Coalition for Disaster Resilient Infrastructure

THE RESILIENCE IMPERATIVE

FORWARD THINKING ON HYDROGEN INFRASTRUCTURE

Perspective Paper

MAY 2022

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About the paper

This perspective paper is an initial effort to promote the disaster resilience of hydrogen infrastructure. It seeks to inform policymakers and practitioners on the need for systems thinking approach in anticipating disasters and building suitable buffers.

About CDRI

The Coalition for Disaster Resilient Infrastructure (CDRI) is a global multi-stakeholder partnership of national governments, UN agencies, programmes, multilateral development banks, financing mechanisms, private sector, academic and knowledge institutions. CDRI is committed to working with various stakeholders to promote the resilience of infrastructure globally.

Disclaimer

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Foreword

A global energy transition is underway. The drivers of this transition include equitable access, security and cleaner forms of energy to address climate change. Across several countries, hydrogen is likely to form a critical pillar of this transition. Hydrogen offers a green, carbon-neutral alternative to generate electricity as well as power transport and industry. The report of the Intergovernmental Panel on Climate Change Report on Mitigation of Climate Change, released in April 2022, specifically refers to the role of hydrogen as an energy source for heating, transport and heavy industry.

Realizing the full potential of hydrogen as an alternate energy source for various uses will require massive investments in new energy infrastructure. However, against the backdrop of imminent disaster and climate risks across the globe currently, it is important to ensure the resilience of these infrastructure systems and assets.

The Coalition for Disaster Resilient Infrastructure (CDRI) has been working to understand the contours of the vulnerability of the hydrogen infrastructure globally, cutting across geopolitical, technological, financial and knowledge dimensions. As a follow-up to the DRI Dialogue conducted by the Coalition on 14th January, 2022, I am pleased to receive CDRI's Perspective Paper "The Resilience Imperative – Forward Thinking on Hydrogen Infrastructure". This is a timely input given the rapid development of technological solutions and policy shifts supporting investments in hydrogen infrastructure globally.

As a first in the series of the several knowledge products planned by the Coalition, the paper is in line with the objectives of CDRI's knowledge initiatives aimed at providing futuristic perspectives with a strong leaning toward influencing policy and practice. The Coalition welcomes collaborations with other like-minded agencies to support the global transition to cleaner energy pathways – in a manner that is disaster and climate-resilient.

Kamal Kishore

India Co-Chair, CDRI Executive Committee and Member Secretary, National Disaster Management Authority (NDMA), India

We are witnessing an unprecedented time in human history. Today, the world is facing overlapping health, environmental, and economic crises — each as complex as the other. The United States is committed to addressing the climate crisis by investing in adaptation and resilience while promoting independence from non-renewable energy sources. Across the globe, U.S. Government agencies collaborate and partner with other nations to help meet bold international climate commitments by accelerating their transition to more widely accessible, affordable, reliable, and sustainable energy that spurs economic growth, powers health systems, and reduces emissions.

As of 2021, renewable energy installations have surpassed coal-fired and fossil fuel installations globally, providing clean and affordable energy for millions of people, while mitigating the impact of climate change.

The Biden-Harris Administration acknowledges that global problems require global cooperation and solutions. As the climate crisis intensifies, engaging the global community is the only way we will tackle these challenges. It is in this context that the U.S. Government has partnered with the Coalition for Disaster Resilient Infrastructure to support the global transition to clean and renewable energy and promote the resilience of new and existing infrastructure systems, which together mitigate climate and disaster risks in support of sustainable development.

As co-chair of the CDRI Governing Council in its current term, the United States is proud to support the launch of the CDRI's Perspective Paper "The Resilience Imperative – Forward Thinking on Hydrogen Infrastructure." Hydrogen, an abundant and green alternative resource for energy generation, is fast emerging as a vital solution for climate challenges. With utility across several industries, green hydrogen is a focus for policymakers and companies in the energy sector as a game-changer for the energy transition.

