discussions around the theme: "*How can we design near-term (to 2030) demonstration and deployment efforts in the H_2 economy that catalyzes an order of magnitude expansion in each of the subsequent decades?*" This framing was chosen to challenge participants to think beyond initial projects, and towards the structural elements needed to support longer-term growth at scale and speed. The specific targets of a cumulative order of magnitude expansion per decade over multiple decades was selected to bring out the need for urgency in the near-term and sustainability over longer-term.

As with the first workshop, participants were encouraged to discuss and debate their views from perspectives of their specific roles and organizations, but reach consensus where possible on priorities for overall success at an ecosystem level. Content for the Workshop was drawn from interviews with stakeholders, public content, and independent analysis by the authors of outcomes from the first Workshop.

The second Workshop had a total of 34 participants, including 18 people who had participated in the first Workshop and 3 facilitators. The second workshop included increased participation from capital providers, including input from venture capital, private equity, corporate funding, and institutional and infrastructure finance. This contributed to the identification of an additional pressing need to those identified in the first Workshop, namely the mobilization of sufficient capital to sustain a full and growing pipeline of projects across the ecosystem.

This section presents a synthesis of the Workshop outcomes. Additional content generated by the Workshop is included in Appendix A.

4.2. Systematically reducing systemic risk

The second workshop examined enablers for a rapid, expansive, and sustainable growth of a clean H_2 ecosystem. Participants were asked to identify the essential features necessary in three areas: establishing use case clarity; enabling market formation; and creating a sufficient base of supporting infrastructure and equipment supply to allow expansion of clean H_2 production. To focus the exercise, they were also tasked with identifying indicators of progress in developing the necessary ecosystem-level capabilities and capacity in each area.

1. *Use case clarity*

   There is currently a robust appetite to explore an inclusive suite of potential use cases, spurred in part by government incentives and venture capital in search of aggressive returns. However, commercial success, and the ability to attract much larger pools of infrastructure investment capital, requires more than just technical feasibility. End-use case clarity is needed. This means identifying where clean H_2 offers a combination of superior economics, customer acceptance, and the ability to reliably deliver at scale, and where it does not. A pragmatic appraisal of the *current* situation indicates some cases where H_2 appears favorable, others where it is possible but unfavorable, and others where the situation remains unclear [21].

   Use cases will need to consider integration with the broader energy system. Costs incurred from connecting to the overall system could alter the economic calculus of a given project, and of course, sequencing also matters. For example, the consumption of low-carbon electrons by grid-connected electrolysis imposes a system-level opportunity cost since that energy might otherwise be used elsewhere. The simultaneous build-out of clean energy generation and the competition for the resulting clean electricity has raised the possibility that electrolyzer projects be required to include "additional", temporally-matched clean energy generation to qualify for the highest US production subsidies [22]. This could require developers to choose between expanding project scope or claiming smaller incentive credits.

   System integration requirements could also create advantages for clean H_2. For example, successful deployment of nuclear power at scale could ease the competition for clean electrons. Tailwinds could also arise in situations where use cases impose nuanced design requirements. An example is zero-emission transit bus applications, where entire fleets must be refueled in relatively short overnight windows. H_2 fuel cell buses can be refueled relatively quickly. This creates an advantage over battery electric buses, which may offer higher energy efficiencies, but incur significant additional costs or recharging time when large bus fleets are involved [23]. System integration requirements can vary by geography, reflecting local differences in the market, infrastructure, or regulatory environments. Understanding such nuances is an important step in evaluating use cases.

   While it is premature to declare the long-term viability across all H_2 use cases, there are a number of signals that might indicate the emergence of "winning" use cases that can anchor the initial development of a robust clean H_2 ecosystem through the 2030s. Such signals include:

   - the standardization of contracts and a move towards larger market volumes;
   - crowding-in by competitors into attractive use cases and abandonment of unfavorable ones;
   - crowding-in of participants in the supply chain that can reliably deliver both H_2 production and the necessary equipment and infrastructure at scale; and
   - a progression to non-recourse debt financing for follow-on projects indicating the retirement of systemic risk around a given use case.

Within specific use cases, evidence that clean H_2 is gaining traction could include:

- **Chemicals.** Adoption of CI requirements on chemical products (domestic use and exports); adoption in politically important geographies (e.g., Gulf Coast); development of pipeline infrastructure from large facilities to service the broader ecosystem; increasing share of clean H_2 from electrolysis;
- **Transport.** Direct adoption indicators such as vehicle fleet size and number of refueling stations; a sustained record of safety;
- **Industry.** Growth in number of facilities using H_2; piloting is difficult and expensive, so an uptick in pilot and demonstrations would be a positive sign; CI requirements in hard to decarbonize products (e.g., steel) would improve the prospects for clean H_2 use; and
- **Heating.** Expansion of transmission and distribution infrastructure (e.g., pipelines), including the emergence of standards for blending into natural gas pipelines.

2. *Market formation*

There was debate amongst participants as to whether clean H_2 markets need to reach a "merchant" or "spot" market status, or whether alternate models such as well-organized bilateral contracts are sufficient. Early in the process, captive arrangements in large-scale facilities offer a path to deploying large volumes of "clean H_2" relatively quickly, but over the long-term, participants noted that a merchant market with clear price discovery mechanisms would help clean H_2 compete in use cases beyond the chemical sector.

Pre-requisites for merchant market formation include adequate distribution infrastructure to allow spot delivery (e.g., open access pipelines), mechanisms for validating and transacting the value of low CI, and a minimum number of market participants to ensure liquidity. Participants voiced an expectation that this would occur through regional market development (possibly in an evolutionary manner from established H_2 ecosystem such as the Gulf Coast, or around clean H_2 hubs being advanced by the DOE with IIJA funding).

Participants also considered what adjacent markets might have useful elements that could be adapted to an emerging clean H_2 market, but did not reach agreement on any particular model as the most appropriate for the current situation. Possibilities that were discussed include:

- Renewable energy markets – Power production agreements (PPA) transactions rather than merchant market; mechanisms for decoupling and trading low CI attributes via Renewable Energy Credits (REC); small actors connecting to small actors (distributed production and use) early on, with larger facilities paired with larger facilities
- Natural gas markets – Price benchmarks (e.g., Henry hub); possible frameworks adapted from natural gas pipeline transactions; and
- Voluntary carbon markets – Mechanisms for transacting CI value.

3. *Infrastructure and supply chain*

Growing a clean H_2 ecosystem from a few early demonstrations to more than 50 Mtpa within two decades requires not only significant commitments of private capital, but coordination across the clean H_2 ecosystem including synchronization across manufacturing supply chains and supporting infrastructure. Initial markets can be created by adapting current business models for large scale H_2 production and use facilities within the chemicals and refining sectors. Vertically integrated supply arrangements sidestep the issues around offtake risk, but vertically integrated arrangements often do not disclose pricing information. The formation of broader markets to support emerging applications will require transparency in economics to support price discovery, and resolving a number of commercial issues that can arise from an organic growth model centered around large "captive" supply anchor projects.

Additional synchronization challenges arise due to lead times for building out of sufficient enabling infrastructure and supply chain capacity. Facilities such as factories and pipelines take time to permit and commission; aligning these schedules to rapid expansion plans for clean H_2 projects imply investments in manufacturing capacity and supporting infrastructure *before* the projects related to direct production or use reach FID. This introduces a dimension of risk that some investors may be uncomfortable with; inadequate investment in supply chains could become rate-limiting for growth.

Indicators that infrastructure and supply chain are developing at a pace that can support long-term growth include:

- A strong pipeline of projects for distribution infrastructure and manufacturing capacity;
- The development of CO_2 trunklines in strategically important parts of the country;
- Declining processing times for permitting of pipelines and storage facilities;
- Co-evolution of electric transmission to support the allocation of "clean electrons" to electrolysis and grid support services back to the grid;
- Emergence of regional hubs for manufacturing with complementary capabilities and a robust workforce; and
- Clarity on international trade arrangements for supply chains, including the competition for raw material inputs.

4.3. Priorities for action in the 2020s

Using the S-curve framework as a basis for discussion, the final exercise for the Workshop was a group discussion on the priorities for action through the end of the 2020s to position a clean H_2 ecosystem for growth through the 2030s and beyond. Participants were divided into groups and each group was tasked with identifying the foundational elements needed to support a period of clean H_2 ecosystem growth at speed and scale. Responses were grouped into two categories: Foundations and Elements needing increased attention. Figure 14 summarizes the outputs elaborated below.

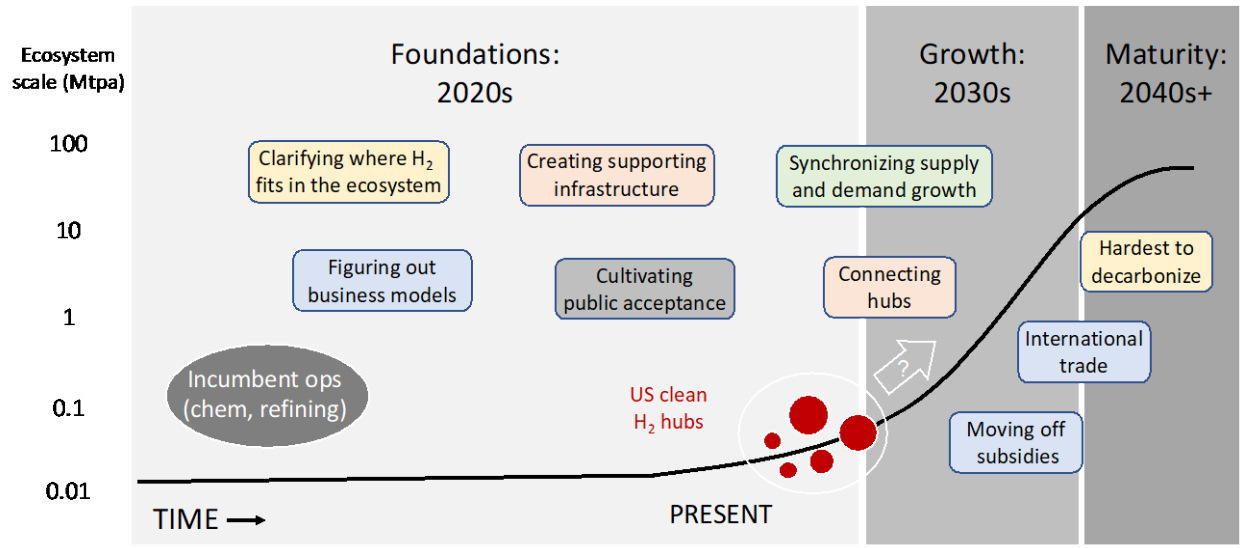

Figure 14. Capabilities needed at different points along a S-curve trajectory for expansion of a clean H_2 ecosystem.

1. *Foundations*

   Responses centered around the exploratory nature of early stage projects, including hubs, with an emphasis on learning. The DOE hubs initiative was recognized as a valuable platform to stimulate validation of technologies, clarification of business models, definition of regulatory frameworks, development of supply chains, and construction of shared infrastructure. All of these elements have already been recognized as necessary for "commercial liftoff". Participants also noted the importance of workforce mobilization and community support.

   The need to build public acceptance was also cited – across two dimensions. First, public support for energy initiatives manifests in the form of funding and subsidies, patience for the emergence of business cases, and willingness to pay a premium for products. In the US, consideration of community impacts and environmental justice as criteria for clean H_2 hub awards is intended to burnish the social license to operate by delivering benefits directly to local communities. The importance of avoiding the perception of needing to get it "perfect on the first try" but rather focus on identifying viable and scalable practices that can support longer-term growth was also noted. To this end, setting realistic expectations on the extent and timetable of benefits was cited as an important consideration for building and maintaining support.

   Second, public skepticism can quickly coalesce into entrenched opposition, which can lead to permitting and other types of delays. Delays are particularly costly, because they undermine the case for financing. This is seen in efforts by midstream companies to route pipelines, and renewable energy developers siting wind, solar, and transmission assets, indicating that all development will need to carefully manage stakeholder engagement and be especially sensitive to local community concerns.

2. *Elements needing increased attention*
   Participants reiterated the importance of the indicators of maturing use case clarity, market formation, and supply chain and supporting infrastructure identified above in signaling a transition into a Growth stage.

   Whereas the Foundations stage is about identifying technical configurations, workable business models, and commercial arrangements, the Growth stage is about expansion. Success in the first wave of projects and clean H_2 hubs was deemed critical in generating momentum, but the ultimate indicators of a successful transition to Growth is the ability of organizations to execute. Practical evidence of this transition at the organization level includes adoption of consistent terminology and standards, convergence of engineering packages into standardized packages, the development of standard terms for transactions, and evidence of progress in cost reductions through scale and learning curves.

   From an institutional perspective, this means stakeholders across the ecosystem will need to converge on expectations around markets and commercial arrangements. There is still room and the need for technical innovation, but systemic risk related to workable models for cooperation and competition will have been mostly retired. The workforce component will take on a greater urgency, as staff will be needed to design, construct, and operate facilities across the expanding ecosystem.

   Overall, there was agreement that the 2020's are about validating technical approaches, identifying workable business cases, creating infrastructure, and clarifying what to scale. There are multiple possible paths and the "winners" will be selected by a combination of economics, politics, and technology. Winning paths will then attract capital and gain momentum. Some initial ideas that seem good will fall by the wayside. The best technology ideas may not win because it will be a matter of who moves first. Rather than looking for a single deterministic path, we should be thinking about how to learn as much as possible from the activities of the current phase – learning about what works and how to make it better, and what doesn't work so we can pivot or discontinue.

   Looking across the full range of stakeholder inputs from the study, there was general agreement on many aspects of the current technical and commercial state of the clean H_2 ecosystem, and the immediate and long-term challenges that must be overcome to achieve scale. However, responses from the interviews and discussions during the workshops revealed areas where some stakeholders held divergent views and also had limited situational awareness about the constraints of other stakeholders. While players generally have a clear understanding of their immediate situation and competitors, broader situational awareness is uneven. Even large, connected players do not have a complete picture. Conversely, new entrants were motivated to engage larger and incumbent players, but did not necessarily appreciate the complexity of internal decision-making within the larger companies. Finally, there was evidence of a gap in appreciation of the specific transactional requirements between some industry players and different investors. Those directly involved in financing were generally aligned, but a common understanding of what it takes to truly "unlock trillions" in private capital is lacking.

5. Roles for clean H_2 hubs in reducing systemic risk

The section synthesizes stakeholder inputs to offer a perspective on how the clean H_2 hubs in the US can be used to address systemic risk in a way that makes large-scale investment possible. Simply building interconnected projects is not enough. A concerted effort is needed to clarify business models and develop supply chains. Moreover, "chicken-and-egg" situations are likely to emerge and will need to be overcome with strategic coordination. In this section, we identify five critical issues - illustrated in Figure 15 - related to systemic risk that hub activity can help address.

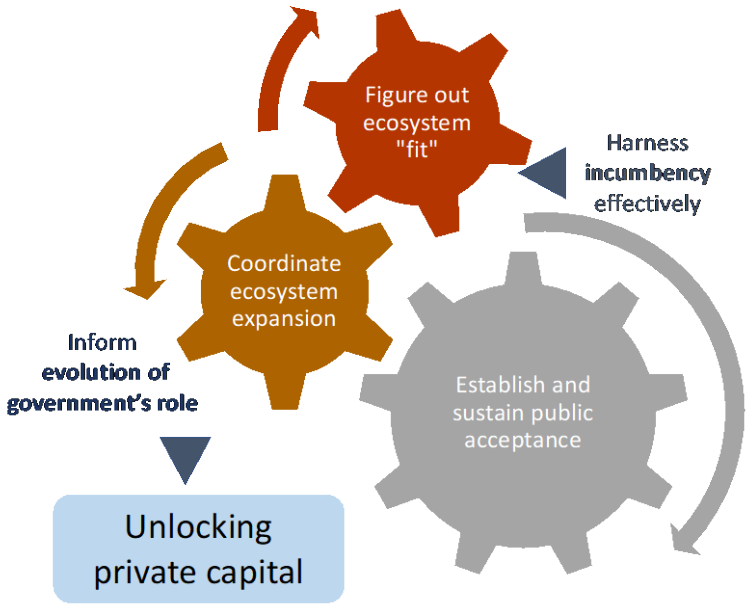

Figure 15. Aspects of systemic risk that must be addressed to unlock large-scale private investment in clean H_2 ecosystems.

1. *Determine how H_2 "fits" in the future clean energy ecosystem.*
   Clean H_2 hubs provide a valuable platform to test different use cases, and their interactions with each other. This includes integration into the larger ecosystem and the resolution of questions related to the competition for clean electricity, the procurement of water, harmonized standards for tracking CI and transacting value, and integration of H_2-based services such as longer-duration energy storage.

   Resolution of such issues would show growing confidence in market viability, and the operating plan for hubs could be developed with an intent to facilitate these elements. In this regard, we align with recommendations from Energy Futures Initiative [9], but go further to argue that such actions should be connected to efforts to directly address the key reservations of infrastructure investors. Moreover, H_2 hubs need not focus exclusively on H_2 technologies; there is an opportunity to explore system-level integration with other clean energy technologies. This positioning could help uncover system integration issues, while improving

connectivity of the H_2 ecosystem to pools of capital interested more broadly in decarbonization.

From a capital formation perspective, use-case clarity accomplishes several things. First, it underpins a proper understanding of the risk profile so that different pools of capital can find entry points commensurate to their risk appetite. Second, it allows business cases for individual projects to come to the fore, as financial players become increasingly confident with the underlying investment environment. Therefore, it is crucial that as the market renders judgment, risk profiles be updated and (near-term) weaknesses in use cases be clearly acknowledged. We should not be afraid of this, since it is a natural consequence of a maturing investment environment that is needed to attract increasing amounts of capital.

2. *Coordinate supply and demand growth.*
   By encouraging simultaneous commitments from multiple participants across the ecosystem, a hub framework offers a degree of assurance for both the market and investors that an initial ecosystem will be built. Such an arrangement allows individual participants to hedge their counterparty risk; a given producer could find several off-takers, and a given user could source clean H_2 from multiple providers. The initial market created around hubs could also aid price discovery. As the initial market created by a hub expands to the point where it is large relative to individual suppliers and users, the risk to subsequent producers and users is further reduced. Similar benefits are conferred to manufacturers deciding on capacity expansion, and investors financing common infrastructure.

   Clean H_2 hubs offer learning opportunities beyond their initial contribution into market and supply chain formation. The diversity of hub designs anticipated for the US program (and around the world) should provide data to better understand the critical market sizes for various use cases, the power dynamics that emerge in commercial negotiations, and additional hurdles that may emerge as markets expand. These insights allow investors to develop a clearer appreciation of the evolving risk-reward profiles, allowing them to expand their engagement across the supply chain. Hubs may also offer an opportunity to adapt market-shaping strategies from other industries, such as enlisting “quarterbacking” organizations into roles to assist in market formation and the coordination of supply and demand growth [24].

3. *Establish and sustain public acceptance.*
   Clean H_2 hubs will need to cultivate both active acceptance and avoided skepticism. In the US, hubs are a high visibility effort, in terms of both direct funding as well as the impact on mobilizing private industry, entrepreneurs, and local communities in the bidding and construction process. The creation of new business models and ecosystems are often accompanied by hype, high-profile failures, or middling successes which can cause public sentiment to shift. In light of this, there is a need to create an environment where any particular success does not create unrealistic expectations and any particular failure does not erode public support, and create active opposition.

   Effective communication is a key element for creating and maintaining the trust needed to build and maintain public acceptance. The problem is there does not exist a mechanism for

individual stakeholders across clean H_2 ecosystems to communicate in a single voice. There is a need to convene a public-private cooperative that acts in this capacity. In the US, such an entity could include: (1) DOE as a key public proponent; (2) private industry and the coordination mechanisms they create to bid on hubs; and (3) public interests that also need to be engaged. The first two parties are already engaged in hubs activity, but giving voice to public interests, either directly or through "quarterbacking" organizations could enable the robust discussion needed for long-term acceptance [24].

Two aspects of public acceptance - the evolving role of government, and the need to reconcile differences between incumbent industrial players and the environmental movement - warrant further attention. The final two issues address these aspects.

4. *Guide evolution of government's role as the ecosystem matures.*
   The clean H_2 ecosystem is enabled by technology, but the current wave of global activity is driven primarily by policy. Generous incentives in the US have been a game-changer in stimulating project interest, as well as prompting discussion within the European Union and China about how to level the playing field.

