Workshop Report

A Global Hydrogen Future

March 2023

KAPSARC
مركز الملك عبدالله للدراسات والبحوث البترولية
King Abdullah Petroleum Studies and Research Center

ENERGY FUTURES INITIATIVE

Joint Message from **Ernest Moniz**, president and CEO of EFI, and **Fahad Alajlan**, president of KAPSARC

The Energy Futures Initiative and the King Abdullah Petroleum Studies and Research Center have launched a two-year research collaboration motivated by a shared desire to accelerate the clean energy transition to a low-carbon future.

The substantial resources of the Middle East and North Africa (MENA) create an opportunity to develop clean hydrogen at scale. Global market demand will shape the region's hydrogen export potential and facilitate a low-carbon economy.

The research program will have a principal focus on the development of a global hydrogen market, the value of hydrogen to the global economy, and the potential demand for clean hydrogen as a fuel and feedstock in a decarbonized energy system.

Collaborative analysis also will highlight the role of policies and regulations, technological advancement, and economic empowerment in advancing the circular carbon economy.

KAPSARC
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King Abdullah Petroleum Studies and Research Center

ENERGY FUTURES INITIATIVE

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LIST OF ACRONYMS

ASEAN: Association of Southeast Asian Nations

ATR: Autothermal reforming

CBAM: Carbon Border Adjustment Mechanisms

CCUS: Carbon capture utilization and storage

CSIS: Center for Strategic and International Studies

COP: United Nations Conference of the Parties

DRI: Direct Reduction Iron

EAS: East Asia Summit

EFI: Energy Futures Initiative

EIA: Energy Information Administration

ERIA-ASEAN: Economic Research Institute for ASEAN and East Asia

ESG: Environmental, social, and governance

ETS: Emissions trading system

GHG: Greenhouse gasses

IEA: International Energy Agency

IIJA: Infrastructure Investment and Jobs Act

IRA: Inflation Reduction Act of 2022

JODI: Joint Organisations Data Initiative

KAPSARC: King Abdullah Petroleum Studies and Research Center

MENA: Middle East and North Africa

MT: Million tons

NDC: Nationally determined contribution

OECD: Organization for Economic Co-operation and Development

PEM: Polymer electrolyte membrane

PTC: Production tax credit

PV: Photovoltaic

SMR: Steam methane reforming

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EXECUTIVE SUMMARY

The Energy Futures Initiative (EFI) and the King Abdullah Petroleum Studies and Research Center (KAPSARC) convened an invitation-only in-person workshop titled A Global Hydrogen Future. The full-day event was held on Oct. 11, 2022, in Washington, D.C., and brought together 68 subject matter experts and speakers to discuss a global hydrogen market in the context of climate goals and the omnipresent need for energy security and affordability.

The workshop's intent was to gain expertise from a broad spectrum of actors in the hydrogen field as to opportunities and challenges in leveraging global infrastructure....

The workshop's intent was to gain expertise from a broad spectrum of actors in the hydrogen field as to opportunities and challenges in leveraging global infrastructure—in production, trade, and distribution—for the transition of hydrogen from a specialty chemical to a fuel and feedstock globally. Within this structure was an acute spotlight on the Middle East and North Africa (MENA) region as to how alternatives to fossil fuels can play a more active role in producing affordable, reliable, and low-carbon energy that supports human and economic development, and global decarbonization. Acceleration of decarbonization efforts extends, in part, from nationally determined contribution (NDCs) commitments—which are at the heart of the Paris Agreement of the United Nations Framework Convention on Climate Change—and pressing geopolitical considerations. As a backdrop, the conflict in Ukraine exposed energy issues, chiefly energy security, which remains one of the most consequential public policy debates.

Presentations and discussions at this first workshop of the planned two-year joint work project focused on considerations surrounding investment, regulations, policy, and global market value chain conditions necessary for the promotion of hydrogen as a replacement fuel and feedstock. The enhanced conversation surrounding the development of a global hydrogen market occurred through three simultaneous breakout sessions, where attendees' expertise could be voiced and gathered.

For these sessions, EFI and KAPSARC developed and sent three white papers (Appendix C) to participants ahead of the workshop, ensuring a baseline knowledge of the latest policies and research in the hydrogen space. The papers respective to each session are titled: 1.) Global Hydrogen Policy and Regulatory Review; 2.) Financing a Hydrogen Future; and 3.) Developing a Global Hydrogen Market. They are reviews of current studies in each topical area (regulatory and policy, finance, and the value chain) including questions used by breakout session moderators to stimulate vibrant conversation. Consequently, the group produced 10 major takeaways informing the analytical basis of the joint work program's next phase. What follows is a representation of these 10 takeaways in a two-part chart. The full text recounting conversations on these topics resides in the Afternoon Breakout Sessions section. ■

Key Takeaways From A Global Hydrogen Future Workshop

1

Applicable regulation exists today to spur initial hydrogen development; however, more regulation is needed on the demand side to enable the true market potential of hydrogen as an energy commodity.

Participants noted the need for more regulation in several high-priority areas to realize fully the potential for hydrogen as a primary energy commodity and carrier. Such areas included policy to support market development, which could mean standardizing the definition of "clean" hydrogen and derived commodities or implementing Carbon Border Adjustment Mechanisms (CBAM).

2

Advocacy and buy-in are necessary to the development of a hydrogen market.

Hydrogen as a fuel and feedstock is commonly misunderstood, and incorrect perceptions could impede development. Participants discussed how sharing early hydrogen success stories could enhance community awareness and facilitate the uptake of hydrogen as a fuel source.

3

Global data standardization applied on a regional basis is essential for hydrogen market development.

Throughout the conversation, there was consensus that greater standardization is needed for data sharing. Consistency and transparency in hydrogen markets could mitigate price fluctuations and produce concrete outcomes of the producer-consumer dialogue to instill greater confidence in the industry and spur growth through investment.

4

Traditional oil and gas producers are well-positioned to be hydrogen producers.

Nations with active sovereign wealth funds could direct funding toward hydrogen market development, which could be leveraged further to develop hydrogen markets.

In addition, fossil fuel-producing nations can further decarbonize existing industries with low-carbon hydrogen production, e.g., large ammonia, methanol, and refining sectors.

5

The financial industry will require high-yield investments that demonstrate value across the supply chain.

Participants agreed that long-term off-take agreements, demonstrating demand or public-private partnerships may be needed for financing to occur at a scale sufficient to support regional and global market development. Another possible solution discussed was sovereign guarantees and blended financing, which would ensure a government backstop.

There was a consensus that the current focus on project finance is insufficient to develop regional and global markets and that policies must also attract equity market investments.

Key Takeaways From A Global Hydrogen Future Workshop

6

Pricing hydrogen as an energy commodity will be challenging in the early stages of market development.

There was a consensus that pricing mechanisms for hydrogen need to insulate producers and end users from volatility risk and ensure confidence in a developing market.

However, participants disagreed as to how hydrogen should be priced. Pricing formation is seen as scaling up from a boutique industry (i.e., viewing hydrogen as a specialty chemical) to a global fuel, or as part of the process of adopting an entirely new fuel source.

7

Midstream transportation challenges must be resolved to facilitate development of a global hydrogen market.

Participants noted the many challenges associated with transporting hydrogen molecules by ship and pipeline, such as the energy required for liquefaction and the potential for leakage, which could diminish the climate benefits of building a hydrogen economy.

In addition, challenges exist with maintaining hydrogen purity and building infrastructure, such as pipelines, shipping vessels, and ports, which could be solved by local hub-and-spoke networks and policies for national or regional market creation.

8

The concentration of critical minerals and manufacture of electrolyzers represents a challenge to the widespread emergence of a green hydrogen economy.

Participants viewed China's control of electrolyzer and solar PV manufacturing as a potential restrictive single point of failure. Although, the energy transition cannot happen without broad and deep international collaboration.

Production of hydrogen electrolyzers and fuel cells could drive up demand for nickel, platinum, and other minerals, even though the market effects will depend on the shares of the different electrolyzer types.

9

Increasing demand from Europe and Asia will spur the growth of a global hydrogen market.

The conversation on hydrogen demand cited Europe and Asia as potential markets, driven in part by decarbonization goals and energy security needs. Participants identified the ongoing crisis in Ukraine as a lead indicator that will drive multiple solutions to meet energy security and climate goals, including further development of renewable energy sources and clean fuels.

10

Using hydrogen as a commercial fuel, and ammonia as an energy carrier, could help create a growth in demand.

To encourage hydrogen market development, the discussion centered on increasing the use of hydrogen as a fuel and for ammonia production. These uses were discussed as the primary options with the potential to increase hydrogen demand. Participants noted that the production of ammonia from low-carbon hydrogen would take advantage of existing infrastructure and will help to decarbonize global shipping.

INTRODUCTION

In June 2022, EFI and KAPSARC launched a joint work program to analyze a range of decarbonization issues, with an emphasis on hydrogen, carbon capture, utilization, storage, and system modeling of options and opportunities. This program builds on EFI-KAPSARC's history of collaboration, such as in the Global Gas Study and MENA regional workshop, and EFI's portfolio of work products, including two major U.S.-focused studies of the developing hydrogen supply chain. These analyses and their associated workshops, white papers, and reports will provide base recommendations as to how resource-rich nations can play an even greater leadership role in the clean energy transition in MENA and around the world.

To anchor the initial workshop, it was necessary to establish a common understanding of the role that hydrogen currently plays in the global economy and the potential demand for clean hydrogen as a fuel and feedstock in a decarbonized energy system. While speakers agreed to have their comments shared and attributed, in order to hold frank and constructive conversations in the afternoon work sessions, participants agreed that their comments would be non-attributable.

Though initial market development will likely entail the retrofit of current hydrogen facilities with carbon capture and the repurposing of existing infrastructure, new projects and other hydrogen forms may develop as decarbonization tools and drive global hydrogen market development.

Coincidentally, the leaders of the United States and Saudi Arabia welcomed the finalization of a Partnership Framework for Advancing Clean Energy in July 2022 as part of the Jeddah Communique.[a] This partnership focuses on "substantial investments in the clean energy transition and addressing climate change, with a particular focus on renewable energy, clean hydrogen, human capacity-building in the nuclear energy field, and cooperation in nuclear-regulatory aspects, carbon capture utilization and sequestration, development of sustainable materials, and other initiatives under the Circular Carbon Economy Framework, where Saudi Arabia aims to be a global leader."

The EFI-KAPSARC collaboration is consistent with the goals of the Jeddah Communique, released by the U.S. and Saudi leadership at the conclusion of President Biden's visit to Jeddah. That communique, among other things, made a commitment to energy security and climate cooperation between the United States and Saudi Arabia. The EFI-KASPARC collaboration will support the goals of this effort to support and advance clean energy.

a The Jeddah Communique (July 15, 2022) outlines the strategic partnership between Saudi Arabia and the United States over the coming decades. The document's tenets aim to advance mutual interests and a common vision for a more peaceful, secure, prosperous, and stable Middle East.

As countries work to address the many issues associated with climate change through their NDCs and net-zero commitments, they must develop ways to balance CO_2 reduction targets against the reliability and affordability of energy sources. The themes that will inform the next phases of this two-year program on the potential of hydrogen and the development of an associated market, include the following:

- Recognize that both traditional and alternative energy sources are necessary given the overarching security and economic implications associated with sustainable change.
- Understand the need to optimize an existing asset base that can maintain the supply of energy for the next several decades with a societal and regulatory demand to achieve the transition in the immediate future.
- Create a level playing field for investment, where investors are incentivized to increase production of clean energy while still directing capital into the necessary technologies and research and development to achieve reduction targets.
- Agree that, in free and competitive markets, the measure of success can be as simple as the lowest cost of energy that has the lowest cost of avoided CO_2, with consistent standards of measure and reciprocity across both domestic and international jurisdictions.
- Ensure that a planned exit and managed decline delivers a sustainable energy supply, along with sustainable earnings for the future of businesses, and that it includes the transition of a highly skilled energy workforce that can create next-generation solutions.