The paper's launch is timely, amidst the International Conference on Disaster Resilient Infrastructure, which is bringing together key decision-makers, practitioners, and communities from across the world to discuss challenges, identify best practices, develop collaboration, and importantly, galvanize global actions. The paper underscores the complexities of hydrogen infrastructure globally, while reinforcing the importance of resilience as we transition to renewable energy sources. It is our hope that this paper influences planners and decision-makers and serves as a resource for all stakeholders on a transition to a clean and resilient future.

Veena Reddy

Executive Committee Co-Chair, CDRI (2022-2024)
Mission Director, USAID/India

Abbreviations

CDRI	Coalition for Disaster Resilient Infrastructure
CEN	European Committee for Standardization
COP	Conference of the Parties
DOE	US Department of Energy
FCHEA	Fuel Cell and Hydrogen Energy Association
GFDRR	Global Facility for Disaster Reduction and Recovery
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPCC SROCC	Intergovernmental Panel on Climate Change's Special Report on the Ocean and Cryosphere in a Changing Climate
IRENA	International Renewable Energy Agency
LLIC	Low Lying Islands and Coastal Regions
R&D	Research and Development
SIDS	Small Island Developing States
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
UNISDR	United Nations Office for Disaster Risk Reduction
USA	United States of America
USD	United States Dollar

Summary

As a potential energy source of the future, hydrogen is witnessing significant commitments in the form of policy support and investments for infrastructure development by different stakeholders.

Several countries across the world have varying approaches to hydrogen. For instance, India aims to be the global hub of green hydrogen while Japan emphasizes the adoption of an overall hydrogen economy. However, the promise of hydrogen in the transition to a net zero emissions future is fraught with challenges in production, storage and utilization. A cogent perspective on disaster and climate resilience of the hydrogen value chain with its infrastructure systems, subsystems, components and assets is conspicuous by its absence in the current discourse. There is a clear need to recognize and understand the vulnerabilities in the value chain including dependence on renewable energy sources in the context of a changing climate, the impact of hydrogen production on available natural resources, mainly water, need for investing in specialized transport infrastructure, among others. There is a need for unified standards and certification systems for disaster resilient hydrogen infrastructure as well as building the capacity of various stakeholders across the process chain to plan, design, implement and monitor hydrogen infrastructure with resilience as a critical metric. Including disaster resilience of infrastructure in the discourse could yield exponential benefits if incorporated at this stage of the nascency of the hydrogen economy. This indeed is the core message of this Perspective Paper.

Prepared with inputs from different stakeholders globally, this paper presents key reflections based on discussions with representatives from senior policy-making bodies, private businesses and industry, research, and advocacy institutions. These were complemented by a secondary literature review. Based on these practical and theoretical insights, the paper seeks to inform stakeholders on the importance of taking a holistic approach to the resilience of infrastructure for driving the hydrogen economy and to introduce future programmatic offerings by CDRI.