   Despite the current positive environment, policy uncertainty remains a significant concern to private capital. Changes in policy on time scales shorter than the typical economic life of assets introduce risk and can impair or strand capital assets. In this regard, the expiration of the 45V PTC for new projects at the end of 2032 represents a key test of the sustainability of a US clean H_2 ecosystem. If the costs have decreased and other conditions for market development and capital formation are met, then private capital could invest in projects with favorable economics without further subsidies, and the ecosystem would be expected to enter a Growth phase with little to no further intervention [7]. Conversely, if unsubsidized economics for clean H_2 projects remain challenging or other foundational elements are missing, then additional interventions would be needed to stimulate the desired growth.

   As hubs in the US (and globally) come online in the late 2020's, they will provide a near-to-midterm learning platform to understand the effectiveness of current policies and help target the next wave of interventions to address specific market failures and shore up weaknesses in the ecosystem. A variety of additional actions to aid the transition from the Foundations stage to a Growth stage (Figure 1) have been suggested in our research and by other studies. These include: developing mechanisms to expedite, but not short-circuit, the permitting process; offering backstops for enabling infrastructure siting and development well in advance of anticipated supply and demand expansion; government procurement mandates to soak up early-mover supplies; and incentives to stimulate activity to connect hubs in the 2030s [7,9**Error! Bookmark not defined.**]. Debate around the details of these and other additional interventions in the late 2020s and early 2030s should be actively grounded in the continuing experience generated by the hubs and other early mover experiences.

5. *Harness incumbency without being captured by it.*
   From an investment perspective, the ability of a team to execute on a project is fundamental. In this regard, the domain expertise, balance sheets, and track record of existing energy

companies offers a degree of credibility with the infrastructure investment community that can be leveraged to accelerate the first wave of projects and stimulate successive waves of activity.

Herein lies the challenge. Incumbency is susceptible to institutional inertia which, in the form of entrenched interests or established processes, favors incremental rather than disruptive change to existing business models and their underlying assumptions. This exists at the level of both organizations and individuals. At best, it can slow progress towards an ultimate goal of deep decarbonization. At worst, it can result in surface changes to business strategy and gaming of incentives without committing to structural change.

One example of how incumbency can be leveraged is the design and execution of CCS by oil and gas companies [25]. Although CCS projects draw on many of the subsurface databases, and technical and execution skills needed for hydrocarbon extraction projects, the "value" of a unit of sequestered CO_2 is much lower than hydrocarbon products. For organizations and processes developed for more lucrative operations, this carries difficult implications in the form of lower return expectations for financial decisions and constraints on capital budgets for technical design. The ability to adapt to this reality could set the pace by which incumbents are able to utilize their historical advantages.

Hubs activity will provide evidence on how far businesses are really willing to go in evolving their roles and processes to align with the realities of a sustainable clean H_2 ecosystem. While the natural tendency of most organizations is to favor incremental change, government subsidies have the potential to catalyze realignment within organizations, and reset expectations around decision-making – both in capital discipline and in operations – by reducing the financial and political risk to executives seeking to transform their organizations.

Assuring the authenticity of incumbents' commitments as perceived among the broader community will be crucial. This can only be accomplished by insisting on unprecedented transparency and through rigorous engagement (e.g., review of core assumptions, and verification of future commitments) by external stakeholders and private investors. Such activities can occur through direct engagement, or through facilitation by "quarterbacking" organizations conducting shuttle diplomacy [24]. Regardless of the specific mechanisms, mandated transparency and sharing the learnings of these reviews can encourage the evolution of legacy processes, while simultaneously improving trust among environmental groups, and educating the investor community as a necessary step towards capital formation.

6. Case study: Accelerating the adoption of clean H_2 in the US chemicals sector

This case study draws on baseline knowledge and on input provided at the workshops to offer recommendations to accelerate the uptake of clean H_2 production and use in the US chemicals industry.

The US chemicals sector is currently one of the largest domestic consumers of H_2, with over 90% of it produced by steam methane reforming. It was well-represented in this study, in both interviews and workshops. With recent government subsidies greatly strengthening the economic case for action, it is well-positioned to lead the adoption of clean H_2 due to its historical experience with producing and using H_2 safely, established business models for both captive and merchant H_2 to mitigate offtake risk, and strong balance sheets and track records of success to ensure adequate capital for projects.

The case study reviews opportunities for the use of clean H_2 to support decarbonization, including replacement of high carbon intensity H_2 feedstock, but also as a source of industrial heat and power. There is the opportunity for both evolutionary (incremental) change and revolutionary (disruptive) change, and stakeholder perspectives on the barriers to action are presented in the context of chemical sector use cases. Different corporate approaches to prioritizing clean H_2 projects are surveyed, drawing on content from the study and public announcements from the broader chemicals industry. Sector specific "chicken-and-egg" problems are discussed, along with possible targeted interventions drawn from a detailed look at the underlying drivers. Capital allocation is also discussed, with a particular focus on the transition period where legacy assets face a decision for stranding versus upgrading.

6.1. Carbon footprint

The US chemical and refining sectors accounted for about 350MMtCO_2 in 2021, or 5% of the nation's CO_2 emissions, and is considered among the "hard-to-abate" sectors [26]. There are two types of contributions: emissions related to H_2 feedstock production, and emissions associated with energy use (Figure 16). About a quarter of emissions in 2010 were generated by the production of raw H_2 feedstock; roughly 95% of the 9 Mtpa of H_2 used in 2010 was produced by reforming of natural gas, at an average CI of 9.4 tCO_2/tH_2 for about 80 Mt CO_2; total H_2 use has grown to about 10 Mtpa in 2020, and is still dominated by SMR [27-30].

The bulk of emissions from the chemical sector are associated with energy use. Figure 17 shows an inventory of the relative contributions from different modes of energy (direct fuel combustion, steam, and power) across the different uses. Cogeneration, powered by natural gas, accounts for about 35% of this contribution (91 of 257 Mtpa CO_2) with another 66 Mtpa of CO_2 due to natural gas combustion for heat. Altogether 61% of the energy related emissions are related to natural gas as a fuel (157 of 257 Mtpa). Efficiency measures across the industry notwithstanding, the structural distribution of carbon emissions from energy use is similar in 2020.

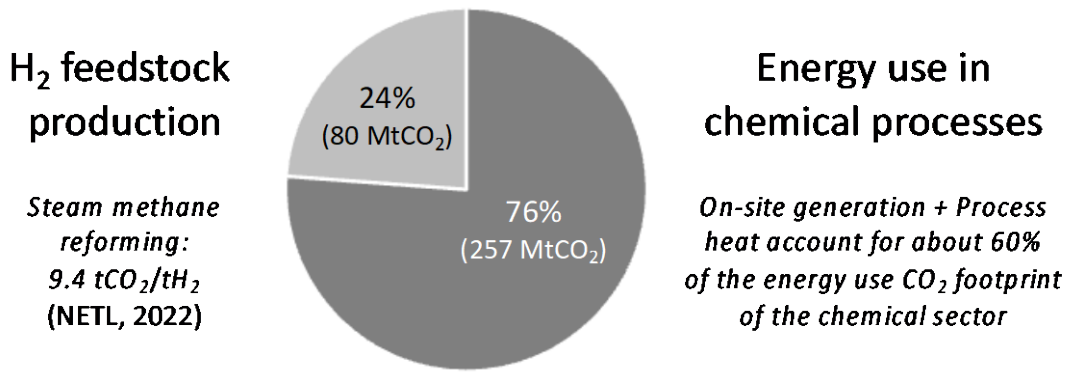

Figure 16. Carbon footprint of the US chemical sector. The carbon footprint of the US chemical sector in 2010 was approximately 337 $MtCO_2$. The carbon footprint of the H_2 feedstock was computed assuming 95% of the 9 MtH_2 used in 2010 was produced by SMR with an average carbon intensity of 9.4 tCO_2/tH_2 The energy use in chemical processes was reported by the US DOE [30].

The combined contributions to carbon footprint from natural gas use in H_2 feedstock production and direct natural gas as a fuel accounted for about 70% of the sector emissions. Low CI H_2 can be a substitute for natural gas in both these capacities.

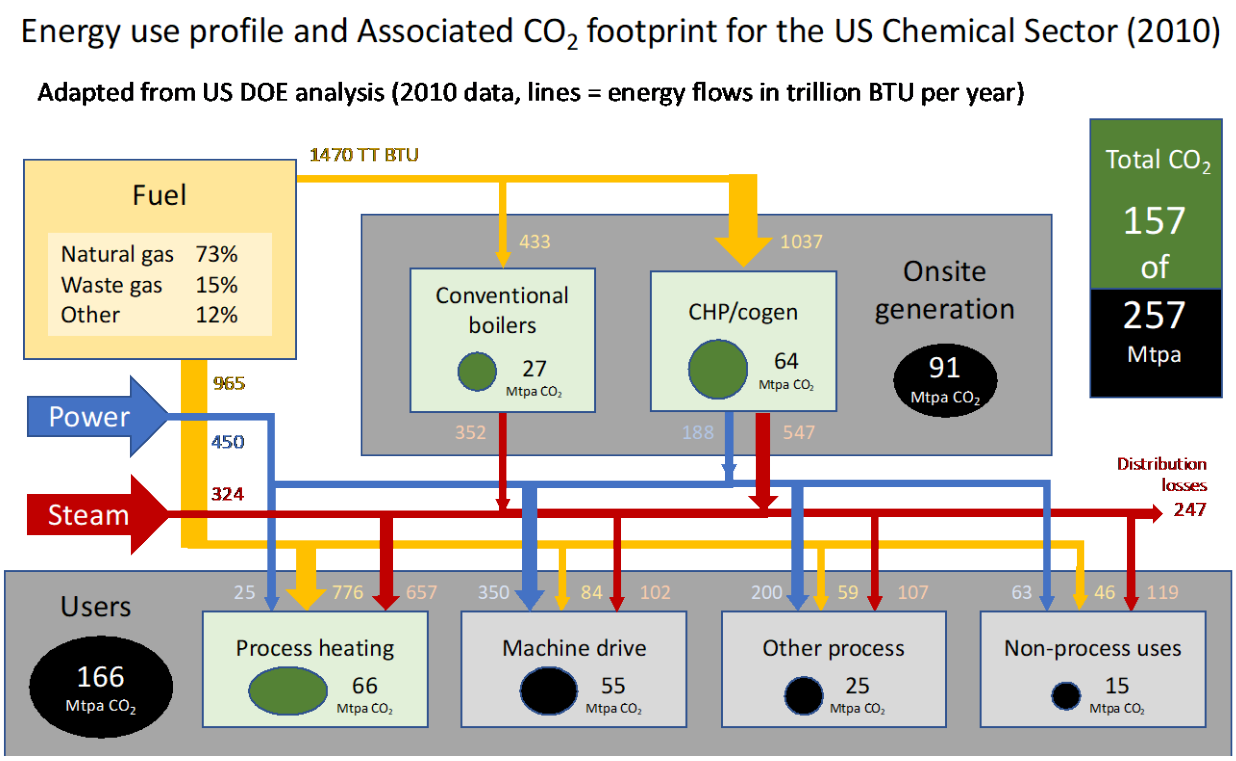

Figure 17. Energy use profile and its associated CO_2 footprint, US chemical sector 2010.

6.2. Opportunities for clean H_2 adoption

Large, captive facilities wherein H_2 is consumed at or near the point of production account for more than half of current domestic H_2 use (60% in 2014) [31]. The majority of these facilities are associated with the chemical sector; SMR and ammonia facilities are the primary examples. These types of facilities have three attributes that make them a logical starting point for the adoption of low CI H_2:

- **They are technically compatible with CCS.** About two-thirds of the CO_2 produced at a SMR plant arises from the chemical processes (reforming and water-gas-shift) that convert methane into H_2 and CO_2. The process flowsheet at SMR facilities has a high pressure CO_2 removal system to produce intermediate purity H_2. The CO_2 product of this separation step can be purified and compressed to pipeline quality CO_2 with relatively minor modification of the base process.

  The remaining CO_2 is produced by combustion of natural gas to provide heat and power for the SMR. This CO_2 can be captured from the boiler flue gas using a post-combustion step, or alternatively, removed using approaches such as substitution of H_2 for natural gas as a boiler fuel. Additional concepts, such as oxy-fuel combustion (where natural gas is combusted with pure O_2 rather than air to facilitate CCS) or direct electrification are also possible methods for reducing this contribution to emissions.

- **Operating companies have experience designing, financing, constructing, and operating these types of facilities.** When combined with government incentives (viz., 45V or 45Q) that make the economic case viable, the ability of incumbent companies to move forward on large-scale projects offers a path towards immediate progress towards significant clean H_2 uptake, and reductions in CO_2 emissions. The long-term sustainability of the project pipeline will depend on market development and cost reductions, but just the first wave of projects (as evidenced by multiple announcements of large-scale blue H_2 projects) stimulated by IRA incentives could deliver several Mtpa of clean H_2 by 2030.

- **Large-scale captive projects offer on-ramps to expand production and use of clean H_2 beyond the immediate captive process.** On the production side, a large blue H_2 facility could also host an electrolysis facility. As shown in Figure 12, green H_2 production from electrolyzer modules can ramp up in smaller increments. A captive facility offers the opportunity to introduce and ramp up green H_2 in a manner that controls operational risk. This approach allows the captive facility to begin with a smaller initial capital investment, and learn how to operate electrolysis systems at scale with less risk to the reliability of downstream operations.

  On the use side, large-scale captive operations could sell a fraction of the clean H_2 produced and used for external applications. For example, the demands from fuel cell vehicle refueling stations are on the order of 1 tpd per station, which is much less than the hundreds of tpd at a large captive facility; it is not difficult to imagine an arrangement where a captive facility might install a liquefier and support some tens of refueling stations. The diversification of end users could stimulate a positive feedback loop in which additional clean H_2 production is brought online. In the longer term, the captive facility could evolve into an anchor production site that could support both the original captive use, as well as the larger ecosystem,

A second opportunity to use H_2 to reduce chemical sector carbon emissions is as a substitute for natural gas fuel in cogeneration systems. Boilers and combined heat and power systems are ubiquitous, not just in the chemical sector, but throughout the industrial sector broadly. As noted above, decarbonization of cogeneration can occur in three ways:

- **CCS.** Cogeneration systems can be retrofitted with CO_2 capture in two ways. First, post-combustion capture systems are a relatively mature technology, but remain an expensive option. Disposition of the captured CO_2 can be a challenge at sites that are either far from geological storage or generate insufficiently large quantities of CO_2 to make the economics of pipeline transport competitive.

  A second option is oxy-fuel combustion, where O_2 is substituted for air. This creates a flue gas stream containing CO_2 and water, rather than CO_2 and N_2. The resulting separation of CO_2 from the flue gas is greatly simplified, but the oxy-fuel approach does not solve the issue of CO_2 offtake. In addition, the production of O_2 requires additional facilities, such as an air separation unit. This approach is likely only feasible at sites that already have O_2 production capability (e.g., autothermal reforming). An intriguing option is a hybrid blue-green site, where byproduct O_2 from electrolysis could be repurposed for oxy-firing of boilers.

- **Direct electrification.** The efficacy of electric heating for decarbonization is dependent on the carbon intensity of the original electricity. This approach will also require capital investment. There are also some questions about the efficiency of such systems compared to combustion processes, but electrification could be an option for greenfield facilities where low cost, low CI electricity is readily available.

- **H_2 as a fuel.** Like direct electrification, this approach sidesteps the CO_2 disposition question, but its efficacy depends on the CI of the H_2. Existing boilers could be retrofitted with H_2 capable combustors and controls, and the logistics of delivery and storage are lessened for large captive facilities that are generating H_2 onsite.

Each of these approaches for decarbonizing cogeneration has merits and drawbacks for different use cases across the chemical sector and industry broadly. All three are being developed through active research and pilot testing by different companies. Decarbonization of cogeneration is a microcosm of the clean H_2 ecosystem in that it faces many of the same questions concerning use-case clarity, first mover penalties and shared learning, and uncertainty on cost trajectories.

6.3. Practical considerations

We conclude with a few comments on how the findings of this study can apply to the adoption of clean H_2 by the chemical sector:

- **Capital mobilization.** Relative to other use cases, systemic risks around end use are relatively low. While there may be technical questions about some operating components, neither the operational scale nor the capital requirements for projects represent a significant step in ambition, relative to projects that established companies in the sector have historically pursued. Given the ability of incumbents to also finance

projects using their balance sheets, the availability of capital – provided the economics of a project satisfy targets on return – is not likely to be limiting.

- **Willingness to pay.** Although IRA incentives have been a major driver of a first wave of project announcements, a sustainable path to growth will require the market to offer a premium that properly values low CI to support the business case of subsequent waves of projects after incentives have expired.

  One path that was suggested by a participant from a chemical sector user of H_2 is to use government subsidies from the first wave to support a premium product offering (with low CI as a differentiating attribute), but at discount to the actual premium required without the subsidy. The intention is to establish public acceptance, with the goal of creating a market expectation that eventually requires low CI as a standard rather than premium offering.

- **An evolving role for government.** The chemical industry is subject to strict anti-trust regulations, and several participants in the study indicated that this has prompted a degree of caution amongst companies in the sector, restricting their ability to discuss cooperation in developing business models to value low CI. Clarification of anti-trust rules as they pertain to some of the coordination issues could help with some of the sequencing issues identified during this study.

- **International trade**. The chemical sector stands to benefit from internationalization of the clean H_2 ecosystem. This applies to both the development of the supply chain and to the export of energy products. The ability to draw on foreign suppliers of equipment could also reduce project costs and support aggressive construction timelines.

  Energy exports to regions willing to pay a premium for low CI products are a driver for some of the large project announcements in the US. In particular, the shipping of ammonia to Japan and the EU is being actively explored. There are pertinent questions that are being worked out: (1) the technical maturation of the logistics – including bunkering and end use (direct utilization of shipped carrier, or cracking back to H_2), and (2) appropriate frameworks for carbon tracking and qualification for incentives (i.e., should exports qualify for 45V credits?)

- **Incumbency.** In aggregate and as individual companies, the chemical sector is front and center for the issue of incumbency. The question of "willingness to pay" arises directly from the commercial implications of substituting low CI feedstock into existing processes. Subsidies from the IRA can initially support the change, but longer-term sustainability may require changes to the business model to educate and engage customers for when the eligibility period for subsidies expires. Different appetites for longer-term change, across and within companies, will impact the effectiveness of market formation efforts.

  The clean H_2 ecosystem is also expected to attract new entrants – both large companies drawn from adjacent spaces, and smaller companies formed to take advantage of emerging use cases and supply chain opportunities. Existing commercial relationships between chemical sector incumbents will need to adapt to engage these new players.

7. Conclusion

Developing a clean H_2 economy at the scale envisaged by net-zero transition pathways for the US requires political will, technical readiness, and economic viability. There is a window of opportunity through the 2020s in which these elements are present or actively being put in place, and which could provide the foundation to catalyze the required speed and scale of expansion through the 2030s and 2040s. However, success also requires alignment and action on the part of individual actors throughout the ecosystem. Local processes and constraints can create inadvertent bottlenecks and barriers, and these must also be addressed to allow progress.

This study examined these barriers, their underlying drivers, and ways to address the gaps in perception and action across the value chain and its interaction with the pools of private capital needed to support growth. We specifically focused on the capital discipline protocols of actors and the need to extinguish systemic risk if we are to mobilize the level of private capital, especially construction finance, that will be needed to develop and build out the infrastructure associated with a large clean hydrogen economy in less than 3 decades. Such systemic risk stems from considerable uncertainties around future sustainable use-cases, technology cost trajectories, supply chain evolution and access to enabling (shared) infrastructure. Ultimately the desired speed and scale of the expansion in the face of such uncertainty calls for a level of coordination to ensure supply and demand growth are synchronized.

To assure success, there may be a legitimate case for 'quarterbacking' organizations like those that have assisted the pharmaceutical industry with, e.g.: market formation (e.g., by organizing buyer's clubs); shuttle diplomacy to bridge divides between key players in the ecosystem or the general public; and coordination of expansion of supply and demand along with enabling infrastructure and supply chains.

Landmark climate policies in the form of the IIJA and IRA providing access to considerable grant capital for Hubs and production cost subsidies over the next decade will stimulate investment clean hydrogen projects. However, it remains uncertain whether that investment will provide a foundational legacy that catalyzes the allocation of private capital through the 2030s and 2040s to build out a clean hydrogen economy at the scale of 50 to 100 million tonnes per annum. The chances of doing so will be enhanced if we get five things right this decade:

(i) Sort out those use cases that provide a compelling commercial case at scale;
(ii) Develop the capacity to coordinate supply and demand growth;
(iii) Establish a basis and guidelines for enduring public acceptance;
(iv) Evolve the role of government; and
(v) Learn to harness incumbent organizations and systems without being captured by them.