This workshop was informed by the initial EFI Global Gas Study report, which identified high-level issues in MENA. The following is a general agenda of the workshop:

- **Opening and Welcoming** (Ernest Moniz, EFI, and Fahad Alajlan, KAPSARC)
- **The Climate Change Context** (Jonathan Pershing, The Hewlett Foundation)
- **Global Hydrogen Overview Panel Discussion** (Moderator: Melanie Kenderdine, EFI; Panel: Adam Sieminski, KAPSARC; Martin Wilhelm, Geopolis Energy Partners; Han Phoumin, Economic Research Institute for ASEAN and East Asia)
- **U.S. Hydrogen Overview** (Alex Kizer, EFI)
- **MENA Hydrogen Overview** (T. Mason Hamilton, International Energy Forum)
- **The Hydrogen Value Chain** (Rami Shabaneh, KAPSARC)
- **Breakout sessions:**
  1. Regulatory / Policy (Moderator: Alex Kizer, EFI)
  2. Finance (Moderator: Peter Fazio, Barclays)
  3. The Hydrogen Value Chain (Moderator: Jane Nakano, Center for Strategic and International Studies)
- **Summary of each Breakout Session Discussion and Key Findings**
- **Discussion of Crosscutting Issues and Linkages** (Facilitator: Richard W. Westerdale II, EFI)
- **Closing Remarks** (Fahad Alajlan, KAPSARC, and Ernest Moniz, EFI)

WORKSHOP SUMMARY

EFI President and CEO Ernest Moniz (left) and KAPSARC President Fahad Alajlan (right)

The workshop's morning plenary session began with welcoming remarks from Ernest Moniz (EFI) and Fahad Alajlan (KAPSARC). They were followed by a presentation by Jonathan Pershing (the Hewlett Foundation) titled The Climate Change Context and A Global Hydrogen Overview panel discussion moderated by Melanie Kenderdine (EFI). The panel discussion featured Adam Sieminski (KAPSARC), Martin Wilhelm (Geopolis Energy Partners) providing an EU perspective, and Han Phoumin (ERIA-ASEAN) with a view from Asia.

Participants then attended three presentations that staged the afternoon breakout sessions. The first presentation delivered by Alex Kizer (EFI) provided a U.S. Hydrogen Overview. The second presentation by T. Mason Hamilton (IEF) focused on a Hydrogen Overview of the MENA region. And concluding the morning, Rami Shabaneh (KAPSARC) focused on The Hydrogen Value Chain.

Morning Plenary

Welcoming and Opening Addresses

Former Secretary Ernest Moniz's opening remarks noted President Biden's July visit to Jeddah and the joint U.S.-Saudi Arabian commitment to a clean energy future, underscoring passages from the Jeddah Communique that "welcomed the finalization of a partnership framework for advancing clean energy, with substantial investments in clean energy transition and addressing climate change, with particular focus on renewable energy, clean hydrogen … carbon capture utilization and sequestration, development of sustainable materials, and other initiatives under the Circular Carbon Economy Framework, where Saudi Arabia aims to be a global leader. ..."

Moniz then placed the EFI-KAPSARC partnership in the context of the need for broad and deep analyses of paths to a net-zero carbon emissions future. Moniz noted the potential role for hydrogen in meeting global targets for deep decarbonization and what the opportunity presents, for both the EFI-KAPSARC partnership and the experts at the workshop, in helping to formulate opinion on a global hydrogen future.

Moniz specifically noted the versatility of hydrogen, not only as a low-carbon fuel needed for important industrial processes but also for the power and transportation sectors. This versatility could make hydrogen an essential component of the clean energy transition. Moniz also noted the promise of hydrogen hubs and regional attributes of North America and MENA, both of which have abundant clean low-carbon renewable electricity options that are essential for a clean energy future.

In addition, he discussed the system integration needs of the low-carbon electricity and fuels sectors and how hydrogen could play a major role in this regard, especially for those sectors that lack other technology options for deep decarbonization. Moniz acknowledged the challenges of demand creation for hydrogen as an energy source, carrier, and storage medium but also noted that recent legislation passed by the U.S. Congress and signed into law by President Biden—the Inflation Reduction Act of 2022 (IRA)—will provide substantial financial incentives and policy support for hydrogen supply, demand, and infrastructure. This act and other recent laws provide clear indications of the tremendous interest in the United States of the role hydrogen could play in the clean energy transition.

Moniz closed his speech with a challenge to the group, supporting the work ahead, stressing that technological advances need to weave together production methods, pricing, business models, financial strategies, standards, and policy structures at scale and at an accelerated pace to help achieve a net zero-carbon future.

Fahad Alajlan's opening address also acknowledged the cooperative history of EFI and KAPSARC before focusing on how timely the workshop is considering the evolving landscape in Europe, which has put all energy options "back on the table."

> **"North America and the MENA region are two places that will play very centrally on the supply side. There are other parts of the world, major population centers such as Japan and Europe, who will be dependent on the major export-import dynamic that will have to develop."**
>
> Ernest Moniz
> *EFI*

Taking this landscape into account, he noted that at the 2021 United Nations Climate Change Conference (COP26), conversations about hydrogen seemed more ideological but now development is necessary and moving forward rapidly. Recognizing the challenges of meeting demand with supply he identified regional strengths, noting that costs may differ, but North America and MENA are likely to be cost-competitive producers.

Alajlan posed a question, however: How will hydrogen demand develop and how do "demand centers" evolve in regions such as Europe and Asia? Contemplating suggestions for government-led incentives, Alajlan stressed that climate change, energy security, and affordability should be part of any policy objective. In moving forward with energy transition, he challenged the group to think beyond the color-defined methods of hydrogen production and focus on the overall low-carbon content of hydrogen fuel.

Finally, Alajlan noted that we've all seen failed projects and those should inform but not impede how we can build, scale, and finance a global hydrogen market that supports hydrogen as a clean energy commodity that meets the needs of many different economic sectors. He closed by challenging the group to help advance the clean energy transition and "make the right choices" as we move forward.

The Climate Change Context

Jonathan Pershing of the Hewlett Foundation delivered a keynote address on *The Climate Change Context,* providing essential insight into how the climate crisis is changing energy investing, employment, and geographic advantages and how inaction now will cost more later.

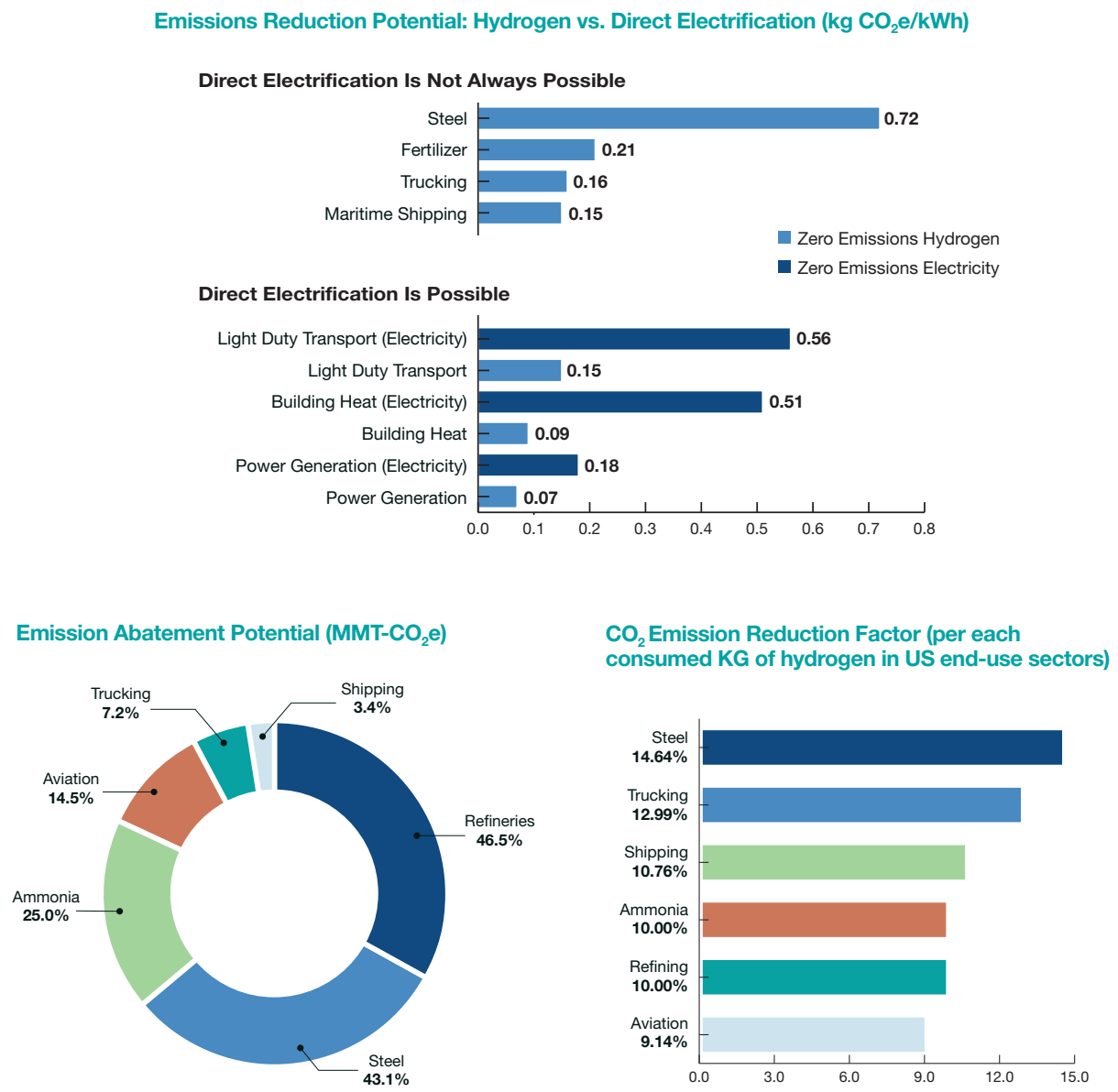
Pershing began his presentation with how the rising global temperatures from increasing greenhouse gas (GHG) emissions create detrimental consequences around the world. He noted electricity and heat production as the largest contributors to global GHG emissions, followed by transportation, manufacturing, and construction (largely cement and similar materials), and agriculture. He added that emissions generated by these sectors are increasing rapidly and given the current emissions trajectory, it is going to be very difficult to meet the goal of limiting global warming to 1.5°C above pre-Industrial Revolution levels. Pershing noted that the planet is currently at 1.1°C of warming and already experiencing impacts—such as floods in Pakistan, devastating hurricanes in the Gulf of Mexico, and the worst drought Europe has seen in 500 years. Pershing warned that these weather events will only worsen as the planet nears 1.5°C and that, according to leading research, greenhouse gas emissions need to fall 43% by 2030 to avoid even more extreme climate events.

Pershing explained that hydrogen is an important piece of the climate solution but has greater value in some sectors over others. He noted that hydrogen is an asset for decarbonizing hard-to-abate industrial and transportation sub-sectors. For example, switching to hydrogen can have emissions reduction potential for steel, fertilizer, trucking, and maritime shipping. However, direct electrification may have greater emission reduction potential for sectors such as light-duty transportation, heating, and power generation (Figure 1). Pershing took note from the International Energy Agency's (IEA's) "Net Zero by 2050: A Roadmap for the Global Energy Sector,"[1] which suggests that by 2030, 150 million tons (Mt) of low-carbon hydrogen should be available (850 gigawatt [GW] electrolyzers), and 435 Mt of low-carbon hydrogen (3,000 GW electrolyzers) should be available by 2045. Pershing then noted that the radical changes that need to take place to spur growth in hydrogen production on this level offer a large-scale opportunity for investment but are not without challenges.