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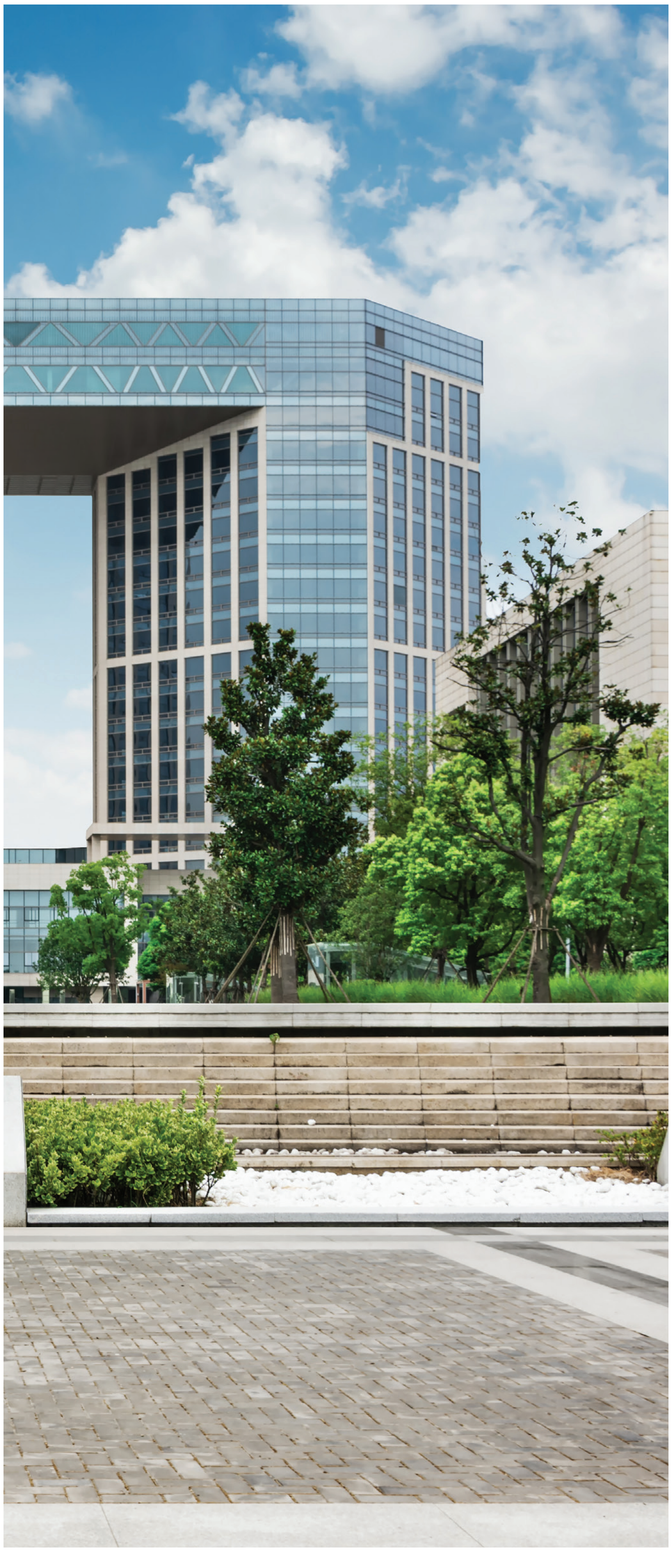
01 Hydrogen and the Envisaged 'Net Zero' Future

Countries worldwide have pledged to limit the global average temperature rise to well below 2°C above pre-industrial levels and aim for limiting temperature increase to under 1.5°C as part of their commitments to the 2015 Paris Agreement, (United Nations Framework Convention on Climate Change [UNFCCC], 2016), which is also reflected in the commitments of the Conference of Parties (COP26). The Glasgow Breakthrough Agenda comprised a series of agreements to rapidly scale up clean technologies that will help meet the 1.5°C target (UKCOP26, 2021). One of the key actions in five economic sectors included an agreement to make hydrogen affordable with renewables and making low carbon-based hydrogen globally available by 2030 (UNFCCC, 2022).

Hydrogen is seen as one of the critical factors in the world's transition towards an envisaged net zero emissions future (World Energy Council, 2018; International Renewable Energy Agency [IRENA], 2019; International Energy Agency [IEA], 2021) and the shift to hydrogen as an energy source is now gaining considerable momentum.

The IEA Net Zero Roadmap to 2050 scenario also suggests that hydrogen will constitute about 10 percent of the total final consumption in the world's transition to net zero emissions (IEA,2021).

Hydrogen investments have been steadily increasing, majority being driven by the private sector; the projected investment outlay for global hydrogen is to the tune of US$ 15 trillion by 2050 (Reuters, 2021).



Hydrogen Value Chain

The hydrogen value chain comprises several infrastructure systems, sub-systems, components and assets – upstream, midstream and downstream. The efficiency of the value chain is dependent on several aspects including the disaster and climate resilience of infrastructure across various levels. In this context, hydrogen valleys or hubs are being developed in specific geographic regions in which several components of the value chain are integrated (IEA, 2021). The hubs are characterized by a large-scale setup covering most aspects of the value chain.