Although the primary focus of this study was on the clean H_2 market in the US, our findings could also have relevance to clean energy finance beyond H_2 and regions outside the US. Acting on the key lesson from this work – the need for a high-resolution appreciation for institutional decision-making, as a complement to efforts in the technical, commercial and policy arenas – will be an essential step in unlocking capital and progress as the energy transition moves forward.

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Appendix A

Primary data: Notes from interviews and workshop discussions

Contents

Acknowledgment of study participants (Chatham House rule)

Princeton University gratefully acknowledges and thanks the following people (professional affiliation in parenthesis) for participating in the study and sharing their perspectives:

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- Robert Kumpf (Specialist Executive, Deloitte)
- David Malobicky (Global Market Director, PPG)
- Gary Martin (Senior Director - Energy Transition, Worley)
- Ryan Masumoto (VP - Investment and Business development. MHI Americas)
- Michael McGowan (Specialist Executive, Deloitte)
- Jason Munster (Director of Analysis, DOE - Office of Clean Energy Demonstrations)
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- Eric Peeters (VP Sustainability – Performance Materials & Coatings, Dow)
- Jessica Perkins (Specialist Master, Deloitte)

- Brett Perlman (CEO, Center for Houston's Future)
- Preeti Pincha (Director – Sustainable Systems, Sustainability, Climate and Equity, Deloitte)
- Carol Romano (Procurement Leader, Energy and Inorganics, Covestro)
- Neha Rustagi (Program Manager – Analysis and Code & Standards, DOE - Hydrogen and Fuel Cell Technologies Office)
- Ryosuke Sakai (SVP – New Business Development, MHI - America)
- Brijesh Singh (Manager, Investment and Business Devleopment, MHI - America)
- Richard Skorpenske (VP Sustainability and Public Affairs, Covestro)
- Allison Starmann (General Counsel, American Chemistry Council)
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- Anonymous (1 person requested full anonymity)

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1. Summary of interviews with hydrogen ecosystem and private capital stakeholders

Introduction

This section summarizes the results of interviews and workshop discussions conducted as part of our study to better understand the practical aspects of growing an H_2 economy at scale and speed. The discussions examined both high-level strategic aspects that create "chicken-and-egg" situations as well as specific details related to practical challenges and barriers.

Participants in the study were selected from organizations across the entire H_2 value chain, including those with direct participation in the production, distribution and use of H_2, as well as critical enabling entities such as financing organizations, engineering service providers, and government. Hour-long interviews over Zoom were conducted with 30 people from 20 organizations during the 4th quarter of 2022. Study participants were senior-management level, with nearly 1000 years of collective professional experience. Prior to the interviews, participants were provided with a briefing packet that include some prompting questions. During the interviews, these questions were used as a starting point, and the discussion was allowed to explore the responses. Some interviewees and an additional 20 people were involved in discussions at two facilitated workshops co-hosted by Deloitte and the authors in Houston, Texas on Nov 30, 2022 and Jan 26, 2023.

All interviews and discussions were carried out under the Chatham House rule, wherein the content may be shared publicly under the condition that the identity of the source of the content remains anonymous. What follows is an anonymized record of comments and insights obtained during the interviews and discussion.

Organization of the summary

These notes are organized thematically. Comments have been transcribed to preserve the intent of the source, and may have been lightly edited to ensure anonymity per Chatham House rule. To preserve the essence of the interviews and discussions, contrasting or even contradictory positions held by different sources are reported.

Comments are grouped under the following topics:

- General observations and comments
    - Overview of H_2 landscape
    - Capital deployment for the energy transition
    - Historical analogies for the growth of H_2
- Corporate strategy, Business models, and Institutional factors
    - Decarbonization targets
    - Strategic decision-making
    - Capital discipline and Risk management
    - Business models
    - Role of government incentives

- Technical and economic aspects across the H_2 value chain
    - H_2 production, including "green" versus "blue"
    - H_2 distribution and storage
    - H_2 use
- Challenges to growing to scale at speed
    - Expectations on timing, sequencing and speed
    - Managing uncertainty
    - Building out supply chains, supporting infrastructure, and enabling capabilities
    - Creating standards and Supporting standardization
    - Mobilizing capital
    - Promoting cooperation and knowledge sharing
    - Watchlist of key developments that are indicative of progress

Overview of study participants

Participants in the study were selected from organizations across the entire H_2 value chain. This includes organizations with direct participation in the production, distribution and use of H_2, as well as critical enabling entities such as financing organizations, engineering service providers, and government.

Interviews were conducted with 30 people from 20 organizations during the 4th quarter of 2022. Study participants were senior management, with nearly 1000 years of collective professional experience. An additional 20 people were involved in the workshop discussions.

Methodology

The following question prompts were used during the interviews:
(Not all prompts were used in all interviews.)

1. Background
    - How would you describe your organization and your role in it?
    - What commitments has the organization made in relation to reducing GHG emissions?
    - What corporate commitments have been made that are relevant to clean H_2?

2. H_2 strategy and Business model
    - How do you think your customers think about CO_2 emissions (Scope 1&2 and Scope 3?)
    - What does your company think about the use of offsets in meeting decarbonization targets?
    - Please describe your business model for H_2 production or use, or supporting the H_2 ecosystem.
    - How would your organization determine a valuation for low CI H_2?
      - How would the premium be set?
      - Would you seek to "pass along" costs to customers?

- Expectations for value/premium over time (45V lasts 10 years, what happens after?)
- What supply chain certifications do you need to support a "low carbon" feedstock?
- Are there any technical or commercial barriers for "switching" to low carbon H_2?
- The rate of projects need to decarbonize H_2 use in the US chemical sector by 2035 and/or deliver clean H_2 at x10-20 the current level of H_2 by 2050 is very aggressive. What do you see as the key barriers to seeing multiple projects reach FID in this environment?

3. Capital discipline

- Please describe how your company thinks about business cycle and planning horizons
- Please give an overview of a capital decision process in your company.
- Please give an overview of a product strategy decision process in your company.
- How does cost and cost uncertainty impact the process?
- How does policy landscape and regulatory uncertainty impact the process?
- Please clarify financial assumptions used in your decision process.
  - What is the book life of a capital project?
  - What hurdle rates? (indicative ranges are ok)
- How does your process consider business cycle and economic conditions?

4. Clean energy finance

- Please describe the different types of financial actors investing in the energy transition
  - How do they cooperate, compete, and otherwise interact?
- What do you see as the biggest risks with investing in the energy transition?
- What are the biggest unknowns/uncertainties that make an opportunity "investable" vs "uninvestable"?
- What do you see as the biggest risks that are limiting the rate of investment in clean H_2 projects?
- What sectors do you see as leading vs lagging in moving towards the energy transition?
- What are your thoughts around the emerging business models related to decarbonization?
  - What are some of the approaches being used to establish valuation for carbon intensity reductions?

5. "Blue H_2" and CCS

- What are the planning horizons for various parts of the CCS chain?
- Please describe how your company is thinking about business model for CCS.
  - Is it a service? Who pays for CO_2?
  - How would hand-offs of CO_2 from capture to transport to sink be handled?
- What are the planning horizons for various parts of the CCS chain?
  - Do you use the same planning and financing assumptions for capital investments in capture vs transport vs storage? If not, how do they differ?
  - How does policy and regulatory uncertainty impact the process? (Is 45Q sufficient?)
- How do you think about long-term liability?
- How do incentives like 45Q or 45V impact how your company engages in project development?

6. "Green H_2" and Electrolysis
- What experience do you and your company have with electrolysis?
- From the perspective of project development, what do you see as the differences between "blue" H_2 projects vs "green" H_2 projects?
- What challenges do you anticipate in increasing the scale of electrolysis projects from the MW-scale towards GW-scale?
- What expectations do you have for the cost trajectory of electrolysis projects over the next decade?

Acronyms

45Q	Production tax credit for CCS
45V	Production tax credit for clean H_2
AEM	Anion exchange membrane
B2B	Business-to-business
BOP	Balance of plant
BP	British Petroleum
CCS	Carbon capture and storage
CHP	Combined heat and power
CfD	Contract for difference
CI	Carbon intensity (expressed as tCO_2 emitted per tH_2 produced)
DIY	Do it yourself
DOE	Department of Energy
DOT	Department of Transportation
EIS	Entry into service
EPC	Engineering procurement company
ESG	Environmental, Social and Governance
FEED	Front end engineering study
FID	Final investment decision
FOAK	First of a kind
HFCTO	Hydrogen and Fuel Cell Technologies Office, DOE
IGC	Industrial gas company
IIJA	Intrastructure Investment and Jobs Act
IRA	Inflation Reduction Act
ITC	Investment tax credit
LCFS	Low Carbon Fuel Standard
Mtpa	Millions of tons per annum
NFPA2	National Fire Protection Agency – H_2 Technologies code
NGCC	Natural gas combined cycle power plant
NOAK	Nth of a kind
O&G	Oil and gas

OCED	Office of Clean Energy Demonstrations, DOE
OEM	Original equipment manufacturer
O&M	Operations and maintenance
PE	Private equity
PEM	Polymer electrolyte membrane
PPA	Power purchase agreement -or- Product purchase agreements
PTC	Production tax credit
RD&D	Research, development and demonstration
REC	Renewable Energy Credits
ROI	Return on investment
S1	Scope 1 emissions
S2	Scope 2 emissions
S3	Scope 3 emissions
SAF	Sustainable aviation fuel
SOEC	Solid oxide electrolyte cell
TIC	Total investment cost
tpa	tons per annum
US	United States
VC	Venture capital
WACC	Weighted average cost of capital

General observations

- Overview of H_2 landscape
  - What is driving interest in H_2?
    - H_2 offers a path towards decarbonization.
      - No technology/approach (H_2 included) is a "silver bullet". Comprehensive approaches focusing on cradle-to-grave carbon tracking, can help different technologies/approaches find the proper niches.
      - Opportunities in the chemical industry include:
        - Direct replacement of higher CI H_2 with lower CI H_2 feedstock.
        - The use of low CI H_2 as a fuel to reduce emissions from the production of process heat and power is "low hanging fruit".
    - Government support and aspirations are "helping to accelerate the market"
      - Producers "see a path due to ITC and PTC from IIJA and IRA in the US, and incentives in other places."
      - Pre-IRA vs Post- IRA
        - Before IRA passage … "is Buy America enough?"

        - After IRA passage … best global incentives; players are asking to localize in the US … including Tier 2-4 suppliers.
        - The question for IIJA funding shifted from "let's which projects is viable" to "which projects need IIJA and which don't?
    - Strong corporate commitments reflect shareholder expectations.
        - Early traction with expansion of the industrial base network will help drive public acceptance and reinforce expectations for action.
- What are perceptions about the current state of play (4Q2020)?
    - There is strong interest in H_2 projects.
        - Companies have a variety of postures including:
            - "Lead the journey" because in compliance issues it is easier to lead than to lag.
            - "Want to see it happen, but don't want the risk of going first"
        - There is limited bandwidth across the energy capital projects landscape to support the current queue of possible projects.
            - "Aramco is planning to spend $150B through 2030, but this is nearly impossible due to limitations in people, supply chain, and logistics."
            - About half of energy projects at some engineering firms are related to the energy transition. This includes projects related to CCS, blue H_2, SAF, green methanol, and green H_2. Traditional petrochemical plant projects are being de-prioritized.
    - "More nuance needed" to help H_2 find the <u>right niches and use cases</u>.
        - More "nuance is needed" with respect to decarbonization pathways.
        - Expectations to "electrify everything", while technically possible, ignore situations where H_2 is a technically and economically superior alternative (e.g., "H_2" vs "electric" crackers)
    - Supply "push" is significantly stronger than demand "pull"
        - Pipeline: 7 Mtpa of supply, but only 0.1 Mtpa pipeline of "demand"
        - End users see possibilities due to government policy and incentives, but nothing credibly sustainable:
            - "Haven't identified an end user yet" … "Can't see H_2 today" because current buyers are only at the demonstration stage
            - Market pull for H_2 is generally weak; weaker for clean H_2
    - H_2 could be in the midst of a bubble.
        - "H_2 is at risk of being 'solar in 2003'."

        - The market is paying close attention to the success and failure of high visibility, early champions
        - If these players stumble significantly, it could drive a perception that this is just the latest in a series of "boom-bust" cycles
    - "Dented confidence" can be a problem and start a negative spiral
        - Analysts burned in the early 2000's "still carry scars".
        - If this happens, it might be necessary to wait for a "new generation of analysts" without the structural memory of the negative experience.
    - "Skepticism that energy transition will actually happen" discourages first mover action
  - Macro expectation: "approaching recession will slow investment and activity"

- Capital deployment for the energy transition
  - Capital discipline exists to ensure large projects are executed with managed risk.
    - Within an organization, decisions to <u>deploy capital</u> might be made by different parties within an organization (e.g., corporate) than decisions to <u>operate the asset and manage cash flow</u> (e.g., operations)
  - The energy transition presents a challenge, because the scale and pace requires substantial evolution of multiple sectors of the economy involving turnover of capital assets over the course of about one natural cycle.
    - The <u>scale</u> is a challenge because the capital required is of order $10s of trillions
    - The <u>pace</u> is a challenge because about 20-30 years corresponds to about one capital refresh cycle
    - The <u>complexity</u> is a challenge because multiple changes across different sectors will disrupt known technical and operating practices, as well as business models.
      - Modeling work provides guidance, but models use simplifying assumptions that mean their results need to be interpreted carefully.
      - The ambition of the energy transition suggests that underlying assumptions to models could evolve rapidly, leading to challenges from nonlinearities in extrapolation and in the interpretation of results.
    - To invest in capital projects, then there has to be some mechanism for a customer to share the risk and benefits.
    - Traditional players tend to default to incremental change and will focus on captive demand first and merchant demand afterwards (as the markets emerge).
  - Looking at the technical aspects of the transition, there is uncertainty on a number of fronts:

- There are a number of difficult system-wide challenges on the horizon:
  - Higher levels of renewable power onto the grid
  - Higher demand for power due to electrification
  - Development of supporting connective infrastructure for CO_2 and H_2
  - Establishing a valuation for carbon and reconfiguring business models to include this cost.
  - Scaling of supply chains to support large scale growth.
- Component technologies are at different levels of maturity. Slow progress could create problems with system functionality or economics.
- The pace of change (improvement) is fast relative to asset life.
  - This can create a perverse incentive to wait for the "next generation" that might have better performance or lower cost.
  - Paradoxically, this will slow the development curve.
  - In addition, the rapid pace of change can create information gaps where the ecosystem is not aware of the current state of the art, and different actors have divergent expectations for technology and cost.
  - Finally, the ecosystem may fragment among several standards before converging on a favored solution. This could lead to the stranding of assets that are on dis-favored technology branches.

- Collectively, these challenges increase the risk associated with capital projects and create an incentive to delay.
  - Of particular interest, are chicken-and-egg (cooperative) situations where two parties (e.g., a producer and user) need to cooperatively agree to take risk to achieve a new situation with mutual benefits. Hesitation on the part of either party can result in the default status quo.
- Capital can be obtained from different sources:
  - Traditional players
    - Examples: O&G companies, infrastructure funds
    - Mature processes, with clearly defined risk tolerance.
    - Large energy companies can "just do it" – self-finance (balance sheet) + has ability to execute (track record).
    - A challenge for traditional players is that the evolving H_2 landscape may present "risk" that makes it difficult to reach FID.
    - Infrastructure funds
      - Closed end funds have a 8-10 year time horizon and risk appetite/scope that varies based on the strategy pitched to investors. They seek to underwrite, and harvest (exit) in time window and are unlikely to be "ahead of the curve" in investing for the energy transition; prefer derisked projects.
      - Open end funds represent a larger pool of capital than closed end funds (e.g., sovereign wealth funds; Blackrock;

Blackstone) with no fixed harvest date so they can be flexible. They can be "more vocal, greater urgency," but can also take time to build expertise to deploy capital at scale.

- New entrants
  - Examples: VC, PE, pension funds
  - VC and PE may be good fit for early stage project definition (with smaller investment + early exit potential). This could be catalytic, but can also go wrong if it only results in "bubble" projects.
    - There is a need to move VC-type investors who are used to investing in technology towards the mindset of industrial O&G and utility investing.
  - Lower risk tolerance players (e.g., large pension funds) can support de-risked projects after FID, but will need a proven business model.
  - A significant fraction of the $130T cited by Mark Carney as "ready to invest" capital falls into the "new entrants" category.

- Incumbent infrastructure matters.
  - In sectors with established capital infrastructure, the desire to avoid stranding capital will drive the timing and nature of investment (e.g., near-term retrofits; delays in greenfield facilities).
- Single projects vs coordinated roll-out
  - Capital projects are assessed on a project-by-project basis. Individual companies will priorities different capital projects, but chicken-and-egg situations of building interdependent infrastructure poses a particular challenge.

- Historical analogies
  - Natural gas
    - The natural gas industry may offer useful analogies in understanding how to deploy capital, including pipelines.
    - Reforming is the dominant method of H_2 production in the US today; it could be a natural progression to evolve infrastructure and processes for a H_2 economy.
    - NG price and supply volatility are could be tailwinds for H_2, assuming the proce of clean H_2 could be stabilized (e.g., by low cost electricity for electrolysis).
  - Biofuels
    - Biofuels policy experience may provide a useful reference for the use of incentives and mandates to create demand (to both to <u>comply</u> and <u>overcomply</u>), as well as trading of credits in carbon markets.

Corporate strategy, Business models, and Institutional factors

- Decarbonization targets
  - Global perspective
    - Despite 2050 Net Zero pledges across most of the countries in which the organizations represented by study participants operate, some places (e.g., EU and Canada) are more amenable to action due to regulations and incentives, and companies will seek to make rational business decisions.
    - 2050 targets require major changes to infrastructure over one cycle of capital investment. Evolutionary change is unlikely to move "fast enough" to turn-over the infrastructure, so government Interventions are needed. These interventions need to be a market-supportive, catalytic, and temporary.
    - The passage of the IRA has significantly improved the landscape in the US.
  - Company-level perspective
    - Companies interviewed had 2050 Net Zero pledges, consistent with government commitments in the regions in which they operate.
    - Companies also had intermediate targets for CO_2 emissions reductions ranging from 15% to 60% by 2030 (vs 2020 levels).
    - Responsibility and resources for meeting commitments tended to be coordinated at the corporate level.

- Strategic decision-making
  - Prioritizing activities
    - Systematic analysis of opportunities and a staged approach beginning with existing infrastructure, then building the H_2 and CO_2 ecosystems.
    - Technology agnostic, but rational staging taking into account economics and local factors (e.g., business cycle, regional issues) to adjust timing.
    - "Offsets are needed for short term, but the goal is to achieve structural change, so offsets will only be used as a bridge."
  - Challenges that will need to be overcome
    - "Despite visionary aspirations, companies most qualified to deliver large complex projects will tend to default to incremental variations on their capital allocation that were developed for less dynamic business environments".
    - Risk of stranding assets; transition planning needs to account for this inertia
    - Cross-industry cooperation
      - "Industry's goal is to build moats."
      - Large companies understand their lane, and will defer to other large companies in their respective lanes. "Merchant H_2 projects fall under the domain of IGCs and that is not something that

makes sense [for a large multi-national equipment manufacturer] to get into at this time."

- "Developing the H_2 ecosystem will bring together multiple stakeholders with limited experience directly working together. This could create situations where working out terms will require time and effort."
    - A company pursuing a large electrolyzer project is used to being in the "driver's seat", but due to the large number of prospective projects, electrolyzer OEMs had leverage to be dictate terms. This is a departure from the historical power dynamics which have favored the large project company.
    - Two companies working on H_2 facilities on opposite sides of a river ended up designing separate pipeline infrastructure for their facilities rather than collaborating to create a single system. Sharing is hard.
- Industrial hubs offer the chance to share risk and supporting infrastructure.

▪ Decision-maker background
- Senior leadership in O&G companies and big players rose through the ranks, often from technical expertise. They may lack the detailed knowledge and experience to understand CO_2 and H_2 deeply, and this can create a barrier in terms of educating the decision-makers. In some cases, decision-makers may be embarrassed at their limited understanding and this could be a barrier to moving fast. Education can occur through bringing in experts, as well as incorporating briefings into the capital processes to clarify technical drivers and implications.
- One of the best ways to educate is through the concrete example of actual projects.