> **"Instead of thinking on the color of hydrogen, we need to focus on the carbon content."**
>
> Jonathan Pershing
> *Hewlett Foundation*

After running through climate impacts and the importance of hydrogen, Pershing offered some thoughts, with data, on pathways for reaching net zero by 2050. He suggested that as investments in fossil fuels decrease and investments in clean infrastructure increase, gross domestic products will rise, as indicated in Figure 2. He acknowledged that as painful as job losses in oil and gas extractive industries may be, overall employment in manufacturing renewable energy and related efficiency products likely will increase.

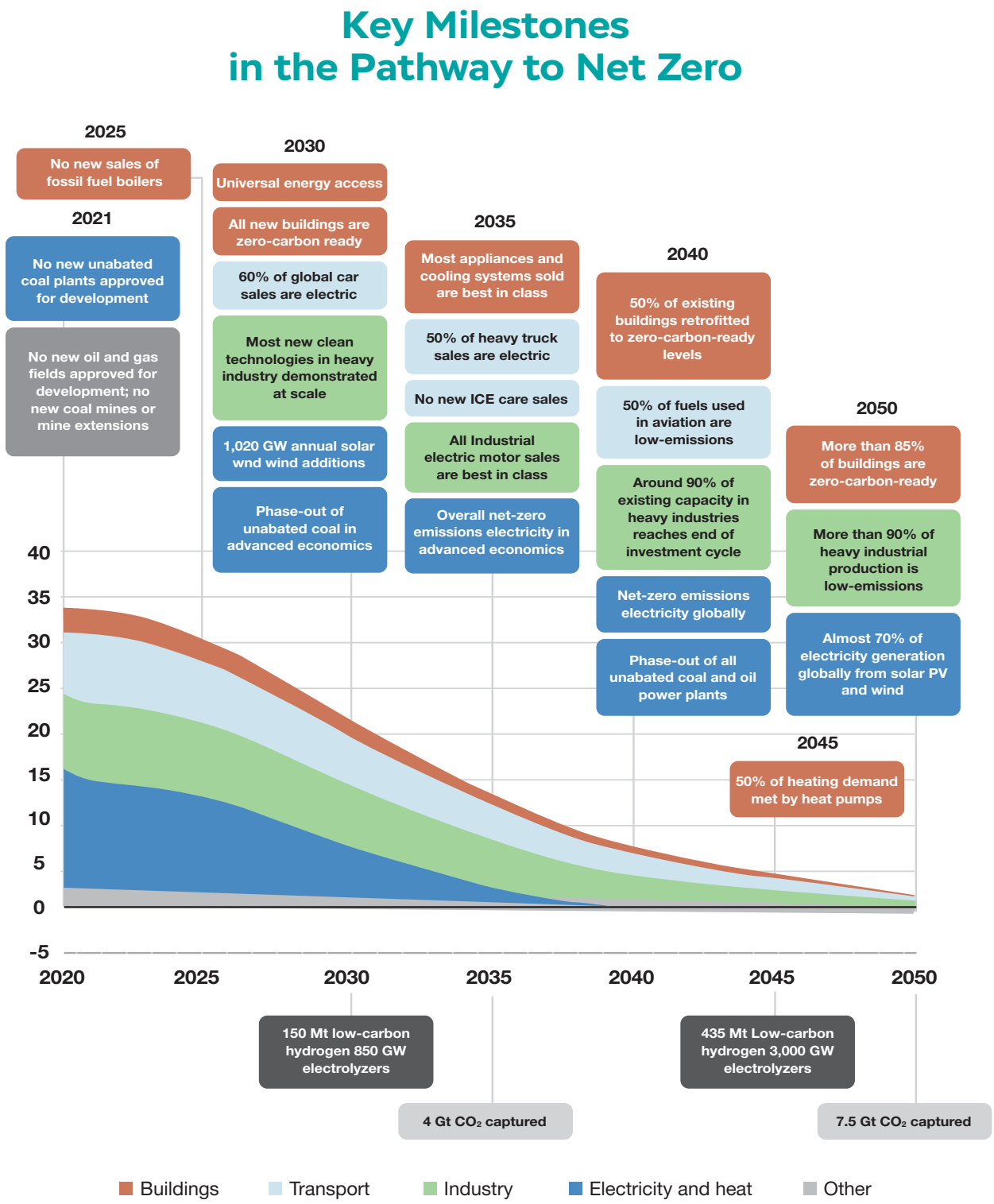
Figure 1 | Hydrogen is a Key Part of the Solution but Not Equally in All Sectors



Source: RMI, Hydrogen Reality Check: We Need Hydrogen — But Not for Everything. Source: RMI, Policy Memo: Clean Hydrogen Abatement.

Pershing, like the previous speakers, touched on geostrategic and global market advantages that will accrue to countries that have critical minerals or zero-emissions industrial capacities. Pershing recognized the inevitable volatility of such a disrupting energy transition without new policies and planning to manage it. In conclusion, Pershing underscored an important global concern: Inaction on climate change could cost $178 trillion by 2070, but if we accelerate the transition to net zero, the global economy could gain $43 trillion over the same period.

Figure 2 | Net Zero by 2050



Source: International Energy Agency (IEA), Net Zero by 2050: A Roadmap for the Global Energy Sector.

Melanie Kenderdine (left), Adam Sieminski (middle), Martin Wilhelm (right).

Panel Discussion—Global Hydrogen Overview

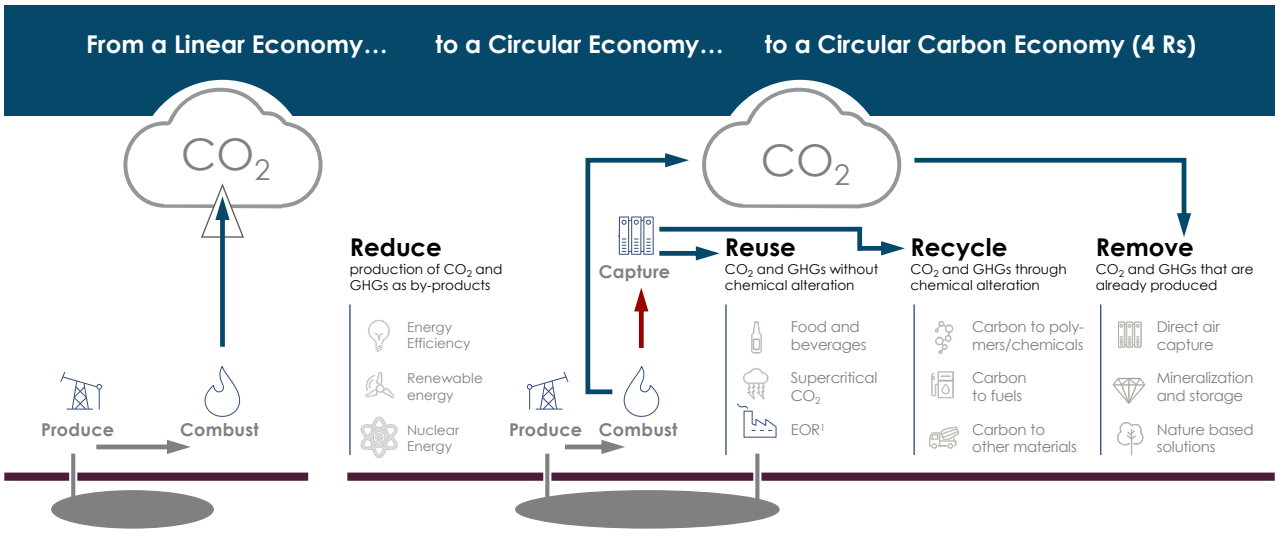
Melanie Kenderdine moderated a panel that examined global hydrogen development. The panel featured three energy experts: Adam Sieminski, Han Phoumin, and Martin Wilhelm. To frame the discussion, each panelist delivered a brief presentation.

Sieminski's presentation focused on The Role of Hydrogen in a Climate-Challenged World, noting that the Energy Information Administration forecasts that global energy consumption will continue to grow through 2050 as supplied by a steady flow of oil, coal, natural gas, and a sharp increase in renewable electricity.

Sieminski pointed out that this increase in demand will primarily originate from countries not in the Organization for Economic Co-operation and Development (OECD) and that a narrow focus on reducing fossil fuel use will result in substantial undesirable socio-economic consequences globally, as today's alternatives to fossil fuels are expensive and can be unreliable or unavailable. To mitigate continued fossil fuel dependency, Sieminski advocated for focus on and development of a "circular carbon economy" (Figure 3), whereby carbon from combusted fossil fuels could be captured and permanently sequestered or used as a value-added product.

In this regard, Sieminski discussed initiatives and pilot projects under the Saudi Green Initiative that are developing and deploying new technologies to reach net-zero GHG emissions by 2060. In conclusion, Sieminski assessed how hydrogen as an energy carrier is part of this initiative that can accelerate the energy transition.

Figure 3 | A Circular Carbon Economy



Source: Adam Sieminski, King Abdullah Petroleum Studies and Research Center (KAPSARC).

Phoumin focused on the Potential for Hydrogen as Game Changer in ASEAN & EAS's Decarbonization Pathways. Phoumin discussed Asia's challenges in matching energy demand with sustainable energy supplies in the transition to a lower-carbon economy. He described the reliance of the region's energy system on fossil fuels, in which 80% of its energy comes from coal, oil, and natural gas. He noted that ASEAN and East Asian countries are committed to the clean energy transition, but that many nations need to balance climate commitments with economic growth and the associated increase in energy demand, energy affordability, and security of supply.

Phoumin said that hydrogen could play a role in Asia's energy transition and noted that already in China, Japan, South Korea, Australia, and Brunei investments in hydrogen technologies are part of their decarbonization strategies. In his closing remarks, Phoumin offered four pathways and areas of focus for the most important regulatory and investment opportunities to promote hydrogen in East Asia:

1. Promote hydrogen use in hard-to-abate sectors.
2. Enable policies that support production of hydrogen and electrolyzer manufacturing.
3. Engage communities through public-private partnerships.
4. Promote/incentivize finance in hydrogen projects.

Remarks from Wilhelm focused on the current energy security crisis in Europe, associated with the conflict in Ukraine, and how Russia has utilized natural gas to exert leverage and influence over European consumers. He walked the group through the effects of gas price increases on households, inflation, recession, and the possibility of stagflation. He also noted how disruptive the gas supply issue is for German manufacturing, which is central to that nation's economy.

Wilhelm stated that, in the European context, despite the near-term concerns about energy security and gas supplies, the green hydrogen pathway remains important to investors. The investment community is looking to the European Commission to provide guidance on and clarification of definitions of clean hydrogen and the regulations that will be associated with its production, transport, and use. In addition, he touched upon how some in Europe are concerned about potential impacts of the IRA and how other incentives in the U.S. will shape the future global hydrogen market.

During the following discussion, Kenderdine asked the panelists how the world could meet such large volumes of hydrogen required in the IEA net zero by 2050 scenario (Figure 2). The panelists agreed that the following are necessary: better measurement and verification systems; less fixation on long-term target numbers; addressing misinterpretations of hydrogen demand; and clear policy roadmaps and innovative risk management to de-risk investments.