A significant number of hydrogen valleys are present in European countries viz. Germany, France, Spain, the Netherlands and the United Kingdom; other major locations are in Australia, Chile, and the United States of America (Europa, 2021). Given the critical role of transport in the value chain, especially for transnational import and export of hydrogen, seaports deserve a special mention. Rotterdam, Netherlands, Zeebrugge & Antwerp, Belgium and New Castle, Australia are developing as hydrogen ports. The national hydrogen strategies of Chile and Australia also focus on repurposing ports into hydrogen export hubs.

There is a significant push towards hydrogen valleys with participation from both private as well as public sector and the value chains are also expected to become cost-competitive in near future. This will be led by lowered costs of production as well as developments in midstream value chain including storage and transportation infrastructure.

Production

- Fossil fuel based + Carbon Capture Systems
- Electrolysers
- Renewable energy: solar, wind

Transportation

- Transport through ammonia
- Pipelines
- Repurposed containers

Storage

- Short term storage: Compressed gas vehicles and containers
- Long term storage: Salt caverns, porous rock reservoirs, depleted oil and gas fields

Utilization

- Transport
- Steel
- Refinery
- Fertilizer

Resilience of Hydrogen Infrastructure

The concept of resilience has gained currency in recent times as the world continues to grapple with increasing frequency and intensity of disaster events. The Global Facility for Disaster Risk Reduction (GFDRR) notes that climate risk alone has resulted in nearly US$ 1.9 trillion in economic losses over the last 20 years (GFDRR, 2015). Besides the loss of economic assets and value chains, the opportunity cost of disasters to various sectors of the economy has been huge. Hence, there has been a visible shift in the global discourse around improving the resilience of infrastructure.

Reliable sources of energy are central to smooth functioning of nearly all social and economic activities in the modern world. Sustainable services and energy security are core to ensuring quality of life before, during and after extreme events. Specifically, regarding hydrogen as an energy source, a focus on reliability and sustainability merits deeper engagement to understand potential risks to assets and systems due to varied natural and manmade hazards. Individual assets/components and the overall value chain may be differentially vulnerable to different kinds of risks affecting the overall performance of the system.

An increasing body of knowledge around the definition of resilience points to certain common characteristics. An infrastructure system that is resilient is characterized by:

Robustness:
Ability to withstand shocks and stresses without degradation or loss of functionality

Rapidity:
Ability to overcome disruption and resume functioning fairly swiftly

Redundancy:
Access to backup alternatives for contingency

A resilient system has sufficient resourcefulness for resumption of services by mobilizing the required support and services during breakdowns. It also includes feedback loops for continued self-improvement (Bruneau et al, 2006, Anand, 2017). The United Nations similarly defines resilience as “The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions” (UNISDR, 2009). Infrastructure resilience is, therefore, defined as “the ability of critical infrastructure systems, networks, and functions to withstand and rapidly recover from damage and disruption and adapt to changing conditions” (NIAC, 2010).

A clear case in point is the strategy to repurpose existing port infrastructure to hydrogen ports or building new hydrogen port infrastructure facilities, which is fraught with risks. The projected surge in multiple climate hazards due to sea-level rise accompanied by an exacerbated increase in anthropogenic drivers such as habitat degradation will impact coastlines (Intergovernmental Panel on Climate Change's Special Report on the Ocean and Cryosphere in a Changing Climate [IPCC SROCC], 2019) and consequently, port infrastructure. Additionally, frequency and intensity of extreme sea levels due to storm surges and extreme waves are also expected to increase, causing risks of flooding in port infrastructure facilities, with detrimental impact both on existing and upcoming infrastructure.

Special Case of Small Island Developing States

The Small Island Developing States (SIDS) face significant energy challenges, given their geographic location and heavy reliance on fossil fuels. On an average, SIDS spend in excess of US$ 67 million per day for their energy needs (World Bank, 2014). The effects of fuel price shocks on the SIDS economies are also high with oil and gas imports comprising 12-37 percent of their total imports. Most SIDS are characterized by a lack of a dedicated energy policy that rationalizes a structured approach to meet their energy needs. Given this background, it is imperative for SIDS to develop and adopt a future-ready energy policy that emphasizes renewable energy, particularly hydrogen. SIDS are likely to benefit most of all economies by replacing fossil fuels in their energy mix with hydrogen (IRENA, 2019). However, the road to a secure energy future in the SIDS may encounter considerable challenges given their vulnerability to climate change. Coastal infrastructure in these countries is at significant risk and the projected increase in both frequency and magnitude of extreme weather events only further exacerbates these risks (IPCC SROCC, 2019). Strengthening the upcoming hydrogen infrastructure in the SIDS will need dedicated policies, funding and capacity for implementation.