- Capital discipline process
    - Practical observations
        - Investment decisions are driven by economics. Sustainability = "tiebreaker".
        - "Good" projects have de-risked technology and execution, high quality credit, and strong business cases (e.g., long term PPAs)
        - For the H_2 economy there is a desire to move faster through the earlier stage "study" gates (pre-FEED and FEED). In response to pressure to accelerate, efforts to develop electrolyzer projects are following a "streamlined process":
            - Technology selection + Standardized design + FEED (fast)
            - Build + Operate
        - Investments in pre-FEED and FEED studies will be a % of TIC
            - Pre-FEED … >$1M; FEED … $5-10M; Project … $100sM to Bs

            - Permitting and financing costs will also add around 1-2% of TIC.
    - Key assumptions
        - The general principle of pushing risk to the party that is most able to cost-effectively deal with it needs to be applied in working on H_2 projects.
        - Cost of capital
            - WACC 10% ; Hurdle rates 13%
            - "For H_2 projects, looking for +2 to 5% higher than renewable power"
            - "Relatively stable since 2000, but not sure about the future"
        - Investment horizon
            - 30-50 year asset life; Net Zero implies all new assets must be low carbon
            - 10 to 20 years: Crackers 15 years; Derivatives equipment 10 years
        - Timeline for H_2 projects
            - Brownfield = 3 years from concept to design + optimize
            - Greenfield = additional time needed for permitting
            - Execution: 2 to 3 years
            - Total: 6 to 8 years form ideation to EIS for projects with internal offtake (both blue and green)
    - There is a difference between how <u>traditional players</u> and <u>new entrants</u> think about capital discipline.
        - Traditional players will run feasibility (at risk) studies, then FEED to get to FID.
            - $50-100M on a $2B project is not unreasonable
        - New entrants want to minimize or skip front-end.
            - Looking for "standard designs" or "modular" adoption, without appreciating the nature of the project.
            - One company tried to go to FID on a $2.5B project with only $50k diligence. They failed; the definition was inadequate to manage the risk

- Business models
    - Valuation and transaction of the carbon intensity attribute
        - Reductions in carbon intensity have cost and value, but how to value and transact this value is still an open question. As a result, it is unclear how to structure commercial transactions for low CI H_2 and demand is uncertain.
            - Producers bear the costs, and need some mechanism to recoup value; end users are interested in carbon reductions, but mechanisms to pay for this are still relatively immature.
            - Government subsidies can help, but are they sustainable long term?
            - Carbon trading markets are emerging, but only in some jurisdictions

        - EU, Alberta, California (LCFS), China
        - Voluntary carbon offset markets are emerging, but still early
    - H_2 is currently traded on the basis of purity (e.g., 99.999%), and carbon intensity is an attribute that can be tracked and traded.
        - Option 1. Physical custody transfers
            - CI is linked to physical molecule and traded via chain of custody.
            - Example: Certification that CO_2 for soda is not from a refinery
        - Option 2. Decouple CI credits from physical delivery + trade separately
            - This could avoid the need to physically transport H_2, leading to cost savings. Tracking methods would need to be implemented for validation and to avoid double-counting.
            - Example: RECs for wind and solar generation
    - Practical considerations
        - For processes (e.g., electrolysis) powered by grid electricity, the CI can change over time as the generation mix varies during the day. An average CI can be generated and traded as an aggregate property, or decoupled from the physical product and traded virtually.
        - Captive internal markets (e.g., refinery + chemical plant) a simpler path towards resolving business models.
- Transacting carbon reductions
    - Producers can currently be compensated for the cost of low CI via government subsidies (e.g., IRA PTC via 45Q or 45V). Long-term, the challenge will be to transition from government subsidies to private markets (e.g., end users).
    - Value propositions for end users
        - Some customers offer a premium for certified sustainability attributes
            - Personal care; Consumer electronics – brand companies, who are driven by marketing
            - Automotive – who have a long history of adoption of bio-derived and renewable content
            - Other market segments are lagging – e.g., Furniture + bedding
            - The volumes are still limited, and there is exploration of appropriate business models
        - Cost structure matters.

- If the relative contribution of H_2 to the total cost of a company's offering is small, then it has more room to offer a premium
  - For a company like Amazon, transport costs are a fraction of total cost of a product (relative to energy companies) so there could be more ability to pay
  - Specialty chemical companies (higher margin) are leading; commodity companies (lower margin) are waiting
- Methods for allocating carbon savings, including across the time frames needed to deliver the projects, will be a key to success.
- Currency
  - This a dynamic space, with lots of experimentation on business models
  - Early adopter "brand" customers might be willing to pay a premium on price, but the broader adoption may require other types of "currency."
    - Offtake contract attributes can be traded-off: Price - duration - volume (multiple sites) - optionality
    - Market share – some customers might trade price for the chance to capture share in existing or emerging markets
    - Co-investment (JV or capital support for projects; joint gov't funding bids, e.g., DOE H_2 hubs)
- Offtake agreements
  - Demand (offtake agreements) sets the schedule for capital deployment; contracts generally need to be finalized 6 to 12 months before FID
  - Contract duration
    - Longer is better, current H_2 offtake contracts vary, and it remains to be see how terms for low CI H_2 is evolve
  - Minimum asset utilization considerations
    - Blue H_2 (harder to turn down), need >70% capacity booked
    - Green H_2 (can be turned down), so can more appetite for merchant risk; power can be re-routed for other use

- Verification
  - Third party verification is essential. Efforts to define standards are underway, and are considering analogous markets (PPA, RECs) and methodologies (attributional or consequential).

- Role of government incentives
  - There are multiple modes of support that target different motivations. Different stakeholders control different buckets of money with different decision criteria.
    - Capital for projects: Loan guarantees, ITC

        - Operational cash flow: PTC
        - RD&D support: DOE funding from multiple offices
    - In the US, the IIJA and IRA incentives are quite attractive.
        - IRA - 45V (clean H_2) and 45Q (CCS) PTC
            - Direct pay option allows the subsidy to be split easily
            - Eligibility period < project life: 10 yr for 45V and 12 yr for 45Q
        - IIJA - H_2 hubs
            - Hubs goal is to drive efficacy and scale in support of CO_2 reduction and catalytic effect to scale afterwards. Will draw on previous DOE experience with smaller scale infrastructure programs to prove industrial scale (including business models)
            - Hubs funding will likely include data access terms to help stimulate knowledge sharing (paid for in part by public money) rather than just subsidize competitive moat building
    - Transition to market sustainability is a major question.
        - "Everyone is relying on the government" with the expectation a transition to a market solution will occur in the future.
        - PTC are expected to play a major role in getting projects started, but what happens after 45V and 45Q eligibility period? How does a project replace the revenue?

Technical and economic aspects across the H_2 value chain

- H_2 production
    - Green H_2: Electrolyzers + Renewable power
        - Project scale and deployment
            - "People think the technology risk is lower than it actually is"
            - Currently operating = 10 MW; FEED = 200 MW; Pre-FEED = 1 GW
            - Deployment is expected to occur in at least two waves of investment:
                - Wave 1 … first 5 to 10 projects
                - 200-500 MW scale projects
                - Get insight into costs and solve integration issues
                - Expectation of lower future costs is an incentive to wait; government support will need to drive the first wave
                - Wave 2
                - GW scale
                - System integration challenges - these projects will likely require storage in some form(s), including H2 storage, maybe energy storage to support matching production profile to use
                - Benefits from the learning generated by Wave 1 …

bigger if Wave 1 is successful; smaller if it is not

- Electrolyzer OEM profile
  - About 10-15 serious established companies + up to 30 smaller ones
  - Alkaline + PEM are the most mature technologies
    - Alkaline (3-4 players) is the lowest risk
    - PEM (3-4 players) offers benefit of flexible operation
    - SOEC + AEM are emerging, but still in the R&D stage
  - Likely evolution will be towards an ecosystem of multiple solutions

- Economics
  - Fixed cost tends to dominate, due to need for capital equipment – utilization is important
  - Cost contribution of electrolyzer equipment is about 30% versus about 70% for BOP; cost of construction is about 50%.
  - Power costs can be managed with PPAs, but expectations for cost trajectories are wide-ranging.
    - "This presents a business decision on whether a company wants exposure to the price volatility of feedstocks. If they are risk averse, they may want less volatility and could pay a premium. If they have good forecasting expertise, they may accept market risk to potentially lower future costs."
  - Optimistic forecasts of future cost reductions for electrolyzers creates an incentive for customers to delay – "why be first and pay a premium, when I can delay and pay less?"
- Matching of use profiles is important
  - Most large volume chemical end user processes are steady-state, so the low CI version also needs to be steady-state.

- Blue H_2: Fossil + CCS
  - Project scale and deployment
    - CO_2 capture can be done readily at reformers; capture from flue gas is more difficult, but commercially mature technologies are available.
    - The development of transport and storage (T&S) of CO_2, particularly pipelines is rate-limiting for CCS projects, including blue H_2
  - Pipeline considerations
    - Two models for pipeline development:
      - Large buildout (trunkline) vs Bootstrap (off existing networks)

- Decisions to proceed depend on sufficient commitment of CO_2 supply. A definitive agreement is needed, but not necessarily a term sheet.
- Some oversizing of the pipeline is standard, but the investment decision rests on lining up the "anchor" sources.
- Source projects take longer to reach FID and build than pipeline extensions, so risk to pipeline operators can be mitigated – if the source is committed, then there should be volumes available to support cost recovery for the pipeline.
- Public acceptance. Midwest pipeline developers are running into issues with community acceptance driven by use of eminent domain and perceptions of environmental risk around geological injection of CO_2.

- Economics
  - CCS value chain can be segmented or vertically integrated:
    - Segmented. Capture sites pay toll for T&S offtake, assessed as a fee on tonnage basis (typically $15-25/tCO2)
    - Vertically integrated. T&S operator pays source a fee ($5/t) for the CO_2, then develops capture to storage and claims 45Q
  - Capture economics
    - Opex for compressors at capture site can be up to $10/t
    - Accelerated capex recovery tied to 45Q eligibility (12 yr) is OK.
  - Different players across the value chain have differing hurdle rate assumptions for investment decisions.
    - Energy provider … 5-6%
    - O&G project … 11-12%
    - Midstream pipeline company 12.5 to 15%
    - "If these types of players are working together, they may value projects differently and this could become a barrier."
  - Comments on 45Q
    - "If the project economics are built around 45Q, it is possible to make it work profitably for 12 years. Without further incentives, the rational business decision could be shut down in Year 13. Additional revenue may be needed to continue operations."
    - Liability requirement: Current year + 3 previous years.
      - This creates an incredibly high reserves burden for a very low probability event.
      - The liability exposure suggests that smaller companies will not have the financial strength to backstop.

        - Insurance companies lack the expertise to properly value this risk. This creates a gap in insurance options.
        - A federal or state backstop could be a solution.

    - Green vs Blue
        - Color designations are confusing. Move to carbon intensity (viz., $kgCO_2/kgH_2$)
        - "Initial project mix is about 50-50% green and blue, but could shifting towards 70-30% in favor of green, depending on how the costs and landscape evolve."
        - Blue has a "100 year head start in technology maturation and project execution experience," but "faces risk of price volatility in NG." The feedstock price issue might be addressed by indexing the price of H_2 product to NG feedstock or using a CfD mechanism (e.g., UK).
        - "Green is too expensive today."
            - Current cost is $8/kg, dropping to $5/kg with most favorable IRA PTC
            - A number of things have to go right (reductions in power cost, supply chain, technology) to deliver on optimistic cost reduction expectations.
        - "Some companies will pay a premium for green over blue for narrative purposes."

- H_2 distribution
    - H_2 transport from production to use site is an important consideration
    - Multiple options exist for distribution
        - Truck (as a gas or liquid) is currently used
        - Pipeline transport
            - Blending is possible, but carries complications with purification.
            - Will vary depending on region of the country (CA, TX are leading)
            - Residential will be decades away given safety risks (including from DIYers)
        - Chemical carrier (ammonia, NH_3)
            - Replacement of traditional fossil fuel-derived NH_3 is not an issue. There are a number of pre-FEED and FEED studies (about half of the projects underway – 5 of 10/month) around green H_2 coupled with NH_3 production for energy export (shipping trade).
            - "The jury is out on NH_3." Cracking NH_3 back to H_2 raises questions about round-trip efficiency; in addition the technology is "not ready"
    - "The market for distributed (<100 MW) facilities based on containerized, modular solutions is expected to grow."
    - H_2 storage (salt caverns)

        - Salt caverns are considered the leading option for large volume storage of H_2. Such facilities are envisioned for buffering purposes and can expect 30-40 cycles per year (vs. 1-2 for NG seasonal storage).
        - Operating lifetimes are 30-50 year by experience, with potential to 100 years, when looking at broader uses from He or O&G storage. Store-recover cycles are driven by compressor capabilities.
    - "It would also be worthwhile to more systematically study the relative costs of moving H_2 (via pipelines) versus moving electrons (via new transmission lines)."

- H_2 usage
    - Broader range of opinions across H_2 users and downstream companies about the business case and willingness to pay a premium for clean H_2:
        - "There is a range of interest and enthusiasm – some customers are eager and others are ignorant; likewise, some suppliers are eager and others are ignorant."
        - "We would be willing to pay a premium for low CI H_2 if we can pass the costs downstream and not absorb the costs entirely."
        - "We have already signed multi-year PPA's and if clean hydrogen would be structured similarly, we would be willing to consider it. It always depends on the financials of the contract and to which sites we would receive the benefit. That defines our willingness to support the cost and length of a contract."
        - "We would expect a certification of the carbon emission reduction associated with the energy supplied. A third-party certification would be most valuable to us so we could then support price increases that would need to be shared downstream."
        - "As you move downstream, you lose visibility [into the clean H_2]." This could help as the cost structure implies a lower price premium, but could present challenges in tracking and valuing low CI.

Challenges to growing to scale at speed

- Expectations on timing, sequencing and speed
    - Competition for labor, resources, and supply chain will stretch out lead times.
    - Large capital projects take time.
        - Urgency is needed now + patience for the outcomes to be delivered given the scope, size, and complexity of the projects
        - Projects need to be viewed as "creating value" and the mechanisms to share risk and reward need to be synchronized to a project time horizon.
    - Taxonomy of players + their postures towards early action
        - IGCs are lynchpin players but secretive. They are focused on competing based on their infrastructure and business models. They have the domain expertise and incumbency, but are conservative/risk averse: "are we at

risk of being the useful idiots who derisk a project so other players can enter and cannibalize our benefits?"
        - Midstream players are needed to build connective infrastructure – H_2 pipelines for centralized green and blue, and CO_2 pipelines for blue.
        - Early movers on the demand side
            - Large strategic players with ESG commitments
            - What is the premium and strategic early movers are "willing to pay"?
        - Smaller companies that are trying to grow aggressively. Large companies have established relationships with each other, which provides a path towards cooperation at scale … but also inertia for smaller players looking to break in. Large companies will wonder if smaller companies can deliver (or even survive)?
    - Permitting (especially for pipelines) is rate-limiting.
        - The process has intrinsic uncertainty, especially impacting timelines. Overlapping permitting processes at the federal, state, and local levels.
        - Delays can be bad and increase fiscal risks especially during current inflationary times. Trend is toward increasing delays rather than streamlining.
        - Litigation risk is a real hurdle that can slow the process
            - Even after permitting approval, there is a period where legal challenges can be brought. This can add months or years to the permitting process.

- Managing uncertainty
    - Cost uncertainty can be managed, but not eliminated.
        - Option 1. Go with a conservative "high bid"
            - Reduces risk, but dampens enthusiasm.
        - Option 2. Bid low, and update with changes
            - Most common approach now; sparking a desire for standardized plants (modular design).
        - Option 3. Bid cost, and abandon if price over-runs become excessive.
    - Uncertainty slows things down, and the landscape is evolving
        - How can contracts be arranged to share risk?
        - How will things evolve as experience leads to price discovery?

- Building out supply chains, supporting infrastructure, and enabling capabilities
    - There are limitations to the pool of engineering talent and EPC bandwidth.
        - Engineering talent is rate limiting. There are not enough people to do all of the work for the current project deal flow. This is slowing the process.
        - Engineering services demand is about 100 projects/year, focusing on early stage definition efforts such as road-mapping and pre-FEED studies
    - There are concerns about the capacity of equipment manufacturers and their ability to expand production.

- It's a seller's market up through the chain.
    - OEMs have leverage because they have the core technology
    - This drives the actors to look for partnerships and value, rather than one-off projects. A portfolio of multiple (10-15) projects is attractive to vendors because is indicative of the potential to reduce overhead.
- However, there are questions about whether vendors will survive, be able to deliver, and scale up their production capacity.
    - Crowded vendor ecosystem can act as a "brake" on activity, due to the uncertainty from counter-party/partner risk.
    - Will there be a shakeout of vendors?
        - For example, wil a few electrolyzer companies emerge as the "go to" players en route to a more standardized set of offerings? Or will the landscape stay dynamic?
    - Can new companies grow fast enough?
        - "Sustained growth at >30% year-over-year is hard."

- Standards and Standardization
    - Data quality and standards (including for life cycle analysis and carbon accounting) need to improve to support development of the ecosystem
        - Currently, the landscape is a "wild west" in terms of offerings, claims, and capabilities
            - "How do we pick who to work with?" – applies to carbon trading, but also to ESG more generally
        - The landscape needs to mature and consolidate around a few industry-regulator accepted standards
        - A possible model for success comes from financial governance.
            - Here, credit ratings processes exist, and there are a few well-accepted, credible agencies that perform these functions.
            - The regulators are also bought in to the process.
            - It is unclear how to arrive at a similar situation for carbon."

    - Trade-offs between customization vs standardization
        - Different motivations from different stakeholders.
            - Corporate stakeholders and financiers can prefer standardization to optimize for speed and strategic considerations.
            - Asset owners (operations) will tend to prefer customization to allow the asset to perform as optimally as possible to meet local targets on efficiency, long-run O&M cost, etc.
        - Customized projects offer best economics and most effective operations Standardized projects offer faster delivery, and lower cost by the NOAK (for green H_2, the 5th project might be 30% lower cost).
        - At the level of project engineering, customization reduces cost (and is preferred by the individual asset owners). Standardization increases

speed by sharing information and reducing the number of design parameters. This can also allow deeper more confident supply chains to develop.
    - The reality is that this is not a binary choice. Some standardization is possible (e.g., modularization of electrolyzer systems), so the real question is finding the balance.

- Standardization of technologies
    - Potential for modularization
        - Creating partnerships with supply chain partners can provide the critical mass of deal flow and production volume needed to justify standardizing around a given module design
    - China is an interesting situation
        - Recent localization/reshoring mandates and subsidies in the EU and US may keep the market diversified
        - In the long-term, cost should win out and it is expected that Chinese production would them have the advantage and gain market share

- Standardization of projects
    - How could it occur?
        - Start with concept and feasibility studies, but then go to a standard EPC package in lieu of pre-FEED and FEED
            - Common practice for mature projects (e.g., wind and solar, NGCC, gas processing facilities in Permian basis for shale, other O&G projects) go directly to a EPC quote after feasibility study
        - Skipping pre-FEED and FEED has the potential to save 1 year of time and $5-10M in costs (on a $B project)
            - Enabled by standardization of offering
            - Requires more than 15 projects to provide an adequate experience base for EPCs
        - For electrolysis projects, standardization requires a coordination between or consolidation of 26 vendors today
    - Standardizing too early in the energy transition can increase risk.
        - Why standardize around this year's electrolysis offerings if the technology is advancing fast enough to force a re-standardization a year or so later?
        - Example: Deciding between 20 MW vs 50 MW scale for modules
    - Retrofits
        - The majority of existing assets for H_2 production use fossil inputs, primarily methane in the US. These are large capital assets, with book life that can extend for another decade or longer. In order to avoid stranded capital, retrofits will need to be considered to

decarbonize this production; this requires a degree of FEED work, so blue H_2 trajectories that involve retrofitting existing plants will benefit less from this standardization.