Three Scene-Setting Speakers

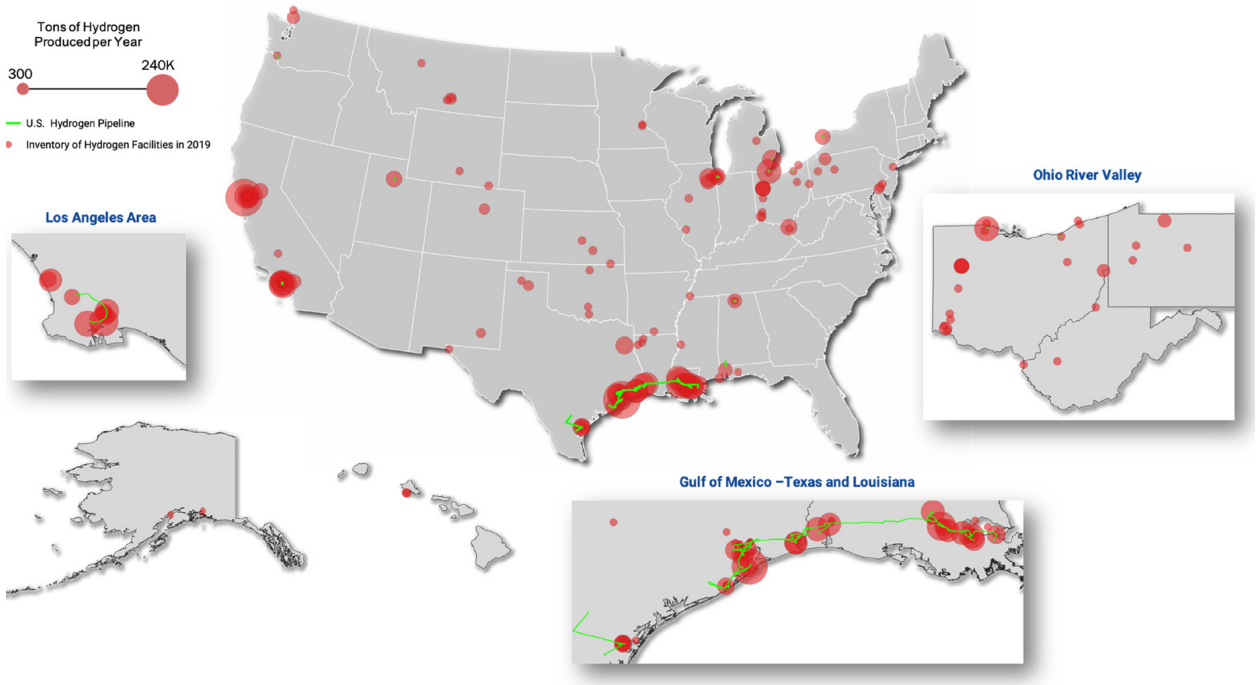
The morning plenary session concluded with three presentations focusing on hydrogen development. The first presentation explored the potential for hydrogen in the United States and was followed by a discussion of hydrogen potential in the MENA region. The final discussion focused on the hydrogen value chain in general. These presentations, along with other speakers and panelists, set the stage for the afternoon breakout sessions.

EFI's Action Plan for U.S. Hydrogen Market Formation

Alex Kizer of EFI discussed studies and analysis of the potential for hydrogen development in the United States. Kizer described the objectives of EFI's hydrogen studies as threefold: **1.)** animate capital investment in hydrogen through policy recommendations; **2.)** inform infrastructure package implementation for hydrogen through the Infrastructure Investment and Jobs Act (IIJA) and the IRA, which are especially for the regional hubs; and **3).** provide thought leadership for new coalitions and pathways for market formation. To further this work, EFI is analyzing the potential impact of clean hydrogen on fossil-dependent communities to assess the environmental ramifications and viability of retooling skilled workers in at-risk sectors.

EFI research found that approximately 11.4 million metric tons (Mt) of hydrogen are produced annually in the United States, more than 15% of the world's total.[2] There are approximately 1,600 miles of hydrogen pipeline in the country, mostly on the Texas Gulf Coast. Approximately 170 production facilities make hydrogen through methane reforming or as a by-product of petroleum refining (Figure 4). Roughly half of U.S. hydrogen is produced and consumed by the same entity—usually a refinery—while the other half comes from independent producers, who sell hydrogen to end users. Merchant hydrogen producers often are located at the customer's plant but sometimes rely on pipeline or trucks for shipping.[3] This setup makes decarbonizing the existing hydrogen industry particularly challenging, given the integrated nature of the current supply and demand.

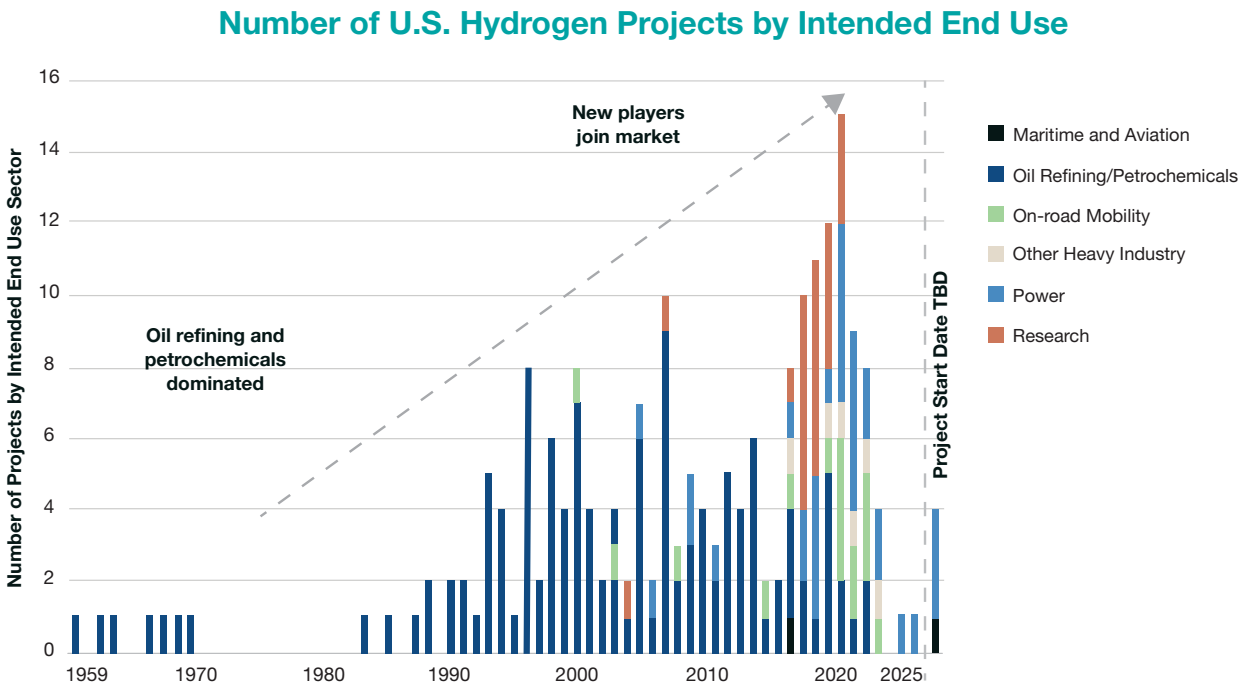
Figure 4 | Current U.S. Hydrogen Production Facilities and Pipelines

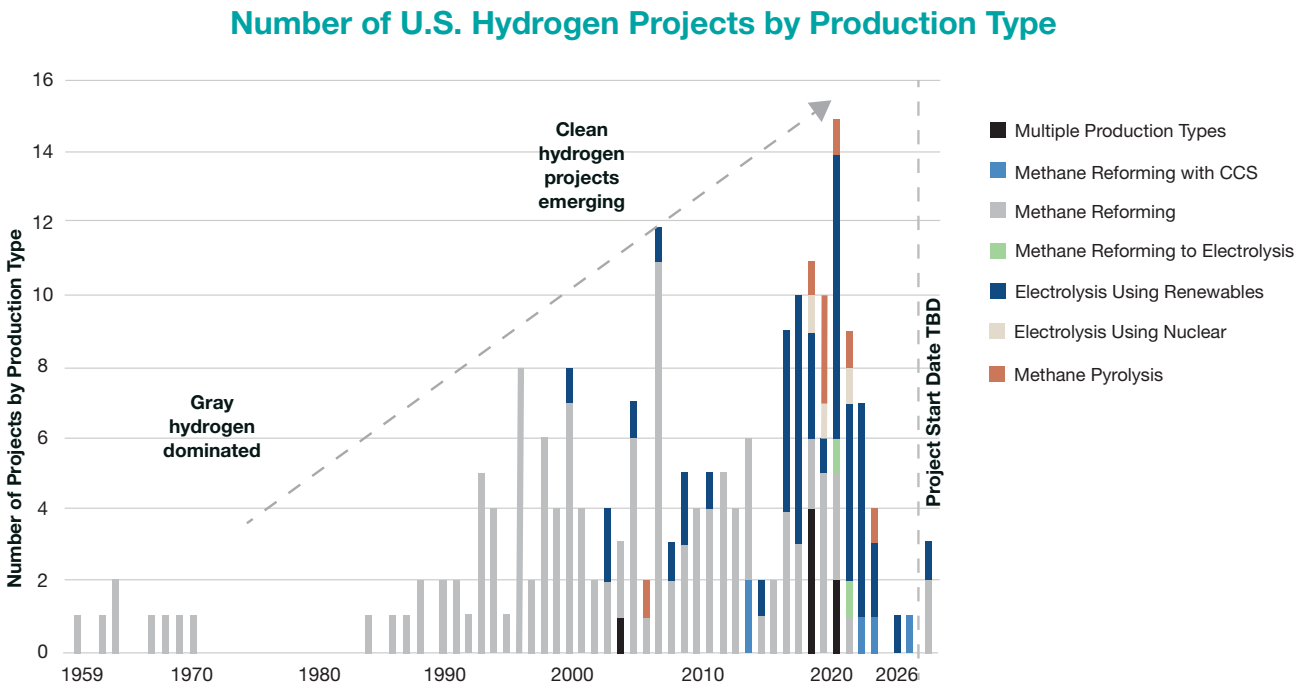


Source: Energy Futures Initiative's The Future of Clean Hydrogen in the United States: Views from Industry, Market Innovators, and Investors.

In addition, EFI's work found that existing hydrocarbon and proposed clean hydrogen projects provide a robust base for hub developments in important regions, most notably in the Texas-Louisiana Gulf Coast. These hydrogen projects are increasingly generated from non-traditional, i.e., not oil, gas, or petrochemical, companies, using non-traditional production, i.e., low-carbon hydrogen/ non-steam methane reforming (SMR) pathways such as electrolysis, pyrolysis, and carbon capture utilization and storage (CCUS) (Figure 5). The intended end uses of these projects are also evolving, as more projects are being used for power generation, research, and other heavy industry as opposed to oil refining and petrochemicals. Additionally, regional hubs are a major focus for U.S. investors. This investment has been spurred by the IIJA and the IRA, which both include incentives for clean hydrogen production.

Figure 5 | Nontraditional Projects Increasingly Are Coming from Nontraditional Firms





Source: Energy Futures Initiative data based on publicly announced projects before September 2021.

Global Hydrogen Outlook: Middle East and North Africa

The second presentation by Mason Hamilton provided an overview of hydrogen in the MENA region. He noted two main obstacles to developing a hydrogen market in the region. First, to encourage the massive investment required to spur growth of a hydrogen market, a more bankable investment environment is necessary. Hamilton also noted a general misconception that hydrogen investments have accreditive earnings, which push down the cost of hydrogen immediately, but that alone is not enough for many investment decisions.

Second, Hamilton warned that relying on "the rainbow"[b] of hydrogen colors, relevant to production method, to write policy and regulation serves only to delay the formation of a hydrogen market as the colors can be confusing and only describe emissions at the point of production, not across the value chain. Hamilton recommended that policymakers should instead work toward standardizing emissions intensity of the full life cycle as an essential way to inform and support market development.

In his presentation, Hamilton highlighted the numerous comparative advantages for hydrogen development in the MENA region, including substantial renewable energy potential; ample natural gas supplies and favorable CCUS geology; long-established energy trade patterns and business connections; a central location between the major demand centers of Europe and Asia; established domestic hydrogen-consuming industries; and multiple state-owned enterprises.

b "The rainbow" refers to the color codes, or nicknames, used within the energy industry to differentiate between hydrogen production methods. The three most common colors used as shorthand are gray, blue, and green. Gray refers to hydrogen produced from processing natural gas in a steam methane reformer (SMR). Blue hydrogen is when a carbon capture unit is put onto an SMR to sequester the captured carbon permanently. Green refers to hydrogen that is produced using renewable electricity to separate hydrogen and oxygen in an electrolyzer.

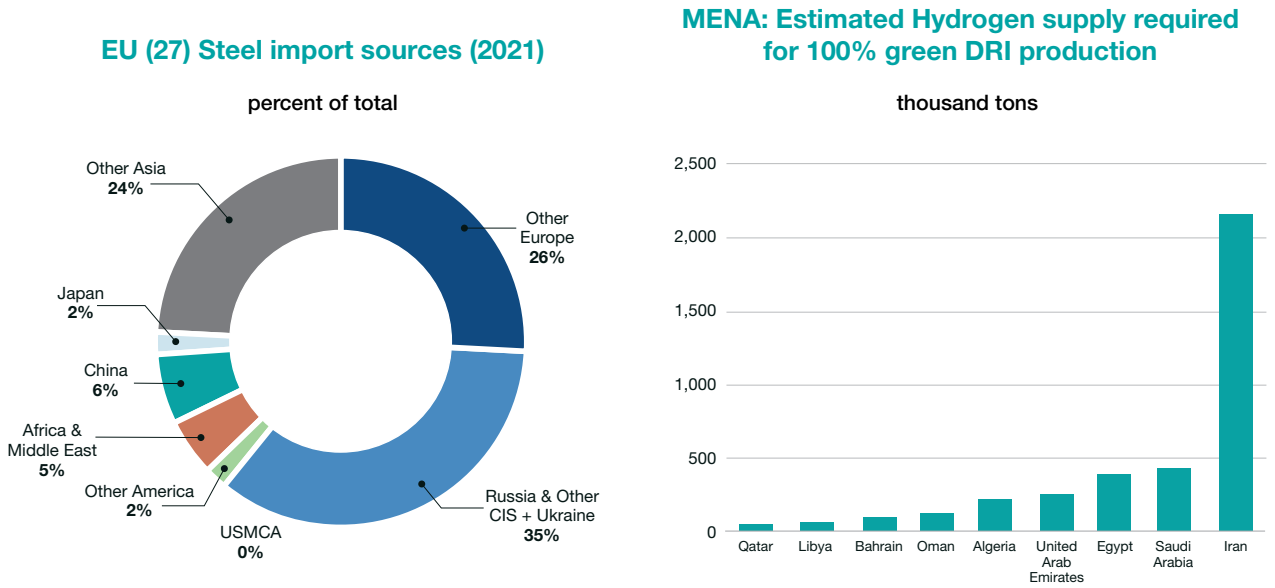
Hamilton also noted that the MENA region has been a historic energy exporter, but long-distance transportation of hydrogen poses energy intensity challenges. He described IEF work that underscores the importance of first establishing local supplies and regional demand hubs as central to unlocking investment funds needed to support eventual development of global supply chains. Such hubs would serve as first-order hydrogen demand centers and can serve as opportunities for the MENA region in diversifying away from pure energy export economies.

Although MENA nations are not among the largest steel producers, the region is already a leader in DRI, producing 46% of the world's total.

Furthering the discussion on diversification in the MENA region, Hamilton described the potential for the "green steel industry" using hydrogen to produce direct reduced iron (DRI) to make steel. Although MENA nations are not among the largest steel producers, the region is already a leader in DRI, producing 46% of the world's total (Figure 6). In 2021, the EU imported 5% of its steel from the MENA region. Focusing on increasing exports of DRI steel to the EU would create an economic opportunity for the MENA region.

Hamilton also discussed how hydrogen production for fertilizers could play an important role both in decarbonizing the MENA region and in reducing vulnerability to food and fertilizer price shocks, as the region is a net importer of food. He also touched upon how, in the water-stressed MENA region, the need for water in hydrogen production poses a challenge and how hydrogen production from renewable electricity would require a major expansion of power generation capacity.

Figure 6 | Hydrogen and DRI Opportunities for MENA Green Steel Leadership



Source: International Energy Agency (EIF), World Steel Association, World Steel in Figures 2022. Source: IEF, World Steel Association, Habib & Iyju (2021).

In conclusion, Hamilton underscored the MENA region's potential for playing a role in developing carbon intensity standards and definitions; sharing statistics and transparent data; establishing contractual norms and transparency of contracts; and leading the way in international hydrogen partnerships and market development.

The Hydrogen Value Chain

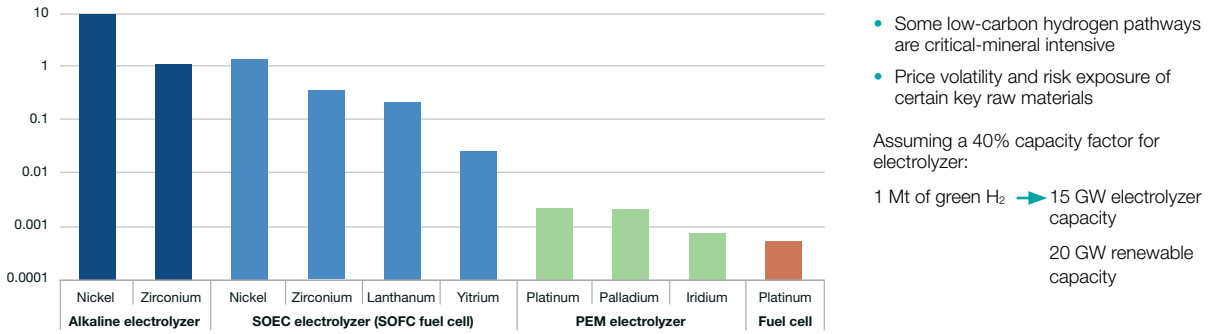
Rami Shabaneh of KAPSARC focused on the hydrogen value chain, highlighting the many challenges associated with developing the entire chain from production to transport to end-use consumer. He also noted that the hydrogen value chain will become increasingly complex as hydrogen use grows. He focused on the uncertainties of future demand, lack of investment, transportation issues, and risks that the availability of critical minerals could present for upstream hydrogen production. He noted that although hard-to-electrify industries are primed to explore the adoption of hydrogen, the investment case for hydrogen in most sectors is still evolving and more policies incentivizing ventures and regulatory frameworks defining parameters are needed to encourage capital spending.

Shabaneh stated that, in addition to lagging investment and policies, there are two additional roadblocks. First, transporting hydrogen represents a major challenge for the supply chain as hydrogen's low volumetric energy density makes it challenging and expensive to store and distribute. Also, transporting large amounts of hydrogen via truck or ship requires large CO_2 emitting energy inputs, which could diminish the climate benefits. He noted that pipelines are the most cost-effective means of transport; however, pipelines are expensive and complex to build over long distances and may include permitting challenges.

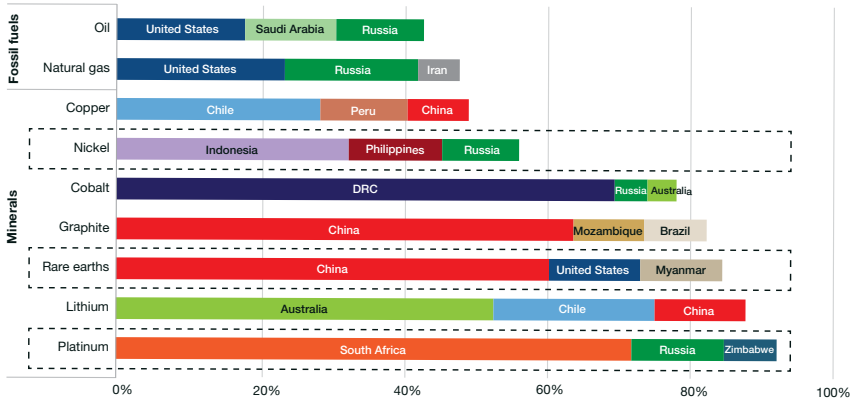
Second, Shabaneh discussed how some low-carbon hydrogen pathways are critical material intensive, which could present challenges in scaling up production if supply chains are disrupted, and prices of these materials are volatile (Figure 7). Polymer electrolyte membrane (PEM) electrolyzers, for example, require platinum and iridium, both of which are currently supply constrained. He noted that in general, critical materials have integrated supply chains and are dominated by only a few nations. This fact could pose challenges for increasing the manufacture of electrolyzers.

Figure 7 | Critical Minerals: Technology Risk?

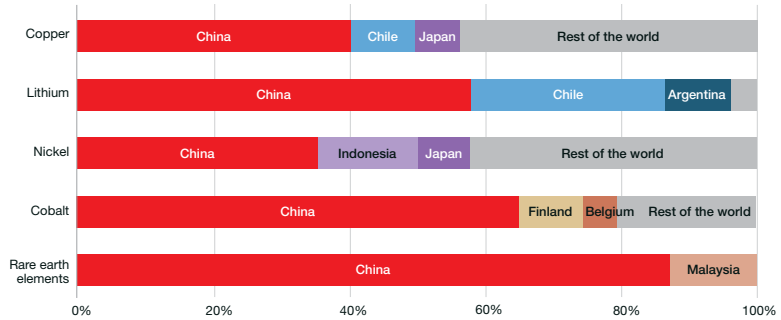
Estimated levelised demand for selected minerals in electrolyzers and fuel cells today



Share of top three producing countries in total production for selected minerals and fossil fuels. 2019



Share of processing volume by country for selected minerals. 2019



Source: King Abdullah Petroleum Studies and Research Center (KAPSARC) and International Energy Agency (IEA), The Role of Critical Minerals in Clean Energy Transitions.

Shabaneh concluded by addressing the next stages necessary for hydrogen market development. He focused on transportation, storage, and distribution challenges with discussion on pipeline opportunities and forms of hydrogen for transporting to end users. He also suggested opportunities for international cooperation in harmonizing regulatory frameworks, standards, and mutual recognition of standards.

Afternoon Breakout Sessions

The three breakout sessions focused on topics relevant to the development of a global hydrogen economy: (1) Regulatory and Policy Issues, (2) Financing Hydrogen Development, and (3) Developing the Hydrogen Value Chain (Appendix C). For each breakout session, a white paper, provided to participants in advance, framed the conversations. The papers presented both a literature review of studies and analysis particular to the discussion topic and posed questions to stimulate discussion and inputs informing the next stage of deep analytical work for the program. The breakout sessions, white papers, and discussion questions are detailed in Tables 1-3 on the next few pages.

Policy and Regulatory Breakout Session

The Policy and Regulatory Breakout Session brought together participants to discuss the regulatory landscape needed for the development of a hydrogen economy. Participants included representatives from academia, the chemical industry, consulting, law firms, think tanks, research organizations, and the oil, gas, and petrochemical industries. This session sought feedback on the creation of regulatory frameworks and policy incentives necessary to support hydrogen market development.

Alex Kizer of EFI moderated the first breakout session, which was framed in advance by the white paper, Global Hydrogen Policy and Regulatory Review. The following are primary points from the framing white paper and a synopsis of the breakout session conversation. Questions asked in the white papers and in the breakout session are included in Table 1.

As countries work to meet decarbonization commitments, more than 25 governments have released strategies to accelerate hydrogen market development through 2050.