- Mobilizing capital
  - Going forward, there is a need to get pools of capital into the "proper lanes"
    - Different assumptions in capital discipline or business models
    - VCs and PE are willing to take front end risk
      - This aligns with helping first few projects, and also supporting the project pipeline at the pre-FID level.
  - The first few projects could provide:
    - Operating experience to derisk the project
    - Test cases to validate business models
    - Opportunities to identify weak links in the value chain for further improvement
    - Base enabling infrastructure that can catalyze future efforts
    - Catalytic demand to support expansion of supply chains
  - "The 'Silicon Valley' venture capital model is not well suited to energy transition because it tends to focus on technology. In the energy transition, technology is important, but there are many other practical issues related to scale-up for with the Silicon Valley model does not have experience."

- Promoting cooperation and knowledge sharing
  - Posture
    - Cooperation = speed, Competition = lower cost … How do we balance the two?
    - Companies are "conceptually comfortable" with collaboration. In the current landscape, there is "unprecedented collaboration" because companies have no other alternative. They need to work together to move forward in the window of opportunity.
    - Declarations of cooperation by senior management notwithstanding, many players in the H_2 space tend to have a culture of secrecy and competition when viewing project development; this makes it hard to drive towards standardization.
  - Value of learnings and sharing first mover risks and benefits
    - There are a lot of unknowns in terms of technology validation, business models, and operations profiles. Companies that invest in projects move up the learning curve. Companies that invest in projects move up the learning curve.
      - It can be kept proprietary to impart competitive advantage.
      - It can be shared to help accelerate the ecosystems growth.
      - This fundamental tension is exacerbated in a rapidly changing environment, and is an issue for the H_2 energy transition.

- Why would a company take the risk to invest in a new technology and then teach its competitors how to use it, rather than use its learning for its own competitive advantage?
- Sharing of precompetitive learning, especially via consortia is path forward.

- Regulatory barriers
  - Coordination across traditional players (O&G) might be difficult because of historical limitations related to collusion; these companies routinely set up Chinese walls (firewalls) between projects (including co-located ones) to comply with regulations and perceptions
  - Anti-trust laws have conditioned natural players like O&G to be very conservative and structured in their interactions. This can hinder innovation.
    - There is a historical sensitivity to anti-trust compliance in the chemical industry. This has resulted in practical challenges for coordination across large groups of companies across the value chain.
      - Chemical sector is "incestuous" in the web of supply relationships that exist. Anti-trust is taken very seriously.
      - This results in an "inhibition effect on collaboration", due to the actual and perceived risk of regulatory compliance.
      - Would it make sense to try to create a "safe harbor" designation to help speed up and create appetite for greater action?
    - General principles
      - US DOJ guiding principle: "competitors must compete". Rationale is to protect the consumer from collaborations that reduce options, increase costs, or otherwise reduce the benefits from market competition. Particularly focused on horizontal competitors, but can also extend to include vertical arrangements. Voluntary pledges from independent actors are ok, but formal agreements can invite scrutiny
      - Voluntary pledges for net zero aligned without explicit cooperation are a gray area. Evidence of coercion is a red flag.
    - How can companies collaborate without violating anti-trust regulations?
      - Direct government involvement
        - If the government is a driver, this provides cover for anti-trust. H_2 hubs will be an interesting test case
      - Standard setting organizations

            - Goal is to grow the market and promote competition for the benefit of consumers. Need to explain why things are pro-competition. Need to have a diverse set of views + broad representation from the ecosystem
        - Companies can collaborate to petition the government
            - There are questions as to how far can you go. Information sharing can leak from its original intended purpose to petition, into areas of competition
        - Open collaboration
            - A truly-open forum is ok. Open matchmaking that shows no unfair advantages conferred to some participants is allowed.
    - Role for government in stimulating change
        - Government needs to understand when to allow moats and when to intervene (without picking winners).
        - In pushing against barriers, the government has several tools:
            - Regulation
            - Funding
            - Convening power
            - Direct demand (e.g., fleets, procurement)
- Watchlist of key developments that are indicative of progress
    - Business models and economics
        - Market data on the "CI premium" – at what threshold is possible?
            - Different threshold for different market segments – depends on margins and elasticity curve for market share (and profitability)
            - How much will people pay in a tougher environment?
        - Adoption of common standards for tracking and trading CI reductions
        - Data on "actual" learning curve rates for electrolyzer cost
    - Supply chain and Critical infrastructure
        - Progress on H_2 and CO_2 pipelines
        - Consolidation of vendors
        - Consolidation around processes for accelerated project scoping and construction
        - Expansion of hubs
    - Policy
        - Carbon pricing
        - Targeted de-risking of permitting (e.g., "no regrets" byway approvals), insurance, and liability
        - Regulatory approvals
            - Adoption of NFPA2 for reduced refueling station setbacks
            - Approval for fuel cell vehicles to go through tunnels
            - Permitting of pipelines by DOT

- Adoption of national standards

2. Summary of Workshop 1

Princeton University (the authors) co-hosted a workshop with Deloitte on November 30, 2022 in Houston, TX. A total of 29 people participated in the event. This first workshop focused on the barriers to growth. Figure A1 shows the agenda and participants in the session.

AGENDA

ACT I	**ALIGN**
	Welcome and Context Setting
	Hydrogen Map Introduction
	What We Heard
	Hydrogen Value Chain Maps Overview
ACT II	**EXPLORE**
	Ideate on Barriers
	Barriers Debrief
ACT III	**ENVISION**
	Prioritize Barriers
	Prioritize Barrier - Debrief
	Brainstorm Enablers
	What's Next
	Closing and Cheers

LAB PARTICIPANTS

Participants	Deloitte
1. Tony Cornwell, *Advisian*	1. Shari Boyd
2. Yu-Cheng Hsu, *Mitsubishi*	2. Amy Chronis
3. Nigel Jenvey, *Baker Hughes*	3. Scott Corwin
4. Gary Martin, *Worley*	4. Matt Floyd
5. Jason Munster, *DOE/OCED*	5. Robert Kumpf
6. Michelle Noack, *DOW*	6. Michael McGowan
7. Ryo Okumura, *Mitsubishi*	7. Josh Nowak
8. Brett Perlman, *Center for Houston's Future*	8. Preeti Pincha
9. Brijesh Singh, *MHI Americas*	9. Geoff Tuff
10. Taylor Sugg, *Denbury*	10. Steven Weinert
11. Poh Boon Ung, *BP*	
12. Cindy Yeilding, *CHF, Denbury, BP (Retired)*	

Princeton	Deloitte Greenhouse
1. Chris Greig	1. Stephanie Chen
2. Anthony Ku	2. Cora Chiu
3. Eric Larson	3. Maya Hoyer
	4. Brooke Lerman

Figure A1. Agenda and Participants for Workshop 1.

The session opened with a "What we heard" exercise introducing participants to comments from individual interviews. Quotes were clustered by topic, and the participants were invited to indicate whether they agreed or disagreed with the sentiment. Results are shown in Figures A2 to A5.

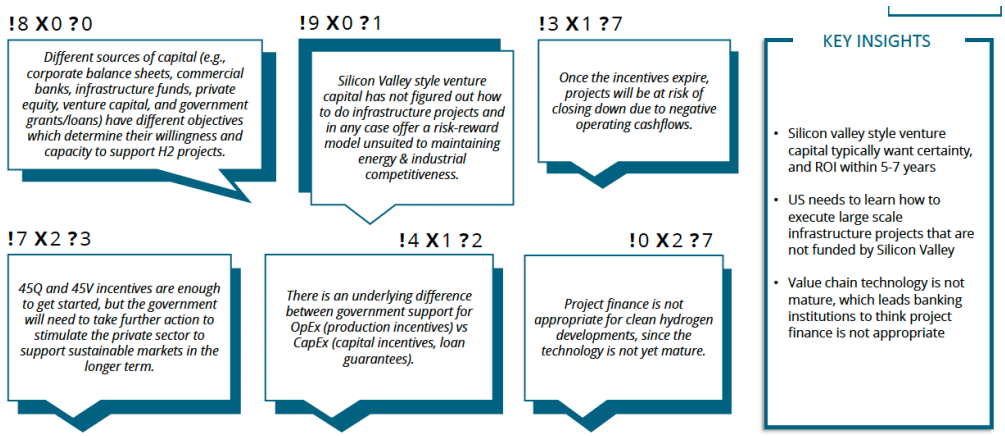


Figure A2. What we heard. ! = This is critical; X = disagree; ? needs more information

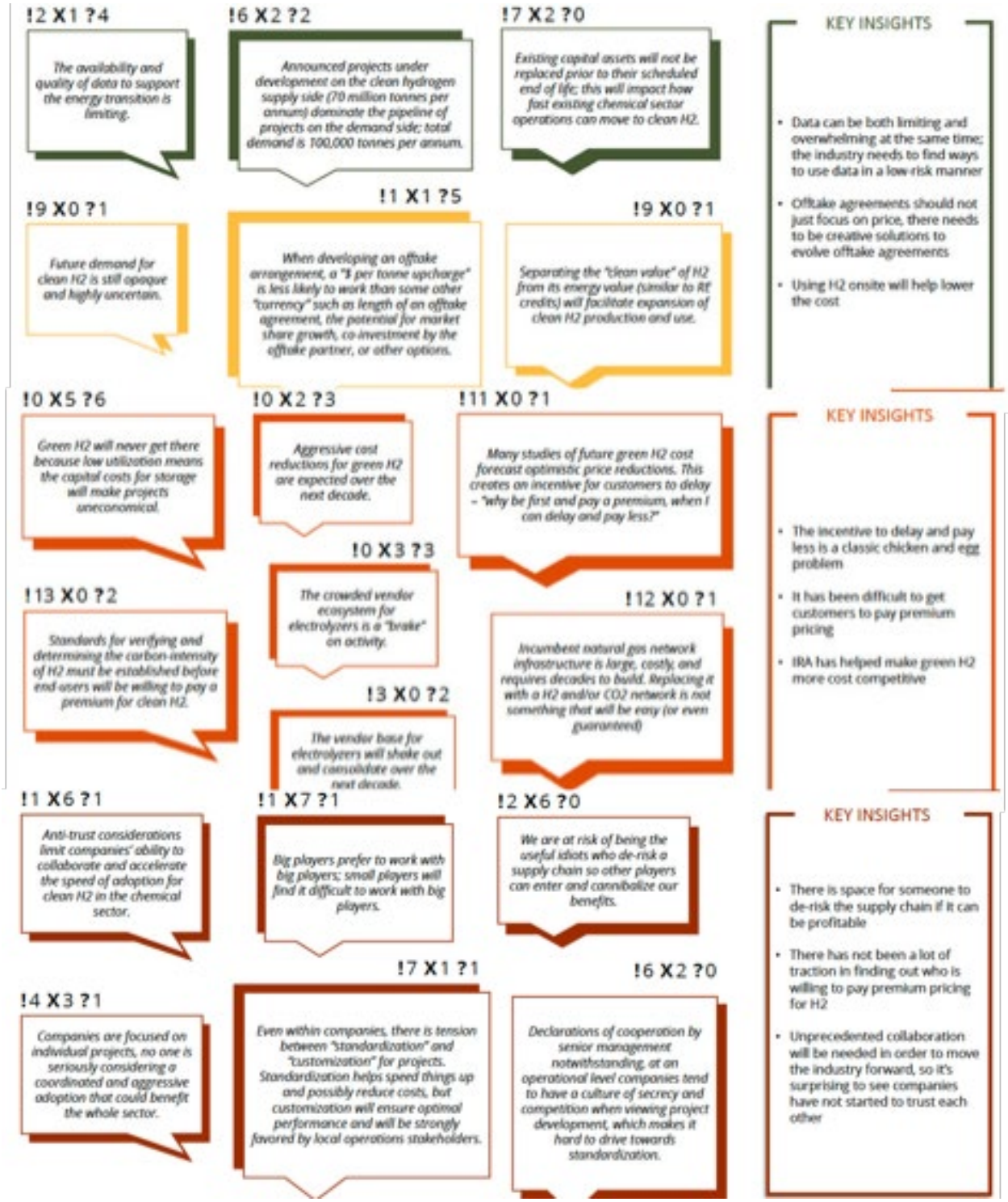


Figure A2. What we heard. ! = This is critical; X = disagree; ? needs more information

The next activity engaged participants in mapping different types of chicken-and-egg situations against the stakeholders involved in each situation. This taxonomy was used to identify and catalogue possible drivers within each theme:

- Business case and Economics – including business model incumbency, cost uncertainty, different expectations on contract terms, confusion around "co-opetition", and low "willingness to pay" for the low carbon intensity attribute;
- Supply chain and Enablers – including poor economics and scalability for equipment manufacturing, and unfavorable social license and economics for supporting infrastructure; and
- Process and Decision-making – including disconnects in incumbent capital discipline and risk management practices, challenges to existing competitive-cooperative arrangements, reluctance by first movers to share learning, uneven enthusiasm and investment in different parts of the ecosystem, and concerns about policy stability.

Workshop attendees were then asked to individually rank drivers in terms of importance and urgency from their perspective, and then reach a consensus view on the top three barriers:

(1) Willingness of off-takers to pay – focused on the underlying economics of investment decisions. This "barrier" includes not just weak demand signals and low absolute pricing levels, but also uncertainty in the evolution of cost and price trajectories over time, and market maturity and its capacity for price discovery. The consensus view was that this is true not just for primary producers of clean H_2, but also further downstream to primary users of clean H_2 who also require a willingness to pay from their end customers to justify the cost premiums for low carbon intensity;
(2) Risk management practices – as a general principle, organizations tend to "push risk" onto their counterparties. In uncertain environments, this can lead to impasses where neither party is willing to assume sufficient risk to allow a transaction to move forward. Participants offered examples in both capital investment decisions related to the primary production, distribution, and use of clean H_2, as well as in the broader ecosystem across the supply chain, supporting infrastructure, and financing communities; and
(3) Policy questions – government support in the US has opened a window of opportunity, not just for clean H_2 but also for other clean energy approaches. Participants noted uncertainty around the durability of policy support over the medium term (into the 2030's), its breadth across the ecosystem, and its effects on the balance of power in the ecosystem between well-established incumbent players and new entrants.

These themes are already well-recognized in general terms; however, the discussion uncovered important nuances on how these factors create sticking points in interactions between (and within) organizations at the level of the individual transactions needed to develop a robust and growing ecosystem. This level of resolution is necessary to identify targeted interventions – internal or external – to address the sequencing gaps responsible for most "chicken-and-egg" problems. For longer-term capital mobilization, a key aspect that underlies all three barriers is the effect of uncertainty over relevant decision time horizons. In stable environments, market participants have relatively mature processes to quantify and manage uncertainty in their investment and operating decisions. However, the energy transition made the landscape more volatile; this has introduced systemic risk which has disrupted traditional risk assessment processes. Risk is less well-understood in an environment where technologies, costs, business models, use cases, and competitive landscapes are subject to disruption over time scales shorter than periods typically needed for debt service on capital investments.

Figures A3 to A6 show primary outputs from the workshop discussions. At the end of the exercise, participants were asked to rank the barriers in terms of urgency and importance. Each participant was issued "currency" in the form of $20 which they could allocate amongst the different barriers. Results of this prioritization activity are shown in Figure A7.

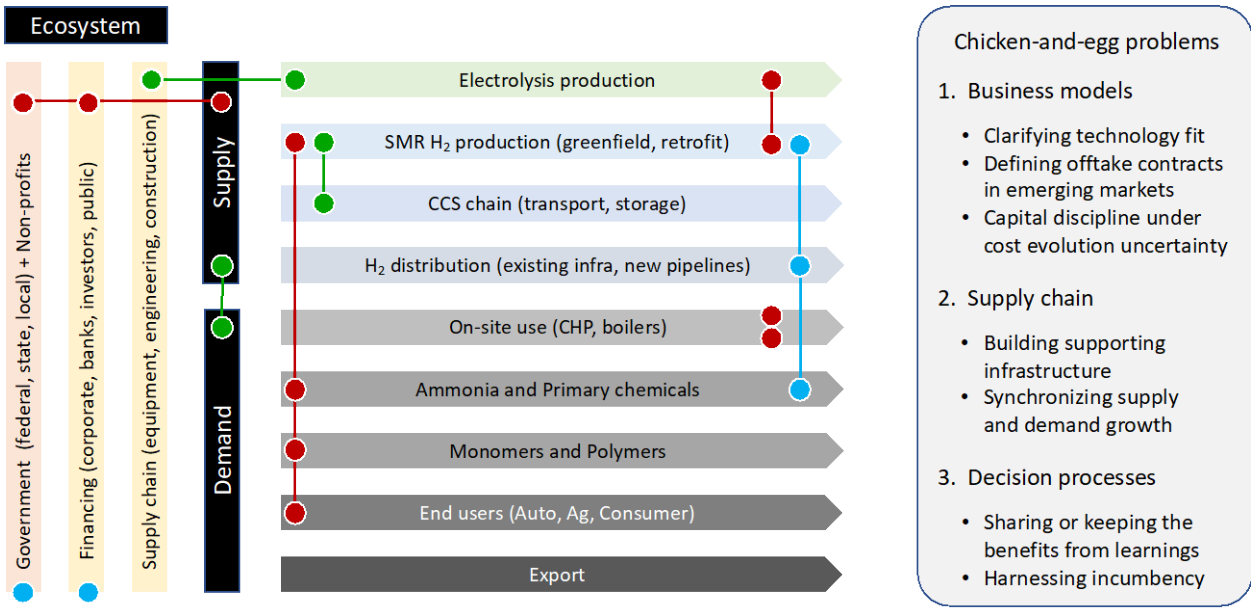


Figure A3. Map of stakeholders within the clean H_2 ecosystem, and types of chicken-and-egg problems encountered between various parties.

BUSINESS CASE AND ECONOMICS						
INCUMBENCY	UNCLEAR STANDARDS	UNCERTAINITY AND ECONOMICS	TERMS AND CONTRACTS	CO-OPETITION	WILLINGNESS TO PAY	MIDSTREAM
• Grey H2 is so deep that we aren't doing cost learning on low-CI H2 regulation required • Scale mismatch Ethylen3 = 3MT p.a Total clean H2 Today < C 1MT p.a • SMR is integrated into existing uses NH3 + MeOH • Path to break-even with incumbent tech needs to be very clear, but this requires coordination that isn't happening especially in OU+OI	• Unclear standards and verification processes	• Uncertainty of international competitive landscape introduces investment risk • Relative economics can shift due to relatability of inputs (e.g. NG, electricity) • Incentives (IRA) will need to be split across project; limited duration; erodes business case, could be showstopper / intensify competition • Lack offtake pricing driving project risks and increased cost	• Different owners, production, transport, use; Cost of capitol, timeline, assumptions, challenges • Contract terms: - Length of agreement - Tri-lateral parties • 3D → 4D Agreements • IP/Proprietary technology (rights/terms)	• Competition with other land use • Competition with other clean energy use • Clean electricity is needed for the entire electrolysis path. Broader sustainability • Coopetition for green electrons and water	• Unclear demand signals and lack of utilization projects • Willingness to pay by end users • Unclear demand for H2 suppliers • Unclear "willingness to pay" for a green premium...efficient uses and markets	• Green electricity production and transmission and water access is needed for electrolytic H2-permitting is too slow • Permitting challenges (external factor) • Midstream limitations delaying contract agreements • Insufficient distribution to meet demand in right timeframe

Figure A4. Summary of outcomes from Business Case and Economics discussion

SUPPLY CHAIN AND ENABLERS			
SCALE	ECONOMICS	EQUIPMENT	SUPPORT
• Scale of electrolysis production mismatched to key end uses • Supply chain to support blue H2 production is not sufficient	• Financing of H2 transport and distribution • Economics of clean H2 not favorable to reach scale • Lack of focus and investment in distribution infrastructure...Who owns and operates?	• Lack of H2 CHP/boilers suppliers. Lack of guarantees of performance eon H2 blends • H2 vehicle supply chain not available • Transportation refueling infrastructure needed to enable transport H2 demands	• Government and community support for H2 transport and distribution • Government and social license to support need for CCS to enable faster CCS development serving blue H2

Figure A5. Summary of outcomes from Supply Chain and Enablers discussion

PROCESS AND DECISION-MAKING				
RISK MANAGMENT	FEEDSTOCK	DEMAND CONDITIONS	POLICY QUESTIONS	ENABLING INFRASTRUCTURE
• Risk is being treated as dogma...addressing with traditional methods • SMR + CCS...Who handles storage? How to handle risk? • Everyone is trying to push the risk out to someone else • Lack of insurers for H2 an CCS projects	• Access to clean electrons and water • Lack of land for RE gas	• Balancing investment in demand and supply	• Early emphasis and attractiveness of exports detract from US decarbonization goals • Insufficient government support for demand application • Role of government? Political uncertainty • Emissions accounting unclear scope 1,2,3	• Lack of regulation framework for distribution and storage

Figure A6. Summary of outcomes from Process and Decision-Making discussion

Participants voted on the top 5 barriers that should be prioritized for resolution in order to rapidly scale a clean hydrogen economy.

Group	Barrier	Votes	Dollar
1	Desirability/willingness to pay	24	$240
3	Risk management	19	$190
3	Policy questions	13	$130
2	Economics	7	$70
1	Uncertainty and economics	6	$60
1	Terms / contracts	6	$60
2	Equipment	6	$60
1	Co-optition	4	$40
2	Scale	4	$40
1	Incumbency	3	$30
1	Unclear standards and verification process	2	$20
3	Demand conditions	2	$20
3	Enabling infrastructure	1	$10
1	Mid-stream	0	$0
1	H2 Midstream	0	$0
2	Support	0	$0
3	Feedstock	0	$0

Top 3 prioritized barriers

Tiebreaker for #5. By in-person voting, these barriers are in order of prioritization

Figure A7. Summary of consensus ranking of top barriers. “Dollar” value reflects importance weighting = participants were given “dollars” to do ranked choice voting.

The final Act of Workshop 1 involved group discussion and brainstorming around the drivers and possible enablers needed to address the top 3 barriers. The results of the group discussions are shown in Figures A8 to A10.

Figure A8. Brainstorm enablers. Willingness to Pay

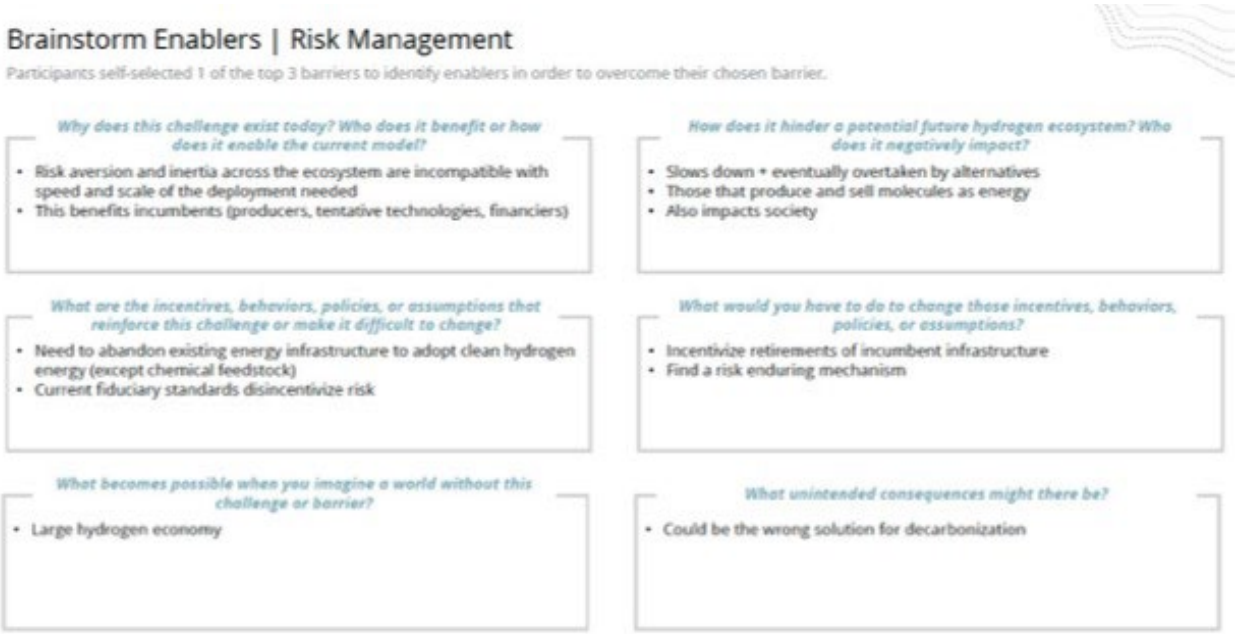


Figure A9. Brainstorm enablers. Risk management

Brainstorm Enablers | Policy Questions = Insufficient Policy Support

Participants self-selected 1 of the top 3 barriers to identify enablers in order to overcome their chosen barrier.

Why does this challenge exist today? Who does it benefit or how does it enable the current model?

- Industry is infancy, so government doesn't know how to set rules
- Incumbent industries benefit
- H2 is only part of the transition fighting for policy attention, and maybe not a large enough share of the solution

How does it hinder a potential future hydrogen ecosystem? Who does it negatively impact?

- Difficult to establish working markets rapidly
- Risk of policy change or lack of confidence in durability
- Risk of permitting delays

What are the incentives, behaviors, policies, or assumptions that reinforce this challenge or make it difficult to change?

- Pressure to get policy "perfect" hinders action
- Strong incumbent industries

What would you have to do to change those incentives, behaviors, policies, or assumptions?

- Establish standards, demand side incentives, permitting, and carbon pricing
- Promote education on value and risks or H2 and development timelines
- Hubs facilitate scaling
- Learn from precedent, e.g., wind, solar, oil and gas

What becomes possible when you imagine a world without this challenge or barrier?

- World domination – lead the H2 industry... USA, USA, USA!
- Success with H2 can spill over to the other energy policy areas

What unintended consequences might there be?

- Shiny penny syndrome (no silver bullet)
- Going too fast to anticipate and mitigate negative impacts
- Picking the wrong policy and not adjusting

Figure A10. Brainstorm enablers. Policy questions

Figure A11 shows a graphic summary of Workshop 1.

Figure A11. Graphic summary of Workshop 1.

3. Summary of Workshop 2

Princeton University (the authors) co-hosted a workshop with Deloitte on January 26, 2022 in Houston, TX. A total of 33 people participated in the event, with roughly half having also participated in Workshop 1. This first workshop focused on the enablers growth. Figure A12 shows the agenda and participants in the session.

AGENDA

	REFRESH
ACT I	Energizer
	Welcome and Opening Remarks
	Lab 1 Recap
	Framework Overview and H_2 Incentives
	DISCOVER
ACT II	Art of the Possible/Probable
	Generate Strategy
	CATALYZE
	Making it Real
ACT III	Making it Real- Debrief
	What's Next
	Closing and Cheers

LAB PARTICIPANTS

Participants

1. Ben Condon, *ECPGP*
2. Cherish Giovinazzo, *H2U Technologies*
3. Nigel Jenvey, *Baker Hughes*
4. Alex Kizer, *Energy Future Initiatives*
5. David G. Malobicky, *PPG*
6. Gary Martin, *Worley*
7. Ryan Masumoto, *MHI Americas*
8. Jason Munster, *DOE/OCED*
9. Michelle Noack, *DOW*
10. Tyler Palmer, *Denbury*
11. Brett Perlman, *Center for Houston's Future*
12. Brijesh Singh, *MHI Americas*
13. James Wang, *Ara Partners*
14. Cindy Yeilding, *CHF, Denbury, BP (Retired)*

Deloitte

1. Shari Boyd
2. Amy Chronis
3. Scott Corwin
4. Alexander Fleming
5. Matt Floyd
6. Hank Haligowski
7. Bob Kumpf
8. Michael McGowan
9. Josh Nowak
10. Derek Pankratz
11. Jessica Perkins
12. Preeti Pincha
13. Geoff Tuff
14. Sharene Williams

Princeton

1. Chris Greig
2. Anthony Ku
3. Eric Larson

Deloitte Greenhouse

1. Cora Chiu
2. Maya Hoyer
3. Brooke Lerman

Figure A12. Agenda and Participants for Workshop 2.

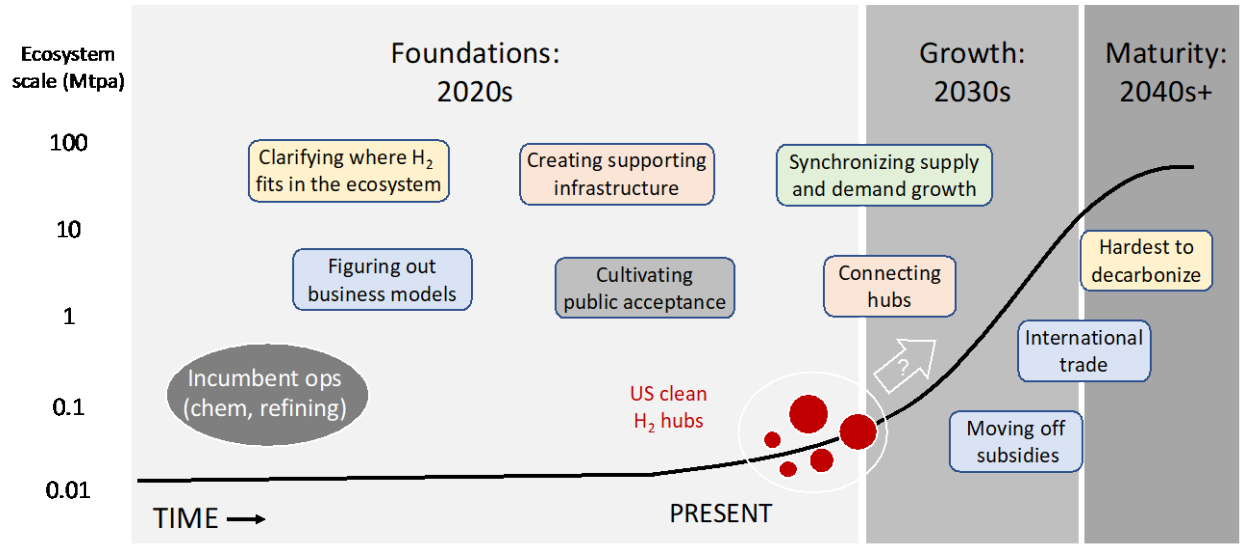


Figure A13. Summary of enabling capabilities that are needed to support evolution of the clean H_2 ecosystem in the US as it progresses from Foundations to Growth to Maturity.

This second workshop examined enablers for a rapid, expansive, and sustainable growth of a clean H_2 ecosystem. The workshop used an S-curve framework, shown in Figure A13, to conceptualize the stages of growth.

In the first exercise, participants were asked to identify the essential features necessary in three areas:

- establishing use case clarity;
- enabling market formation; and
- creating a sufficient base of supporting infrastructure and equipment supply to allow expansion of clean H_2 production and use by an order of magnitude or more over a decade time frame.

Figures A14 to A19 show background information that was provided to participants concerning use cases. Figures A20 to A23 show the results of discussions on the use cases.

Chemicals

Use case: **H_2 is a feedstock for chemicals process**

Alternatives: **H_2 produced via traditional high CI approaches**

What is the state of play?

Blue and green ammonia projects
Blue pilots for large chemicals processes
Strong support from subsidies

How much of a role does economic uncertainty play, and what can be done about managing it to allow decisions to move forward (for each scale of growth?)

Clean H2 commands a premium. Initially covered by IRA PTCs (45V or 45Q).
Long term, market needs to develop a mechanism to pay for low CI.

How fast is the H2 capability evolving? How fast are competitive capabilities evolving?
How are the tech and commercial risks similar? What tech and commercial risks differ?

H2 as a feedstock is going to be hard to displace. The question is blue v green, and cost.

What early indicators might we see that H2 will "win", "lose", or "draw"?

Adoption via blue projects with IRA PTC by late 2020s.

Figure A14. Background information on Use case: Chemicals

Transport

Use case: H_2 for fuel cell vehicles (HDV – high utilization fleet; long haul; trucking)

Alternatives: Battery electric vehicles; Biofuels

What is the state of play? Battery EV has a lead in LDV; HDV to be decided; biofuels are also in play.

How much of a role does economic uncertainty play, and what can be done about managing it to allow decisions to move forward (for each scale of growth?)

TCO matters, as does price volatility. For HDV, use cases requirements (range, fueling speed, vehicle weight) are advantages for H2. Fueling infrastructure and costs are currently limiting.

How fast is the H2 capability evolving? How fast are competitive capabilities evolving?
How are the tech and commercial risks similar? What tech and commercial risks differ?

There is aggressive competition for the HDV use case. Depends on how fast fueling infrastructure and costs can be addressed. Battery cost and charge speed/capacity are evolving.

What early indicators might we see that H2 will "win", "lose", or "draw"?

Bus fleet pilots are under way; trucking pilots start ramping up in 2023.

Figure A15. Background information on Use case: Transportation

Power

Use case: H_2 for gas turbines; H_2 for distributed fuel cells

Alternatives: Renewables + grid; Microgrids

What is the state of play? Turbine OEMs are working on H_2 and NH_3 capability.
Could offer grid services. Questions around NH_3 energy trade.

How much of a role does economic uncertainty play, and what can be done about managing it to allow decisions to move forward (for each scale of growth?)

LCOE matters, but so does the H_2 production and delivery ecosystem. Conversion of NG infrastructure to H_2 for use in turbines requires changes in pipeline and hardware. Blending is possible, but H_2 volumetric thermal content is 1/3 lower than NG, so pipeline balance is needed.

How fast is the H2 capability evolving? How fast are competitive capabilities evolving?
How are the tech and commercial risks similar? What tech and commercial risks differ?

Some pilots in H_2 turbines and pipeline blending. Turbines with NH_3 capability also being demonstrated. Commercial uncertainties around other power generation impacts.

What early indicators might we see that H2 will "win", "lose", or "draw"?

H_2 and NH_3 turbine demos are planned. Large scale demos and commercial EIS schedules in the 2030s?

Figure A16. Background information on Use case: Power

Industry

Use case: H_2 for metals making

Alternatives:

Full decarbonization possible

	Strategy	Examples	Current outlook
Electric arc furnace (EAF)	Maximize secondary flows and recycling by melting more scrap in EAF	EAF – usage to melt scrap	Technology readily available at competitive cost
DRI plus EAF using natural gas	Increase usage of DRI in the EAF	Current DRI plus EAF plants using natural gas (NG)	Technology readily available
DRI plus EAF using H_2	Replace fossil fuels in DRI process with renewable energy or H_2	MIDREX DRI process running on H_2 HYL DRI process running on H_2	Technology available at high cost

What is the state of play?

https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel

https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS_BRI(2020)641552_EN.pdf

How much of a role does economic uncertainty play, and what can be done about managing it to allow decisions to move forward (for each scale of growth?)

How fast is the H2 capability evolving? How fast are competitive capabilities evolving?
How are the tech and commercial risks similar? What tech and commercial risks differ?

What early indicators might we see that H2 will "win", "lose", or "draw"?

Pilots in the 2025-2035 period, but limited commercial driver right now. This could be a latter, hard-to-decarbonize use.

Figure A17. Background information on Use case: Industry

Heat

Use case: H_2 for low CI C&I cogen ; H_2 for residential burners

Alternatives: Electric heat, CCS for low CI cogen ; Heat pumps for residential

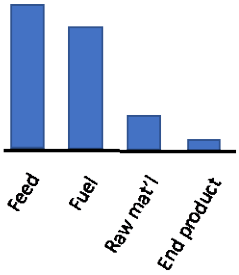
What is the state of play? Low CI cogen could be accomplished via (1) CCS; (2) H2 fuel; (3) electric.
Cost is a driver, since the user would need to receive compensation for the lower CI value.

Low CI residential heat from burning H_2 instead of NG competes with electric heating/heat pumps.

How much of a role does economic uncertainty play, and what can be done about managing it to allow decisions to move forward (for each scale of growth?)

Cogen heat is embedded in industrial processes, so there may be the ability to receive value.
As you move down the value chain, the heatcost is a smaller part of the overall cost stack.

H_2 contribution to product cost stack



How fast is the H2 capability evolving? How fast are competitive capabilities evolving?
How are the tech and commercial risks similar? What tech and commercial risks differ?

Pilots by chemical industry users for cogen. (Cracker H2 used for cogen).

What early indicators might we see that H2 will "win", "lose", or "draw"?

Technically possible, but need to solidify commercial case for adoption.

Princeton University Confidential Information

Figure A18. Background information on Use case: Heat

Trade

Use case: H_2 or NH_3 as an energy carrier for export/energy trade

Alternatives: Electric heat, CCS for low CI cogen ; Heat pumps for residential

What is the state of play? There is exploration of H2 as an energy carrier, shipped as NH_3, LH_2, or LOHC. Pilots are underway, but it is unclear how fast the full ecosystem can develop.

How much of a role does economic uncertainty play, and what can be done about managing it to allow decisions to move forward (for each scale of growth?)

Global decoupling is distorting energy markets. Seaborne trade could compete with build out of renewables/nuclear + grid

How fast is the H2 capability evolving? How fast are competitive capabilities evolving?
How are the tech and commercial risks similar? What tech and commercial risks differ?

NH_3 is shipped and LH_2 pilot was done in 2022. Shipping is technically feasible, but the commercial case is still evolving. There is serious consideration by credible companies, and geopolitics will matter.

What early indicators might we see that H2 will "win", "lose", or "draw"?

Technical development seems to continue through the 2020's. Commercial and geopolitical factors may ultimately decide the viability and scale.

Figure A19. Background information on Use case: Trade

Please indicate in the relevant box below whether this use case in a "winning move"

CHEMICALS		
Up to 1 mtpa 15 Votes	1 to 10 mtpa 15 Votes	10+ mtpa 11 Votes

What are the signs that will indicate if H_2 is a winning or losing use case ?

- Serious H_2 pipeline buildouts ← growth and maturity (ACTUALLY GETTING PERMITS AND BUILDING PIPELINES)
- Contracts for clean H2 in the mkt ← foundation
- Increase H2 utilization equipment orders
- CI requirements for exports or domestic use
- Relatively ready offtake and high C.I today (i.e., Large GHG reduction potential)
- Politically important use cases/geographies
- Green Hydrogen (Co.45Kg) accounting for major share is a strong indication
- Demand drivers (Carbon price, ESG, LCFS, etc.)

Figure A20. Summary of outcomes from Use Cases: Chemicals discussion

Please indicate in the relevant box below whether this use case in a "winning move"

TRANSPORT

Up to 1 mtpa	1 to 10 mtpa	10+ mtpa
3 Votes	9 Votes	9 Votes

What are the signs that will indicate if H_2 is a winning or losing use case ?

- Number of H_2 refueling stations
- Vehicle manufacturing of FCVs + Increased state-wise regulations (e.g., CA CARB) on trucking transition 2035? + refueling stations on major truck routes
  Using H2 to U AMAZON | H2 Tesla
- Sea-borne vessel fueling w/ H_2 carriers
- Losing ease with cost declines, infrastructure buildout, vehicle costs of electric
- Losing if safety incidents w/ H_2
- HD OEM puts FC (H_2) or Hybrid in mainline product (Class 8 Tractor)
- Bragging rights "delivered via H_2" – market demand especially fleets
- Loss of public support if catastrophic explosions/risk incidents/safety
- Public understanding/acceptance

Figure A21. Summary of outcomes from Use Cases: Transport discussion

Please indicate in the relevant box below whether this use case in a "winning move"

INDUSTRY

Up to 1 mtpa	1 to 10 mtpa	10+ mtpa
7 Votes	7 Votes	9 Votes

What are the signs that will indicate if H_2 is a winning or losing use case ?