As countries work to meet decarbonization commitments, more than 25 governments have released strategies to accelerate hydrogen market development through 2050. These strategies address a variety of priorities, such as carbon intensity standards for hydrogen production, durable supply chains, investment portfolio developments, policy incentives, workforce transition, international collaboration, natural gas standards, infrastructure needs and repurposing of existing infrastructure, and production targets. A primary thread across these national strategies is the need for consistency in regulation and other policies to support the development of a global hydrogen market. National strategies also generally acknowledge the need for alignment on emissions intensity to define “clean” hydrogen production requirements,[4] a concept interpreted differently depending on the country or region.

Table 1 | Breakout Session 1 Questions: Policy and Regulatory Issues

Breakout discussion informed by the *Global Hydrogen Regulatory and Policy Review* white paper **Discussion moderated by Alex Kizer (EFI)**
• What regulations should a global market be guided by? Are they local/national issues only or are standards across boundaries needed for transportation?
• Is a carbon pricing market needed for hydrogen market facilitation?
• Do we know how many jobs are created or the value of new job creation? What jobs are transferrable?
• Are national subsidies commercially viable in a global market?
• Can storage become an independent commercial negotiation? Should storage be evaluated independently or as part of a contract?
• To minimize risk, what should be the main features of hydrogen purchase contracts?

In addition to the countries that have announced hydrogen goals, at least 20 governments plan to release formal hydrogen strategies in the next two years. As more countries indicate interest in hydrogen as an energy commodity, establishing a rules-based market system that leverages the varied policy levers of different countries will be essential for lowering costs, increasing supply, and fostering international trade.

The MENA region has several ongoing hydrogen projects but, like many other regions, has no guiding regulatory framework. The global need for deep decarbonization, an abundance of renewable energy capacity, and strategic geography offers the region an important opportunity to diversify away from oil and gas exports. There is further opportunity to build a regional clean hydrogen economy and create a new export market as regional and global hydrogen demand grows.

Kizer started the regulatory and policy breakout sessions with the white paper questions, plus three additional overarching questions:

- Do we have the policies and regulations needed to animate clean hydrogen market development?
- How can we bring down the cost of clean hydrogen production?
- What is the role of international collaboration in effectively globalizing the hydrogen market?

Many participants in this breakout session focused on the need for regional, top-down government-led standardization of essential information and needs, including data sharing, and definitions of what qualifies as clean hydrogen and clean hydrogen-derived commodities. The discussion of commodities,

specifically ammonia and steel, was a major focus and viewed as providing opportunities for developing incentives to drive production and greater partnership at a regional level—to bring together a small group of producer countries to establish standards. It also was noted that increased use of ammonia for fertilizer production could have substantial positive impacts for agricultural output in developing countries.

> **Addressing this change in thinking about hydrogen will require special attention to community engagement and the sharing of information about the many important roles hydrogen could play in a clean energy future.**

Conversely, the fundamental question of "why hydrogen?" was discussed, along with the point that using it as an energy commodity, and not as a specialty chemical, may not be fully appreciated across the world. Addressing this change in thinking about hydrogen will require special attention to community engagement and the sharing of information about the many important roles hydrogen could play in a clean energy future. Analyzing activities in countries including Scotland, Chile, and Japan as examples of hydrogen's energy capabilities was discussed as a means of conveying important information about hydrogen uses. Analyzing and sharing information about hydrogen's flexibility and multiple uses also was discussed, including a review of the role hydrogen technologies could play in avoiding technology lock-in, e.g., converting an LNG plant[c] into an ammonia plant at a relatively low cost.

There was discussion on a range of policy prescriptions for addressing hydrogen market formation, including pore space rights[d] and liability issues associated with the CO_2 sequestration that would be needed for blue hydrogen production. Participants also discussed developing price incentives and pricing mechanisms, such as carbon border adjustments, to facilitate the production of green commodities. Also addressed was the current bilateral contract structure and the need to develop pricing mechanisms, including Henry Hub-like pricing, for distinct regions of the world; this could, in turn, influence the formation of a global market price for hydrogen as an energy commodity.

Takeaway 1:

Applicable regulation exists today to spur initial hydrogen development as a fuel and feedstock, however, additional demand-side regulation is likely needed to enable the true market potential of hydrogen as an energy commodity. Participants noted that hydrogen is currently regulated as a specialty chemical, where the focus is largely on safety, and that regulations on the production and transport of natural gas could be applicable for hydrogen as an energy commodity. The group also discussed the need for regulation in several high-priority areas to fully realize the potential for hydrogen as a primary energy commodity and carrier. There was consensus that additional policy is needed to support hydrogen market development, which could mean standardizing the definition of clean hydrogen and derived commodities or implementing carbon border adjustment mechanisms (CBAM).

c An LNG plant is where gas is liquified for shipping.
d Pore space is generally thought of as a subsurface geologic formation—in this context, used to store CO_2.

Takeaway 2:

Advocacy and buy-in are necessary to the development of a hydrogen market. Hydrogen as a fuel and feedstock is commonly misunderstood, and misperceptions could impede development. Participants discussed how sharing early hydrogen success stories could be a strategy for enhancing community awareness and facilitate the uptake of hydrogen as a fuel source.

Takeaway 3:

Global data standardization applied on a regional basis is essential for hydrogen market development. Throughout the conversation, there was consensus that greater standardization of hydrogen data is needed for data sharing. One participant suggested an organization like the Joint Organisations Data Initiative (JODI)[e] to instill data transparency in hydrogen markets, mitigate price fluctuations, and produce concrete outcomes of the producer-consumer dialogue.[5]

Additionally, the workshop participants agreed that common definitions for clean hydrogen and hydrogen-derived commodities are necessary for the standardization of a global market. Currently, the carbon intensity threshold for what can be considered clean hydrogen varies and standardization is essential for global hydrogen trading and eventual engagement in carbon trading markets.

A strong consensus emerged from the breakout session on the need for policymakers to move away from regulating hydrogen based on the rainbow of production methods and instead focus on standardization of carbon intensity definitions that would, in turn, inform a range of regulations of hydrogen as an energy commodity.

e The JODI provides a reliable, freely accessible, and comprehensive database of energy statistics, particularly in oil and gas markets, by using nationally sanctioned data to offer a fair assessment of global oil consumption and production monthly.

It was suggested that in the near term, it is unlikely that there will be sufficient surplus renewable power to produce hydrogen via electrolysis, so natural gas with CCUS may be the lowest carbon option.

A benefit to focusing on emissions intensity is that it would help establish a tradeable hydrogen market for which standardization of definitions is necessary to protect producers and consumers and enable hydrogen to support decarbonization goals.

It was suggested that in the near term, it is unlikely that there will be sufficient surplus renewable power to produce hydrogen via electrolysis, so natural gas with CCUS may be the lowest carbon option. Participants suggested that policymakers should be careful to craft regulations around full lifecycle emissions intensity so as not to disadvantage production pathways that are essential for market development and growth.

Finance Breakout Session

This session sought feedback on investment challenges and opportunities, as well as views on investing in hydrogen development. The Finance Breakout Session explored the financial bottlenecks and possible solutions to these issues to help support the development of a global hydrogen market. Participants included representatives from consulting, financial institutions, international freight logistics companies, NGOs, the nuclear industry, and the oil, gas, and petrochemical industries.

The second white paper, Financing a Hydrogen Future, framed the session and Peter Fazio of Barclays moderated the discussion. The following paragraphs are primary points from the framing white paper and synopsis of the breakout session conversation. Questions asked in the white papers and in the breakout session are outlined in Table 2.

Successfully implementing and achieving a global clean energy transition requires alignment across political, economic, and technological sectors. To carry out such an alignment, critical focus is needed to:

1. Clearly signal long-term commitments to foster investor confidence
2. Stimulate commercial demand for hydrogen in multiple applications
3. Help mitigate risk and other policy or regulatory hurdles that otherwise reduce the flow of capital to clean energy projects
4. Promote investment in R&D and knowledge sharing.[6]

Top-down, directed financing could enable more ambitious goals, de-risk private investment, and gain support across the value chain for the benefits and opportunities hydrogen has to offer the clean energy transition and deep decarbonization.

Table 2 | Breakout Session 2 Questions: Financing Hydrogen Development

Breakout discussion informed by the *Financing a Hydrogen Future* white paper **Discussion moderated by Pete Fazio (Barclays)**
• What is the Hydrogen Economy and what are the investment opportunities and risks?
• How will ESG[f] or other types of new analytical factors shape investments in hydrogen?
• How will the Inflation Reduction Act in the U.S. and the Carbon Border Adjustment Mechanism in the EU shape future financing for hydrogen?
• What policies would spur investment? How is development financed?
• What are innovative financing mechanisms for spurring investment in hydrogen?
• Could instruments from international financial institutions such as the global climate fund be useful?
• What are the key variables that will drive the export economics for hydrogen?
• What are the challenges of the clean energy transition in relation to the investment attractiveness of hydrogen fuels?
• How can the carbon intensity of hydrogen production affect financing?

f ESG investing—the consideration of environmental, social, and governance factors alongside financial factors in the investment decision-making process.

Hydrogen likely will play an important role in decarbonizing the energy mix, but major investment and development along the supply chain is needed. Estimates vary, however, about the potential market value of hydrogen as a fuel and feedstock in a decarbonized energy system. Many observers estimate that the value of the hydrogen market is expected to double by 2030—from $125 billion to $130 billion today to $250 billion by 2030,[7] and potentially $1 trillion by 2050.[8,9] Currently, hydrogen accounts for only about 1% of the energy mix and is predominately produced using unabated fossil fuels.[10,11] Despite decades of interest and research, however, obstacles remain to scale up a hydrogen market beyond its use as a specialty chemical.

> **Currently, there is a substantial focus on hydrogen production. However, large-scale investment in transportation, storage, and distribution also is needed.**

The nascent stage of a global hydrogen market represents a major bottleneck for capital flows and poses near-term risks for first-mover investors. For a global hydrogen economy to emerge, clean hydrogen must, either through policies, regulation, incentives, or a combination thereof, become cost-competitive or cost-advantaged relative to more carbon-intensive energy sources, and large-scale investment must be de-risked to expand infrastructure across the value chain. Currently, there is a substantial focus on hydrogen production. However, large-scale investment in transportation, storage, and distribution also is needed. The conundrum of whether initial investments should be made in, for example, production or in off-take markets[g] creates an obstacle to investment that must be solved by innovative technological solutions, policy support, and application of existing technologies to upstream, midstream, and downstream challenges.

While new policy and regulatory frameworks are needed to advance the formation of a hydrogen economy, government action is also essential for incentivizing investment in hydrogen to de-risk investment for first movers. In aggregate, estimates hold that "significant investment" is necessary for full hydrogen supply chain development. Some forecast that $5 trillion of investment (into production, storage, distribution, transmission infrastructure) is necessary to reach net zero.[12] To date, few hydrogen power generation projects have been brought to market and those under construction and operation remain small, i.e., less than 50 megawatts, in comparison to fossil fuel alternatives.[13] Investments in the hydrogen industry are, however, increasing, particularly in production technology deployment.[14]

Discussion during the breakout session covered a variety of areas pertaining to how necessary financing is for building a global hydrogen market; how governments like Saudi Arabia's could support or be incentivized to rapidly transition to clean hydrogen; and where along the value chain investments are needed. The discussion during much of the session was not directly correlated to the Financing a Hydrogen Future white paper and instead veered toward U.S.-centric financial markets and policy issues. The deliberation provided important insights into how global financial mechanisms could impact a global hydrogen market and the MENA region.

g "An off-take agreement is an arrangement between a producer and a buyer to purchase or sell portions of the producer's upcoming goods. It is normally negotiated before the construction of a factory or facility to secure a market and revenue stream for its future output." (Investopedia, https://www.investopedia.com/terms/o/offtake-agreement.asp.)