- Equipment orders increase
- CI requirements for exports
- Politically important to decarbonize (There is a political imperative to decarbonize US industry and H_2 is promising option)
- Steel mill OPEX performance after transition
- Net zero steel?
- Difficult to pilot → Pilot would indicate growth
- Regulation may be required to drive switch to H_2

Figure A22. Summary of outcomes from Use Cases: Industry discussion

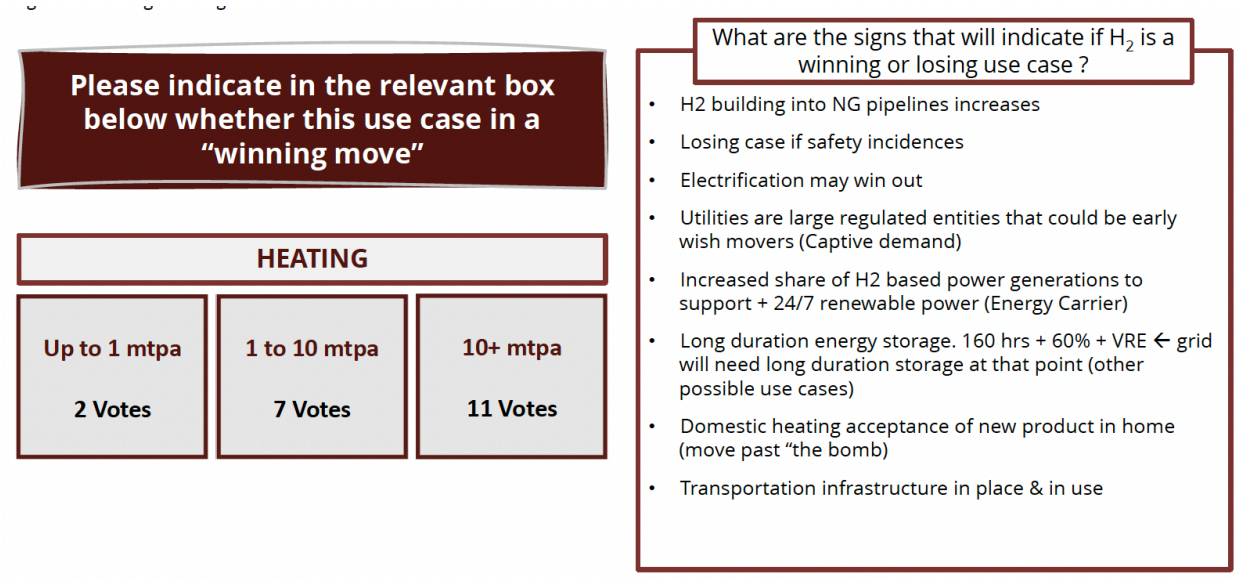


Figure A23. Summary of outcomes from Use Cases: Heating discussion

Figures A24 and A25 show background information provided to participants for the Market development discussions, and Figures A26 to A28 show the results of the discussions.

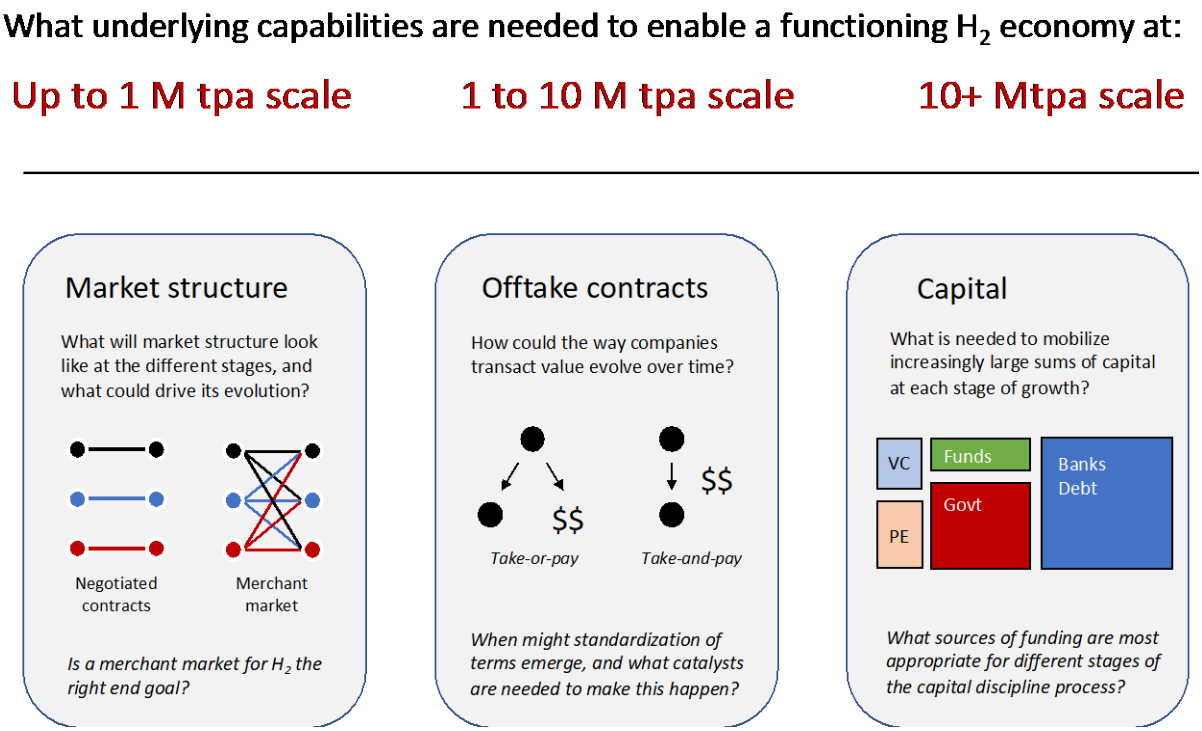


Figure A24. Background information: Market development

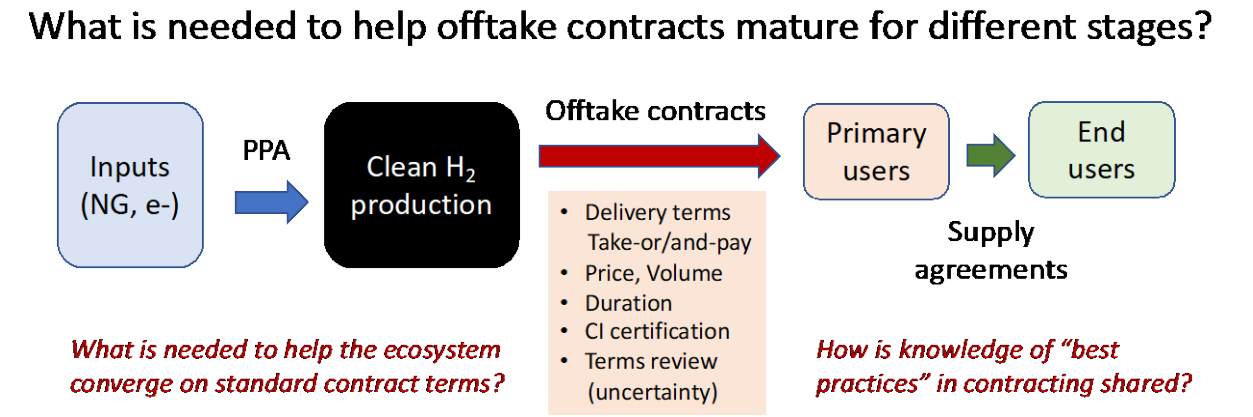


Figure A25. Background information: Market development

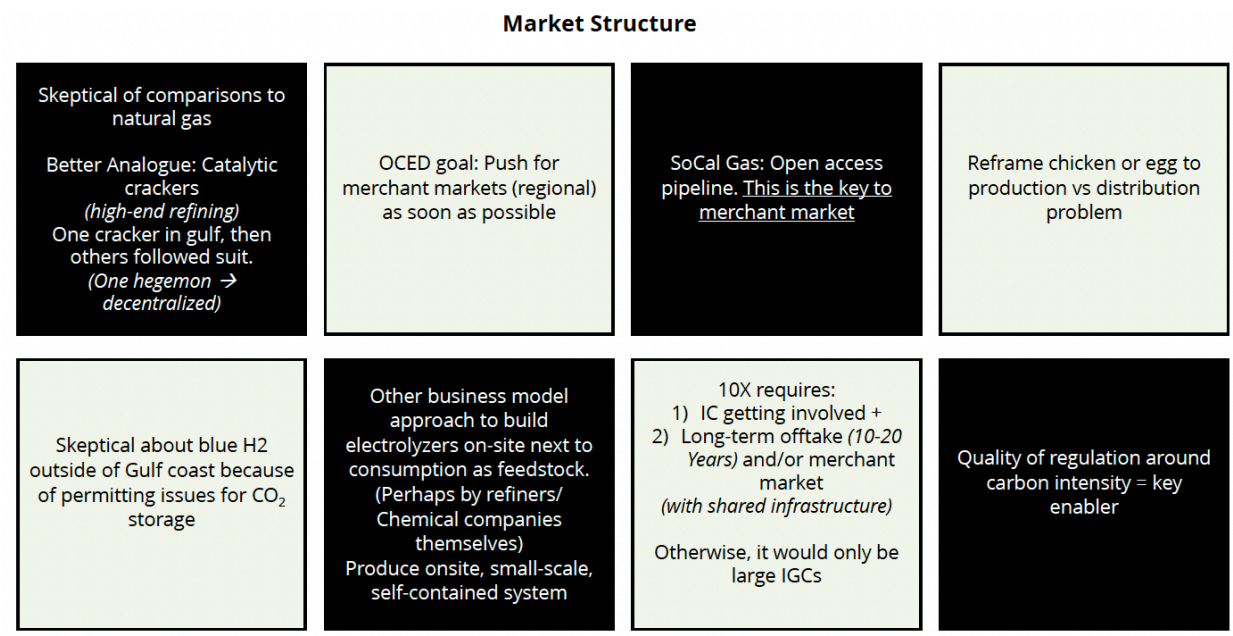


Figure A25. Summary of outcomes from Market Development 1 discussion

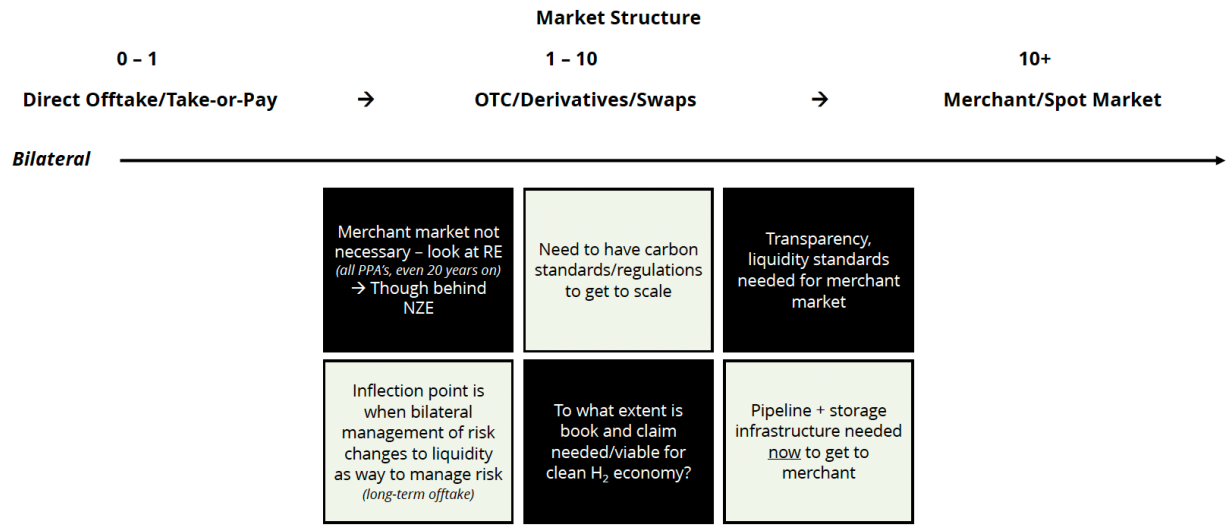


Figure A26. Summary of outcomes from Market Development 2 discussion

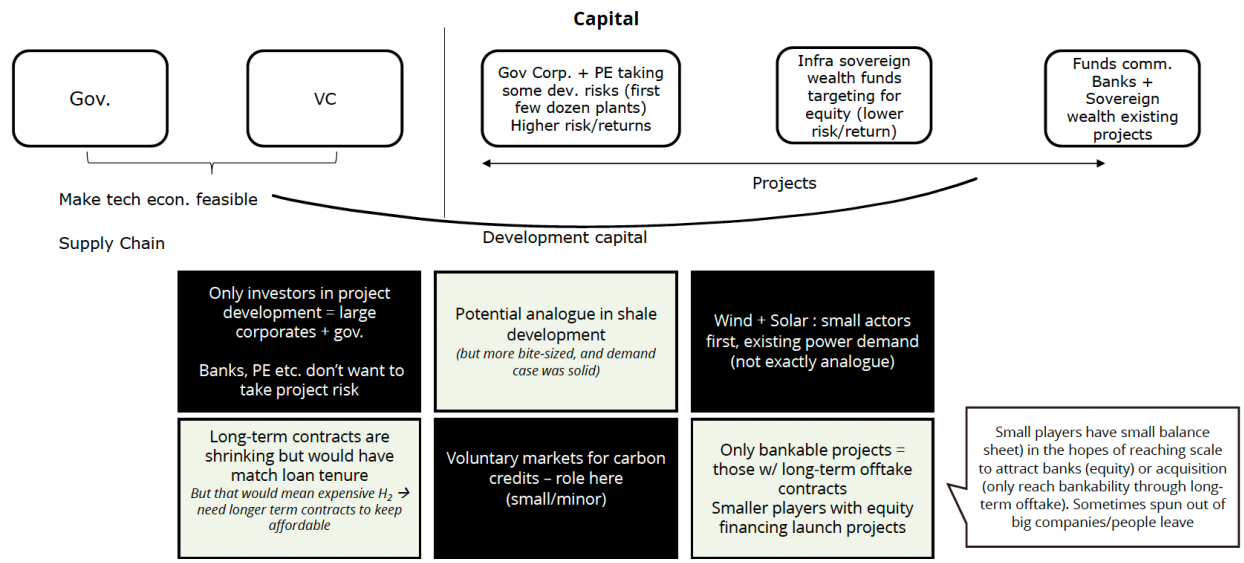


Figure A27. Summary of outcomes from Capital Mobilization discussion

Figures A28 to A30 show background information provided to participants for the Infrastructure develop discussions, and Figures A31 to A33 show the results of the discussions.

What underlying capabilities are needed to enable a functioning H_2 economy at:

Up to 1 M tpa scale **1 to 10 M tpa scale** **10+ Mtpa scale**

Distribution networks

What enabling physical infrastructure is needed to grow markets to 1, 10 and 100 Mtpa scale?

- H_2 pipelines
- CO_2 pipelines for CCS
- Power grid for green H_2
- H_2 storage

What will networks look like at each stage of growth?
Who will build and operate each type of network?
What is needed to help these networks evolve in time for expected market growth?

Supply chain growth

What capabilities are needed to synchronize supply and demand growth at different stages of growth?

47 GW/yr	54 GW/yr Announced
Electrolyzer mfg capacity (2030)	94 GW/yr Pledged Projected demand

What lessons can be adapted from industries that have rapidly scaled manufacturing capacity?

Figure A28. Background information for Infrastructure development discussions.

Distribution networks

What might connective infrastructure look like at the 1, 10 and 100 Mtpa scale?

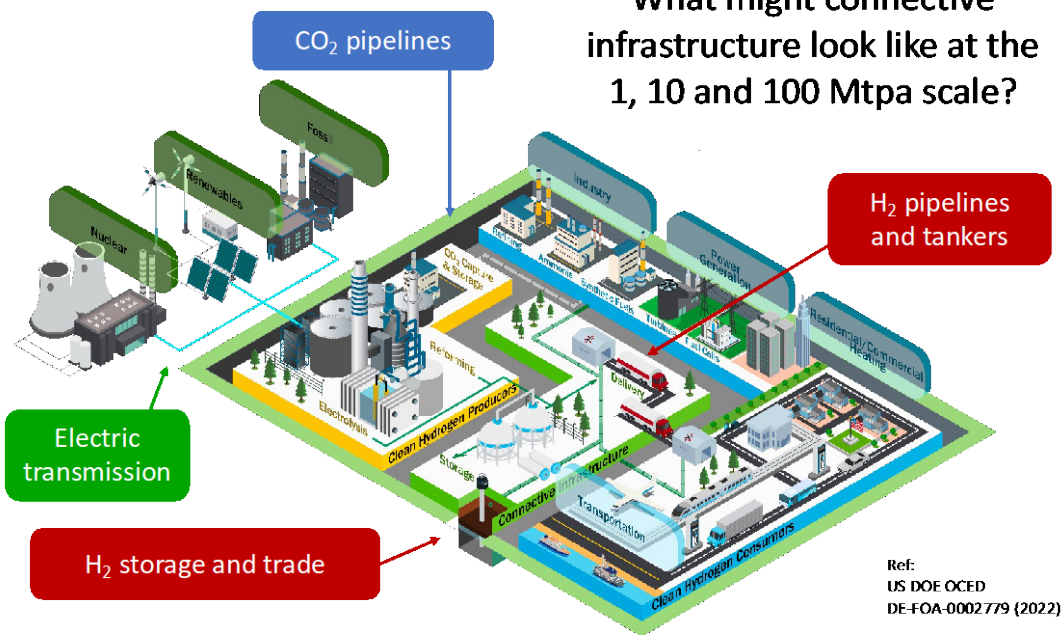


Figure A29. Background information for Infrastructure development discussions.

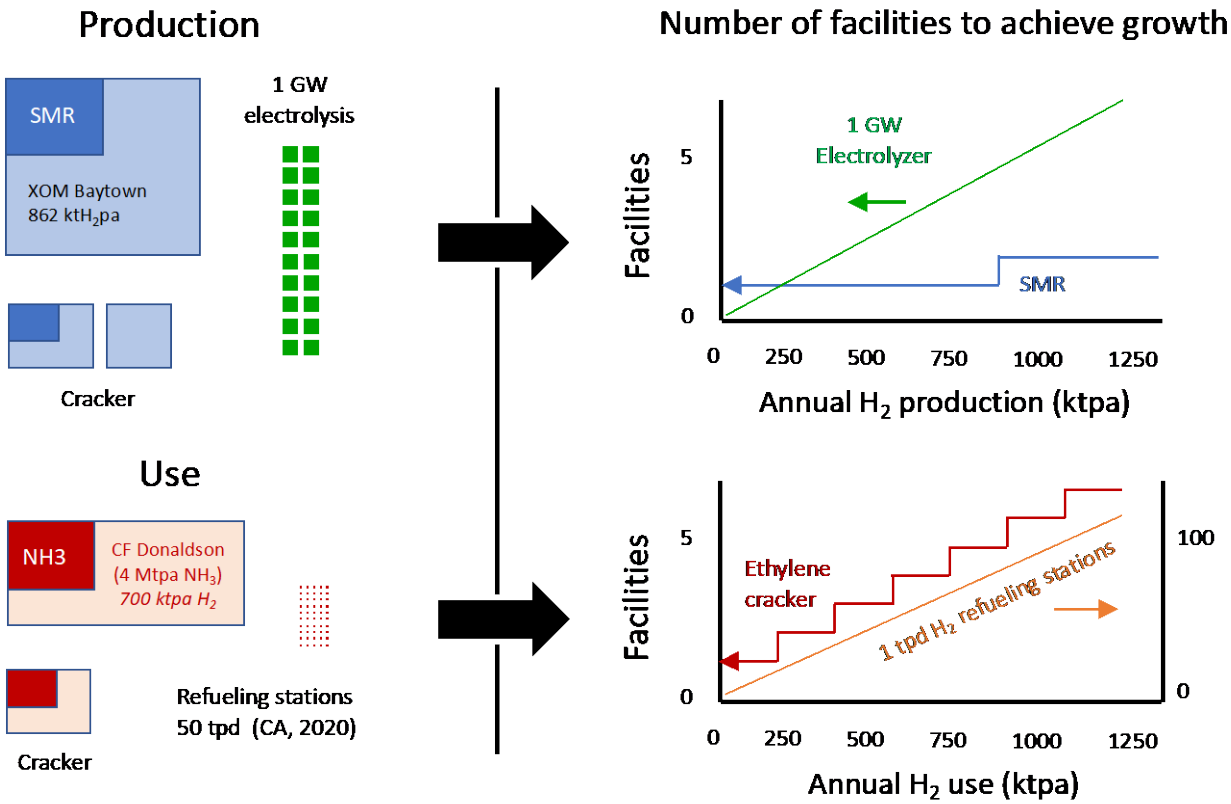


Figure A30. Background information for Infrastructure development discussions.

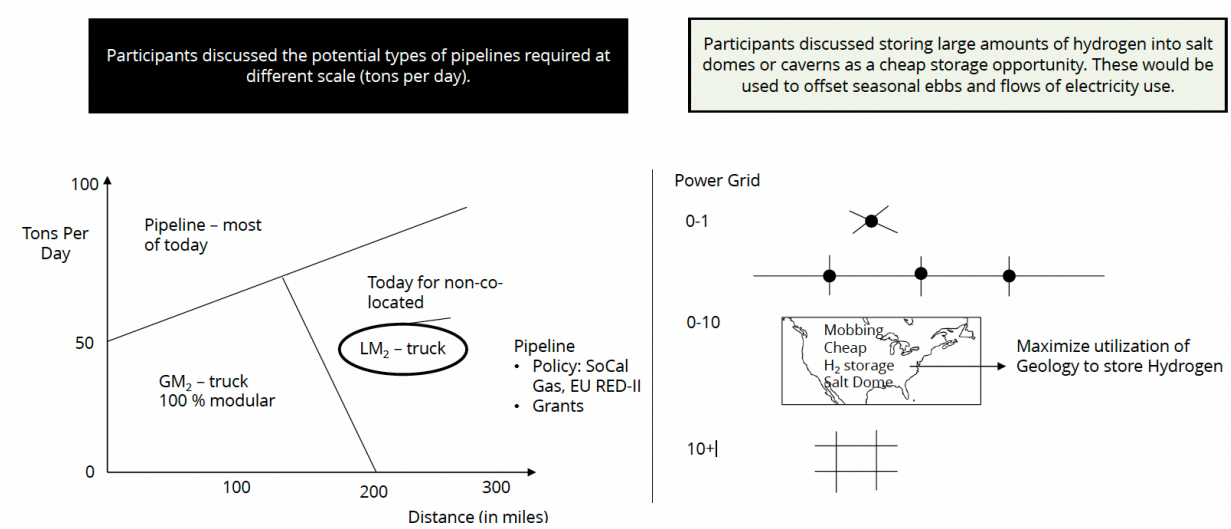


Figure A31. Summary of outcomes from Infrastructure 1 discussion

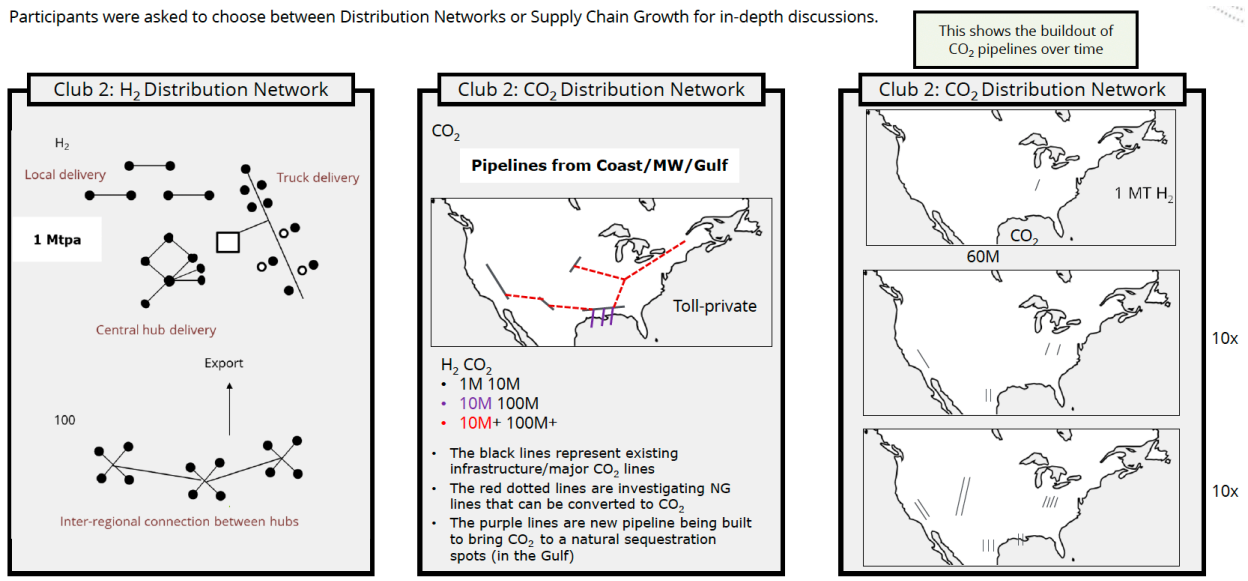
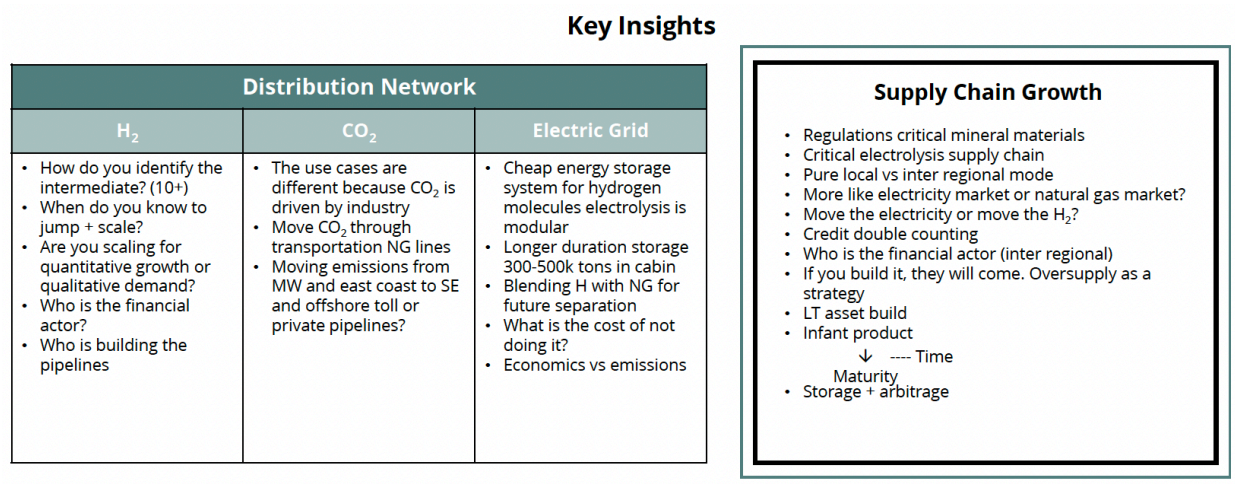


Figure A32. Summary of outcomes from Infrastructure 2 discussion



Key Insights

Distribution Network		
H_2	CO_2	Electric Grid
• How do you identify the intermediate? (10+) • When do you know to jump + scale? • Are you scaling for quantitative growth or qualitative demand? • Who is the financial actor? • Who is building the pipelines	• The use cases are different because CO_2 is driven by industry • Move CO_2 through transportation NG lines • Moving emissions from MW and east coast to SE and offshore toll or private pipelines?	• Cheap energy storage system for hydrogen molecules electrolysis is modular • Longer duration storage 300-500k tons in cabin • Blending H with NG for future separation • What is the cost of not doing it? • Economics vs emissions

Supply Chain Growth

- Regulations critical mineral materials
- Critical electrolysis supply chain
- Pure local vs inter regional mode
- More like electricity market or natural gas market?
- Move the electricity or move the H_2?
- Credit double counting
- Who is the financial actor (inter regional)
- If you build it, they will come. Oversupply as a strategy
- LT asset build
- Infant product
  ↓ ---- Time
  Maturity
- Storage + arbitrage

Figure A33. Summary of outcomes from Infrastructure 3 discussion

Important points from the discussion in each area include:

- Use case clarity – the landscape continues to evolve, so the most important feature is to identify markers that indicate whether use cases are "winning" or "losing" rather than focusing on a static assessment by any given group. Expectations from the workshop group, along with indicators for each sector, are included in the report;
- Market formation – there was debate as to whether clean H_2 markets need to reach a "merchant" or "spot" market status, or whether alternate models such as well-organized bilateral contracts are sufficient. Participants also flagged a need to establish clarity on the validation and valuation of carbon intensity, and whether it is coupled directly to the

H_2 molecule or can be traded as a decoupled attribute (akin to the trading of Renewable Electricity Credits in renewable power generation).

- Infrastructure and supply chain – the routing and expansion of pipeline networks for H_2 and CO_2, and whether they would be operated as open source or private facilities was a key topic. The effect of regional differences in pipeline receptivity, and geology for H_2 and CO_2 storage were flagged as potential drivers for heterogeneity in how clean H_2 markets across the US might develop. Evolution of electricity transmission to support electrolysis facilities was also cited as a foundational piece to support large-scale ecosystem.

The second half of Workshop 2 focused on the question of sequencing enablers. Figures A34 and A35 show raw inputs from participants on what capabilities must be developed during the early Foundations stage of ecosystem growth, and what capabilities must be further added to enable a transition into a Growth stage. Specific outcomes are described in Section 4 of the report.

A graphic summary of Workshop 2 is shown in Figure A36.

FOUNDATION STAGE STRATEGY

Group 1

What are the most important capabilities that need to be implemented in the Foundation stage?

1. Experimentation willingness
2. Permitting
3. Technology (hardware, people, builders, etc.)
4. User education
5. Ability to verify carbon footprints, safety, leakage, etc.
6. Demand forecasting
7. Learning by doing
8. Stakeholder engagement

Why are these capabilities important in order to reach 1 mtpa in the Foundation stage?

- 7 – because never done before
- 3 – to prove it can be made
- 2 – so it can be made
- 5 – so people will pay for it and will allow continued prod

For the important capabilities, what is needed to enable readiness?

- Training & research, e.g. university
- First movers
- Policy support
- Permitting support

Group 2

What are the most important capabilities that need to be implemented in the Foundation stage?

1. State-lever & local govt support + streamlined permitting (project & specific class)
2. Community support a widespread durable
3. Electrolyzer supply chain capacity
4. Workforce mobilization – training including organizational capacity (EPC)
5. Some hubs & other early movers must succeed by 2030

Why are these capabilities important in order to reach 1 mtpa in the Foundation stage?

- 1 2 & 3 projects won't be implemented
- 4 for green

For the important capabilities, what is needed to enable readiness?

- Incumbent workforce plan (equity)
- Workforce mobilization (including EPC org capacity)
- Project finance model
- Infrastructure (pipelines) to start
- Hubs must succeed

Group 3

What are the most important capabilities that need to be implemented in the Foundation stage?

- Financial & carbon optimization criteria
- Business case assumptions & sensitivity drivers (cost benefit)

More innovation solutions ← MFG & support → Leadership knowledge & use case clarity

R&D funding ↖ (All) safety standards ↗ regs

Sign a contract (demand)

Why are these capabilities important in order to reach 1 mtpa in the Foundation stage?

- Engineering org skills & capacity
- Standard alignment
- Identified improvement cost & innovation areas
- Supporting process capacity (aka compression)

For the important capabilities, what is needed to enable readiness?

- Finding people & shifting focus
- Cost predictability/future drivers
- Incentives to ↑ MFG capacity for equip
- $

Figure A34. Summary of outcomes from Foundations Stage discussions

TRANSITIONING FROM FOUNDATION TO GROWTH

Group 1

What capabilities are needed to enable the Growth stage (~10 mtpa)?

CARRYOVER	NEW

• Project finance
• Market certainty
• Continued supply chain
  ○ R&D
  ○ Access
  ○ Quality/quantity availability
	• Standardize design one & build many of new plant
	• Trading/exchange market infrastructure
	  ○ Blue – CCS/pipeline
	  ○ Green – renewable gen/network
	• Little demand "(build it they will come") into actual scale of demand – critical mass
	• Identified 'hydrogen' company – some consolidation – fewer small players
	• Community support/ social interest to operate

Reverse engineering from Mature stage, what needs to be in place each from Foundation and growth (~100 mtpa) stage? (When do you need them?)

- End of life
- Rare earth / or alternatives
- Displacement of incumbent fuels – clear winning proposition
- Integrated storage and transportation network
- Have built new facilities and equipment to use hydrogen
- Interactional component – trading, standards
- Project – self sustaining project/financing pipeline
- Merchant market including derivatives/ straight forward trades

What role do you see the government play in?

- Clarity and certainty in government policy – long-term
- Reduce carbon emissions
- Enabling → permitting/H&S/coordination to streamline
- Knowing when to step back and allow markets to walk → but how do they know
- Role in rotation to import/export
- Less is more

Group 2

What capabilities are needed to enable the Growth stage (~10 mtpa)?

CARRYOVER	NEW
• Labor force development • Policy refinement (lessons learned from foundation) • Stakeholder engagement • Permitting • Learning by doing	• Unprecedented collaboration • Demand forecasting • Process optimization (users and producers), include R&D • Market development • Standards • Supply chains

Reverse engineering from Mature stage, what needs to be in place each from Foundation and growth (~100 mtpa) stage? (When do you need them?)

- Continues from growth, but maybe qualitatively different
- Transportation infrastructure
- Inter-regional/international trade
- R&D for now H_2 use or production technologies
- Supply chain on steroids!
- Govt procurement of H_2

What role do you see the government play in?

- Standard setting
- Regulation
- Incentives for H_2/dis-incentives for high CI (carbon intensity)
- Early-stage R&D
- Procurement of H2
- International trade across supply chain
- Forced sharing of learning

Group 3

What capabilities are needed to enable the Growth stage (~10 mtpa)?

CARRYOVER	NEW
• State & land govt supply • Streamlined permitting • Community support • Workforce mobilization • Entire supply chain – blue/green equipment	• Pumping stations • Storage • Regional pipelines (building on hub success)? • Harmonizing standards & permitting regs across states • Establishing threshold of project finance players • De-risked tech/commercialized • Diversity of end users emerging • Clean electricity must be on track for o-carbon & required scale to support H_2 economy

Reverse engineering from Mature stage, what needs to be in place each from Foundation and growth (~100 mtpa) stage? (When do you need them?)

- Merchant market – deep – liquidity transparency
- Significant regional scale pipeline networks
- Diversity of end uses
  - Chem
  - HD transport
  - Industrial (iron)
  - Heat
  - Power
  - Export?
- Incentives reconfigured

What role do you see the government play in?

- Permitting
- Project support

Figure A35. Summary of outcomes from Transition to Growth discussions

Figure A36. Graphic summary of Workshop 2.

Appendix B. Chicken and egg analysis: Detailed notes

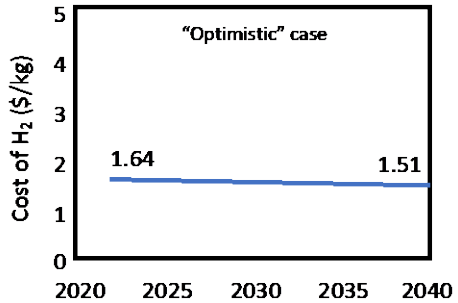
- Business cases
  - Use cases [Figure B1]
  - Blue vs green – cost uncertainty [Figure B2]
  - Revenue stack [Figure B3]
  - Incentives analysis (IRA) [Figure B4]
  - Offtake currency [Figure b5]
- Matching size and scale
  - Supply chain growth [Figure B6]
  - Scales of units and systems; lumpiness of growth [Figure B7]
- Infrastructure
  - CO2 T&S - Financing CO2 pipelines + 45Q [Figure B8]

- Cost and time uncertainty as an investment barrier
  - Expectations for fast cost movements
  - The cost of permitting delays

Fossil H_2 with CCS

- SMR + (retrofit) CCS @ 483 tpd
- Chicken-egg issue: CO_2 T&S
- NG feedstock is the biggest driver of cost volatility. Uncertainty band (mostly) represents effect of NG price volatility

Blue H_2 cost trajectory



$1.64/kg

Capital (21% of base LCOH)
- Engineering components are mature; limited LC from integration
- SMR = 54% of capital ; CO_2 capture + compression = 46% of captial
- Sensitivity assumptions (low-ref-high)
  - LC Optimistic (1.9-2.9-3.8%) ; Pessimistic (0.5-1.7-2.4%)
  - Financing cost of capital (2-6-12%)

Fixed costs & Variable costs (10% and 16% of base LCOH)
- Labor + taxes ; consumables
- Initial assumption is that these are stable over time (infl adjusted)

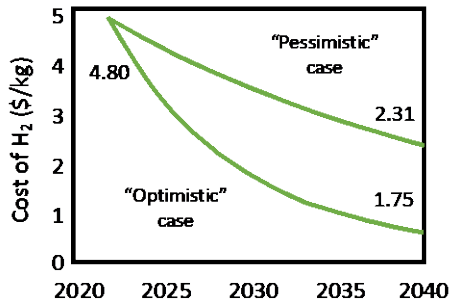
Feedstock (53% of base LCOH)
- This is the dominant contributor
- Natural gas price volatility is a major contributor to uncertainty
- Sensitivity assumptions (low-ref-high)
  - NETL ref assumes $4.42/MMBTU
  - High-low range = ($2, $12/MMBTU)
  - Uncertainty band reflects effects of NG price volatility

CO_2 Transport + storage (adder for blue H_2)
- Drivers: pipeline utilization
- Optimistic-pessimistic ($0.1, $0.3/kg H_2)

Ref: NETL cost study (2022)

Electrolyzer H_2

- 10 MW modules (5 tpd) x (1 to N) units facilities
- Strong forward expectations on capex and energy cost savings.
- Early learning curve data over next few years can reduce uncertainty for capital decisions.



$4.80/kg

Capital (41% of base LCOH)
- Opportunity for improvements by: engineering components, manufacturing scale, and field operation optimization Sensitivity assumptions (low-ref-high)
  - LC Optimistic (10-15-20%) ... DOE EarthShot -80% cost in 10 yr
  - LC Pessimistic (2.5-5.0-7.5%) ... 65% cost out in 20 yr
  - Financing cost of capital (2-6-12%)

Fixed costs & Variable costs (total 2.4% of base LCOH)
- Labor + taxes ; consumables
- Initial assumption is that these are stable over time (infl adjusted)

Energy (56% of base LCOH)
- This is the dominant contributor, with cost reduction potential driven by cost of electricity (COE) and power density
- COE expectations from low carbon electricity
  - Annual reduction rate
  - Optimistic (7-9-11%) ... $53 => $20/MWh in 10 yr
  - Pessimistic (2.5-5.0-7.5%) ... 65% cost out in 20 yr
- Power density expectations
  - From 50.8 to 43.4 kWh/kg (theoretical limit = 33)
  - Optimistic (0.8-1.6-2.3%) ... 10 yr
  - Pessimistic (0.4-0.8-1.2%) ... 20 yr

Ref: IRENA (2020)

Calcs to flesh out chicken-and-egg drivers, quantify, and flag paths forward

- Business models
  - IGC model is focused on molecules and moats
  - Setting up offtake agreements for future H2, including agreeing on terms and pricing
  - 1st mover penalty: Early adopters bear the risk of defining workable business models and creating supporting infrastructure. Since later adopters get to benefit from this learning and activity, there is an incentive to wait and allow other to go first.
  - How do we transition from gov't subsidies (to support early movers) to a sustainable market dynamic?
  - What price premium is appropriate (margin price premium curve)?
    - $100/tCO2 vs 9 tCO2/tH2 from SMR => $0.11/kg premium
    - IRA PTC => $0.6/kg H2 is par to $85/tCO2 (par w/o x5 uplift)
- Cost uncertainty
  - learning curve data
  - globalization is a blind spot
  - blue (SMR) vs green (electrolysis)
    - Expectations for cost reductions. Electrolytic (green) H2 costs more now, but aggressive cost reductions are "expected". How will the changing relative cost of clean H2 from different sources over the next decade impact sourcing decisions and the viability of production projects?
  - CO2 transport costs
  - H2 storage
  - Feedstock price volatility (NG vs electricity)
  - CHP (mass and energy balances)
    - Green – repowering with H2
    - Blue – Oxyfuel + CCS or just CCS
    - Blue + green
  - Effect of IRA incentives on cost curves
- Cooperation vs competition
  - Sharing info – trading off the value of learning (lower cost => market share) vs ecosystem growth (bigger market) – how do you quantify to enable a rational local economic decision, and how do you balance against anti-trust and other regulation
- Time impacts of gov't policy
  - IRA incentives project forward decades because of project selection impacts
    - What will happen from labor?
  - Pro formae for ITC, PTC distortions for H2 and others
- Time vs money
  - Cost of a delay (due to permitting)
    - How does delay/timing uncertainty enter into a NPV calculation?
- Transitioning from govt to market
  - What happens after incentives? Transition from govt to market
    - Cost-out (relative impact and potential on capex vs opex)

        - Capex (loans, PTC to accel payback) vs opex (PTC) … cliffs
    - What fraction of investments in a rapidly evolving ecosystem are "wrong"? R&D yield vs big projects yield? Waste vs price for progress?

At the system level, it further requires sorting out which technologies and technical approaches fit into which niches in different regions, and how they can work together in ways to deliver affordable, reliable, and socially acceptable goods and services. The interaction between technology development, evolving economics, and policy and regulation means that there is tremendous uncertainty regarding how the transition will evolve. This has led to the realization that two important principles that should be guide efforts going forward. First, forecasts and models for the next several decades can provide general guidance, but the complexity of the transition means that any path forward will need to be highly adaptive to the evolving "situation on the ground". Second, a portfolio approach is needed. A diversity of approaches must be developed to fit into different use cases for different regions, and these must be evaluated real time as the situation evolves.