A consensus emerged that new policy and regulatory frameworks are needed to advance the formation of a hydrogen economy and that government action also is essential for incentivizing investment in hydrogen to de-risk investment for first movers. There were disagreements, however, on how hydrogen should be priced: Should pricing mechanisms track the current bilateral contract structures for hydrogen as a specialty chemical, or should new structures be developed to support the use of hydrogen as an energy commodity?

The view of most participants was that suppliers in the MENA region would have strong advantages in meeting the policies of potential off-takers, such as the EU's CBAM, given the short transport distance and strong renewable base for hydrogen produced via electrolysis.

There was general agreement that both incentives and taxes, i.e., on carbon emissions, would be necessary to develop a global hydrogen market. There was also a consensus that Saudi Arabia has an advantage as a first mover in developing global hydrogen markets and that scaling the hydrogen market would benefit from a strong investment base in the region. The view of most participants was that suppliers in the MENA region would have strong advantages in meeting the policies of potential off-takers, such as the EU's CBAM, given the short transport distance and strong renewable base for hydrogen produced via electrolysis.

The discussion also covered financing across the value chain. Participants agreed that to overcome the chicken-and-egg problem—how to match supply and demand—investments should be incentivized and made at all parts of the value chain. Most of the participants viewed this financing as "project finance," but some participants highlighted the potential of and need for investment from equity markets and venture capital. Participants agreed that off-take agreements—essential for demonstrating demand—need to be in place for financing to occur at scale. The discussion also included a focus on international carbon accounting and the requirement for standardization. It was noted by participants that having these standards before or after the start of a project, raises different financing issues for both. There was consensus, however, that such standards should be pragmatic and iterative to accommodate the growth of global and regional clean hydrogen markets.

Takeaway 4:

Traditional oil and gas producers are well-positioned to be hydrogen producers. There was general agreement that both incentives and taxes will be required to encourage global hydrogen market development. Also, nations with active sovereign wealth funds could direct funding toward hydrogen market development, which could be leveraged further to develop hydrogen markets. Participants acknowledged that success on local or regional levels is vital to de-risking investment and developing a global hydrogen market. Fossil fuel-producing nations can further decarbonize existing industries with low-carbon hydrogen production, e.g., large ammonia, methanol, and refining sectors. Participants agreed that further technological improvements and reduced production costs would enable hydrogen use in a broad array of applications.

As noted by speakers and in other breakouts, hydrogen suppliers from the MENA region have a strong geographical advantage relative to supplying hydrogen to primary demand centers in Europe and Asia. Saudi Arabia has developed a substantial interest in hydrogen production, markets, and export. The kingdom could manufacture low-carbon or zero-carbon hydrogen, attractive to the EU, which has a CBAM, as most of its electrolysis uses dedicated renewables and transportation distances are relatively short compared to most potential competitors.

Finally, participants noted that with pricing systems like the European Emissions Trading System, investors are financing projects. But even with a major subsidy, e.g., 45V Hydrogen Production Tax Credit (PTC) in the United States, the market will not progress without policies to create large-scale demand pull.

Takeaway 5:

The financial industry will require high-yield investments that demonstrate value across the supply chain. Participants agreed that investments are necessary for all segments of the value chain, from producers to consumers. Most of the finance discussion focused on project finance, but some participants highlighted the potential of equity markets or using venture capital. Regardless, participants agreed that long-term off-take agreements, demonstrating demand or public-private partnerships, may be needed for any financing to occur at a scale sufficient to support regional and global market development. Another possible solution discussed was sovereign guarantees and blended financing thereof, which would ensure a government backstop.

There was a consensus that the current focus on project finance is insufficient to develop regional and global markets and that policies and project developers need to attract equity market investments as well. Also, cost reduction will require technological innovation. A major difference between the current hydrogen and renewables industries is that companies producing electrolyzers for green hydrogen production are large multinational corporations, while the renewables industry has generally been supported by small startups with venture capital investments.

> **There was consensus that pricing mechanisms for hydrogen need to insulate producers and end users from volatility risk and ensure confidence in a developing market.**

Takeaway 6:

Pricing hydrogen as an energy commodity will be challenging in the early stages of market development. There was consensus that pricing mechanisms for hydrogen need to insulate producers and end users from volatility risk and ensure confidence in a developing market. However, participants disagreed as to how hydrogen should be priced. Given that hydrogen pricing today is based on its categorization as a specialty chemical, seeing a future for it as a fuel and power feedstock is challenging.

The need to determine how to reduce risks to end users and producers during market formation remains an issue. Looking at the LNG industry, participants noted that end users can purchase certain volumes over a long term (20 years or longer). Pricing formation is seen as scaling up from a boutique industry, i.e., viewing hydrogen as a specialty chemical to a global fuel, or as part of the process of adopting an entirely new fuel source.

Value Chain Breakout Session

The Value Chain Breakout Session was the largest of the three, with participants from academia, auto manufacturing, engineering companies, financial institutions, NGOs, oil, gas, and petrochemical industries, and other industries. This session solicited stakeholder feedback on the major bottlenecks blocking development of a global hydrogen value chain and potential solutions to the constrictions.

The conversation was framed by the third white paper Developing a Global Hydrogen Market, which explored the challenges of a global hydrogen market from a supply chain perspective. The session was moderated by Jane Nakano from the Center for Strategic and International Studies (CSIS). The following paragraphs include primary points from the framing white paper and a synopsis of the breakout session discussion. Questions asked in the white paper and in the breakout session are outlined in Table 3.

Table 3 | Breakout Session 3 Questions: The Hydrogen Value Chain

Breakout discussion informed by the *Developing a Global Hydrogen Market* white paper **Discussion moderated by Jane Nakano (CSIS)**
• What regions are attractive for hydrogen growth and why?
• How is the global hydrogen market expected to grow as the technologies for hydrogen production evolve?
• How will the Inflation Reduction Act in the U.S. and the Carbon Border Adjustment Mechanism in the EU shape future financing for hydrogen?
• Does the development of a hydrogen market domestically in the United States provide a competitive advantage for U.S. producers internationally?
• Similarly, what end uses (that are not currently being targeted) are attractive for hydrogen growth and why?
• How will critical mineral supply chains impact market development? How will a shift to energy production dependent on renewables impact the development of a hydrogen market?
• How will the implementation of the Inflation Reduction Act impact hydrogen development in the U.S. and subsequently an eventual global market?
• How can government strategies/policies (at a national and international level) support hydrogen market growth? What sorts of government interventions are needed?
• What other trade aspects for hydrogen need to be considered?
• Will the conflict in Ukraine impact the development of hydrogen in Europe and how?

Currently, most hydrogen is produced using carbon-emitting technologies. The steam methane reforming (SMR) process is currently used to produce most of the world's hydrogen and is used at approximately 1,000 commercial facilities, mostly in China. Coal gasification is another mature technology used for producing hydrogen, but the associated emissions are nearly 20 kgCO_2/kg hydrogen at the point of production.[15] The costs of coal gasification are also typically more expensive than reformation—the former costing $1 to $2.50 per kilogram of hydrogen, whereas SMR/ATRs cost around $0.70 to $2.20 per kilogram.[16] Autothermal reforming (ATR) technology is most commonly used for ammonia and methanol production from hydrogen.[17] Approximately 90 Mt of hydrogen was produced globally in 2020, resulting in 900 Mt of unabated CO_2, the equivalent of 28% of all emissions from the MENA region.[18]

In 2021, global hydrogen demand reached more than 94 Mt, a 5% increase from the previous year and compared to 91 Mt in 2019 (pre-pandemic level).

In 2021, global hydrogen demand reached more than 94 Mt, a 5% increase from the previous year and compared to 91 Mt in 2019 (pre-pandemic level).[19] As of 2021, the oil refining industry was the largest consumer of hydrogen, accounting for 42% of total global demand or 40 Mt.[20] A close second to refining for uses of hydrogen production was ammonia, at 36% or 34 Mt of global hydrogen demand.[21]

Nationally determined contributions[h] and net-zero commitments are major market drivers for clean hydrogen as difficult-to-abate sectors require creative solutions for decarbonization. Cleaner production pathways are needed to achieve national and global emissions targets, such as Saudi Arabia's NDC Paris Agreement target of 278 Mt of CO_2 reduction by 2030.[22]

Many existing industries that rely on gray hydrogen are interested in transitioning to clean hydrogen, as well as developing new markets for hydrogen, such as transportation and stationary fuel cells. With new applications for hydrogen, global demand could rise to more than 200 Mt by 2050.[23] This new demand could be met by a steep increase in zero- and low-carbon hydrogen production if NDCs and net-zero goals are to be achieved. Likely production pathways to produce zero- and low-carbon hydrogen include SMR and ATR with CCUS, as well as renewable electricity-powered electrolysis.

Discussion during the value chain breakout session covered a wide range of issues including regional hydrogen needs and advantages, associated export market development, demand creation, and parts of the value chain where policy and investment focus is needed. The discussion points in the session tracked with the four sections from the Developing a Global Hydrogen Market white paper:

1. Hydrogen Production and the Cost of Supply
2. Development of Global Hydrogen Market Demand
3. Hydrogen Market Development and Pricing – A Natural Gas Analog
4. Hydrogen Trade Possibilities.

h Nationally determined contributions (NDCs) submitted by countries under the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) represent pledges on climate action that seek to limit global warming to well below 2°C, preferably to 1.5 °C, over pre-industrial levels.

Relative to hydrogen production and cost of supply, most participants agreed that Europe and Asia are both attractive regions for hydrogen demand growth. However, while the MENA region is well-suited to become a major hydrogen producer, there was some disagreement about production potential in the United States.

Relative to hydrogen production and cost of supply, most participants agreed that Europe and Asia are both attractive regions for hydrogen demand growth. However, while the MENA region is well-suited to become a major hydrogen producer, there was some disagreement about production potential in the United States. The debate stemmed from participants' views of the Inflation Reduction Act of 2022 (IRA). Some thought the 45V credit made the U.S. more competitive, while others thought the legislation was too internally U.S.-focused and closed off the country from international collaboration, especially with China. Participants also viewed China as a potential risk per Chinese companies' control of a large percentage of electrolyzer and solar photovoltaic manufacturing. Nonetheless, participants highlighted that the energy transition cannot happen without China's collaboration.

The conversation focused heavily on export market development and ways to incentivize demand. It was noted that demand already exists in Europe and Asia, but de-risking measures are needed for producers and customers, including financial or policy assistance that would lessen existing or potential risks, e.g., political, regulatory, technology, capital market risks, etc., through reallocation, sharing, or reducing instruments, i.e., dedicated funds, equity stakes, tax incentives, sovereign guarantees, etc. For countries interested in developing export markets, panelists discussed the importance of resource assessment, workforce transition, hydrogen hubs, and the need for a greater focus on the carbon intensity of production methods.

Regarding the natural gas analog laid out in the white paper, participants felt that LNG should not be used as an analog for hydrogen. In current markets, LNG is more price variable than hydrogen and easier to transport. This point led to a conversation about mid-stream challenges for the hydrogen value chain. Hydrogen is less energy dense than oil or natural gas and it requires much more energy to condense it to a state suitable for shipping. Many participants expressed concerns about transporting hydrogen from the point of production to demand centers and suggested that pipelines were the most effective method of transport. Finally, the policy conversation around the fourth section, "Hydrogen Trade Possibilities," was U.S.-centric and focused on permitting reform for carbon storage and setting a price, or tax, on carbon emissions. The main takeaways from the conversation include:

Takeaway 7:

Midstream transportation challenges must be resolved to facilitate development of a global hydrogen market. Participants noted the many challenges associated with transporting hydrogen molecules by ship and pipeline—namely, that the high-energy input needed for liquefaction is costly for exporters. Also, the potential for leakage throughout the value chain could diminish the climate benefits gained in the buildout of a

hydrogen economy. In addition, challenges exist with maintaining hydrogen purity, as well as with the build-out of infrastructure, such as pipelines, shipping vessels, and ports.

As the market develops, identifying the best trade-offs requires further research and market experimentation.[24] Also, hydrogen storage issues along the value chain are complex, including regulatory concerns, hydrogen life-cycle issues, and costs.[25] To resolve these issues, nations and companies will need to deploy many solutions to meet transportation challenges, which could range from creating local hub-and-spoke networks to focusing on policies for national or regional market creation efforts.

Takeaway 8:

The concentration of critical minerals and manufacture of electrolyzers represents a challenge to the widespread emergence of a green hydrogen economy. Participants viewed China's control of electrolyzer and PV manufacturing as a potential restrictive single point of failure.

Production of hydrogen electrolyzers and fuel cells could drive up demand for nickel, platinum, and other minerals, even though the market effects will depend on the shares of the different electrolyzer types.[26] Alkaline and PEM, the two dominant types of electrolyzers, have very different mineral requirements; solid oxide electrolyzers present fewer mineral concerns, but are less developed.[27] This challenge will greatly impact these technologies' ability to be used at scale and at a cost-competitive rate.

Some participants surmised that the energy transition cannot happen without broad and deep international collaboration.

Takeaway 9:

Increasing demand from Europe and Asia will spur the growth of a global hydrogen market. The conversation on hydrogen demand cited Europe and Asia as potential markets, driven in part by decarbonization goals and energy security needs. Participants identified the ongoing crisis in Ukraine as a lead indicator that will drive multiple solutions to meet energy security and climate goals, including further development of renewable energy sources and clean fuels.

Takeaway 10:

Using hydrogen as a commercial fuel, and ammonia as an energy carrier, could contribute to the growth in demand needed to develop regional and global markets. To encourage hydrogen market development, the discussion centered on increasing the use of hydrogen as a fuel and for ammonia production. These were discussed as the primary uses with the potential to increase hydrogen demand. Participants noted that the production of ammonia from low-carbon hydrogen would take advantage of existing infrastructure and help to decarbonize global shipping.

In the transportation sector, ammonia could play a role as a flexible, non-emitting energy carrier for marine transport. International shipping is currently responsible for about 3% of total global greenhouse gas (GHG) emissions, a percentage that becomes important given net-zero targets and pending and potential carbon border adjustments. If sufficient safety measures were put into place, ammonia could become a new drop-in bunker fuel for ships. Existing pipeline infrastructure, shipping routes, and ports that handle large quantities of ammonia are robust, which could enable a larger role for ammonia in the shipping industry.

Ammonia production itself is, however, one of the largest industrial emitters of CO_2. A major reduction in emissions could be realized with a switch to clean hydrogen, as more than half of the emissions from the ammonia production process are associated with emissions from hydrogen production.

Final Panel Discussion—Breakout Session Summary

Richard W. Westerdale II of EFI convened the concluding panel discussion with the three breakout session moderators Kizer, Fazio, and Nakano. The discussion focused on the crosscutting issues brought forth in each breakout session. Westerdale asked each panelist to summarize the primary takeaways from their sessions (summarized for each breakout session in previous discussions). Moderators also discussed the accelerating opportunities for hydrogen market development and noted that, at least in the United States, there are substantial incentives to spur market growth. The panelists stressed, however, that a greater emphasis should be placed on strategic initiatives—for example on incentivizing and accelerating permitting and infrastructure development—to move global hydrogen market formation forward.

> **"... look if we have to rely on incentives then we're failing because we couldn't afford success."**
>
> Ernest Moniz
> *EFI*

In discussing the bankability of hydrogen projects, Fazio emphasized that project economics must be sound regardless of subsidies, noting that investors are primarily focused on economic viability. Fazio noted, however, that there is growing comfort with subsidies in the United States that support project economics, such as the 45Q tax credit for CO_2 sequestration, and the 45V tax credit for the production of clean hydrogen. Considering whether a project is for hydrogen fuel or renewables, Fazio said that, at present, projects will have a hard time being economical. But he optimistically explained that investors are diverse in this space and have varying risk tolerances. Venture capital investors, for example, are more willing to take technology risks whereas a later-stage investor needs to see proof of technical and market viability. The panelists noted that government support could bring added certainty for investors, pointing to the value of the investment and production tax credits in the recently passed IRA for accelerating energy technology development and deployment through grants and tax incentives.

Considering that there are inherent and substantial risks associated with being an innovator or first mover, one of the panelists spoke about the excitement in Asia over the potential for hydrogen production in both the U.S. and MENA, but that security of supply remains a concern for import-dependent countries. The panelist added that Japanese companies are working closely with Aramco and Australian companies to import low-carbon hydrogen.

The panel then shifted to discussing improvements in technologies that will reduce the cost of low-carbon hydrogen production. A panelist noted that the hydrogen industry has focused on reducing the cost of electrolyzer manufacturing that could, in turn, lower the costs of hydrogen production. Also, successful clean hydrogen projects will optimize energy input configurations from a variety of sources specific to each project or region of production.

The panelists all expressed concerns that China's control of critical metal and mineral supply chains that are required for electrolyzer production, along with its major role in electrolyzer manufacturing, made it one of the leaders in the upstream clean hydrogen value chain.

Westerdale asked each panelist to generate a headline crystalizing their thoughts on a global hydrogen future. One headline: "Address fundamentals: There is a lot to be learned from past failures." Another panelist offered this headline: "Hydrogen is not only for decarbonization but has great potential to revitalize the United States' industrial competitiveness." The final panelist suggested "Like renewables, hydrogen can achieve a cost-cutting strategy" as a headline that underscores the value and potential of developing a global hydrogen market.

Westerdale concluded the panel by circling back to one of the goals of the joint work program: exploring the role the MENA region could play in global decarbonization, with the development of a global clean hydrogen market as a primary component of this critical need. He noted that the region's vast resources and energy industry experience could position it to be a leader in emerging regional and global hydrogen markets. Finally, he noted that the development of a hydrogen economy offered an incredible opportunity for economic and job growth, both of which are crucial for the region.

Closing Remarks

In his closing remarks, Fahad Alajlan praised the day's collaboration and the abundance of information and perspectives provided by the diverse range of participants. He reminded the group about all that was missed during the COVID lockdowns and how much more valuable an in-person workshop is, noting that "one in-person event is worth several virtual workshops." Mentioning a gift that he received during the workshop, a book authored by an attendee titled *Hydrogen is the New Oil*, Alajlan closed his remarks by saying that all the information has been "like drinking from a fire hose, and I've much to take home."

The final speaker, Ernest Moniz, underscored messages from the Finance Breakout Session presentation, reiterating the need for successful financing of clean energy projects and noting that there is not much time left to get to net zero. Moniz acknowledged the risk of investing in a world where geopolitics, climate, and national security issues spill into the energy sector and on down to hydrogen market development.

Moniz added that diverse and substantial investment in hydrogen and other fuels is required as fuel markets in a low-carbon world will be more fragmented, with hydrogen as a needed player in a field of players. Furthering this point, he noted that the evolution of hydrogen markets and a low-carbon economy will require different energy sources and carriers that meet a range of needs. Moniz concluded with praise for KAPSARC's cooperation and the constructive dialogue, input, and expertise from the many organizations represented at the workshop.

In closing, he emphasized that this workshop was just the beginning and collaboration would be ongoing throughout the deep analyses in the days ahead. Analysis, which—reflecting a wide range of interests, organizations, economies, technologies, governments, policy interests, and investment needs— will inform the development of a global hydrogen market.

CONCLUSIONS AND NEXT STEPS

The next workstream of deep analytical work is designed as the centerpiece of the joint study on hydrogen and the circular carbon economy and is set to be: A.) a comprehensive study of the role of hydrogen in the clean energy transition; where B.) all production technologies will be considered as well as hydrogen carriers such as ammonia, methanol, and organic liquids; and, finally C.) to make policy recommendations in three areas: hydrogen meeting energy demand and decarbonization targets; global market formation; circular carbon economy in the global hydrogen market context.

The conclusion of this workshop provided a solid foundation for the next steps. The 10 takeaways for the planned deep dive analytical work are substantial. Importantly there was agreement that hydrogen market developers need to move beyond color coding and more towards growing both supply and demand; significant financing is needed for the development of hydrogen production and related infrastructure from producer to consumer; and risk mitigation mechanisms, agreed-upon basic regulations, and government-directed incentives are necessary at this nascent development stage.

Looking toward global hydrogen market development, the next phase of work will delve into the research and analysis of deep-seated challenges.

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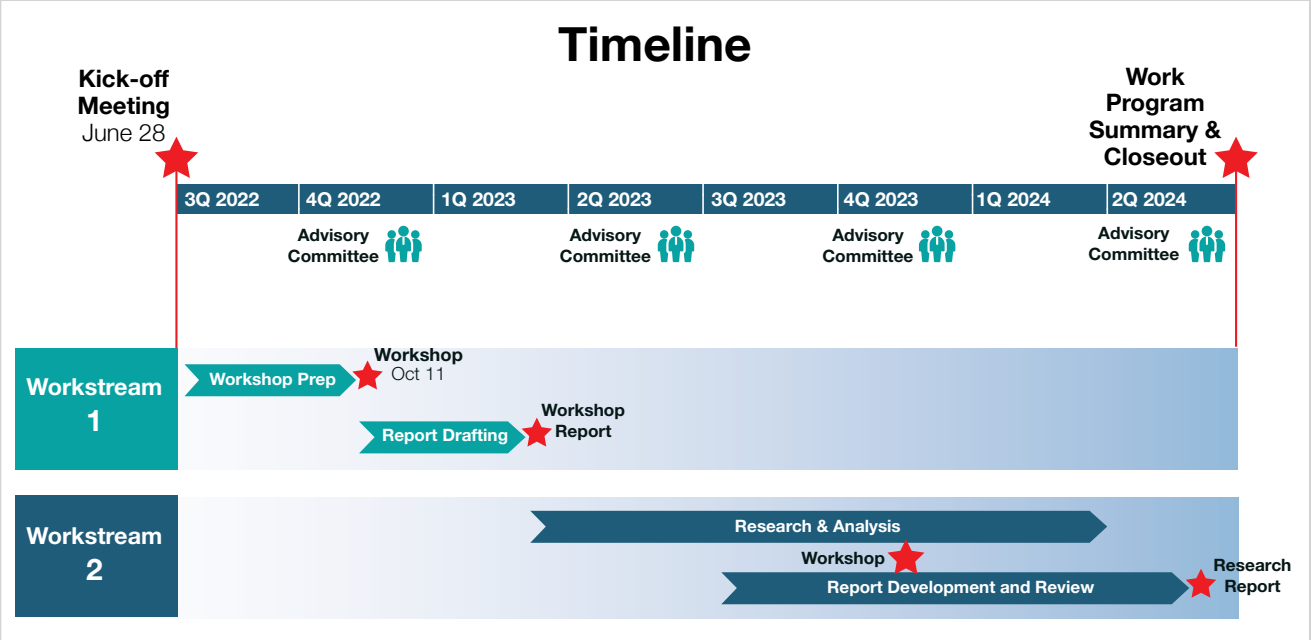

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About **EFI**

The Energy Futures Initiative advances science-based solutions to climate change through evidence-based analysis, thought leadership, and coalition building.

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About **KAPSARC**

King Abdullah Petroleum Studies and Research Center (KAPSARC) is an advisory think tank within global energy economics and sustainability providing services to entities and authorities in the Saudi energy sector.

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