02 Challenges in Achieving Disaster Resilience of Hydrogen Infrastructure

Policy

Limited Policy Perspective

Policy mechanisms are vital to guide the economics and politics of hydrogen. A quick analysis of the global hydrogen policies reveals that a holistic push towards the adoption of hydrogen is imminent. Countries are at various stages of drafting the policies (World Energy Council, 2019; IEA, 2021; IRENA, 2021). While different national governments have brought out full policy documents, roadmaps and vision documents, only 14 countries (as of 2022) have a national hydrogen strategy in place. These include Australia, Japan, South Korea, France, Germany, Netherlands, Norway, Portugal, Spain, Hungary, Chile, Canada, the United Kingdom, and the European Union as a geopolitical bloc. India has notified the first phase of its national hydrogen policy (Press Information Bureau, 2022), that aims to produce 5 million tonnes of green hydrogen by 2030, only recently.

Each of these countries that has published their national hydrogen strategy has a different focus. The main drivers of hydrogen policies globally are decarbonization, diversification of energy supply, fostering economic growth including the creation of jobs, integration of renewables and emphasis on technological independence (World Energy Council, 2021; IRENA, 2022). Most countries seem to be focusing on different aspects of the value chain at this stage. Japan emphasizes the adoption of an overall hydrogen economy having varied applications in different industrial sectors. Australia and Chile, on the other hand, aim to be export-driven hydrogen hubs through large-scale production and dedicated transmission channels (IRENA, 2022).

Policy Discussions, Official Statements, Initial Demonstration of Projects	Strategy in Preparation	Strategy Available
LATIN AMERICA & THE CARIBBEAN		
Argentina Bolivia Panama Paraguay Peru Trinidad & Tobago	Brazil Columbia Uruguay	Chile
NORTH AMERICA		
—	Mexico United States Of America	Canada
EUROPE		
Bulgaria Croatia Czech Republic Denmark Estonia Finland Georgia Malta Luxembourg Lithuania Latvia Iceland Greece Romania Serbia Slovenia Switzerland Turkey Ukraine	Austria Belgium Italy Poland Russian Federation Sweden Slovakia	European Union France Germany Netherlands Norway Portugal Spain Hungary United Kingdom
ASIA		
Bangladesh Hong Kong (SAR)	China New Zealand Singapore Uzbekistan	Australia India Japan South Korea
MIDDLE EAST & GULF COUNTRIES		
Israel United Arab Emirates	Oman Saudi Arabia	—
AFRICA		
Cape Verde Burkina Faso Mali Nigeria South Africa Tunisia	Egypt Morocco	—

Hydrogen National Strategies and Policies (CDRI, 2022) Source: CDRI, 2022; IRENA, 2021; World Energy Council, 2021

Absence of Standards and Certification Focused on Disaster Resilience of Hydrogen Infrastructure

Appropriate standards and codes to support infrastructure investments and scaling clean hydrogen industry are lacking. The available standards and codes are insufficient as they predominantly focus on storage and transportation of hydrogen in addition to those around the general safety, receptacles, piping and pipelines, hydrogen embrittlement etc.

Guarantees of Origin for Green Hydrogen

Guarantees of origin are certifications for green hydrogen being produced using renewable energy. Globally, a range of approaches have been taken by standardization agencies such as the European CEN/CENELEC/TC 6 standard), certification bodies (e.g. TUV SUD) and the consultation processes in energy and climate policy (e.g., EU CertifHy, AFHYPAC and the governments of California and the UK) to define green hydrogen and guarantees of origin.

Standards and Certifications for Hydrogen

Standard	Coverage
International Organization for Standardization (ISO) Technical Committee of Hydrogen Technologies (ISO/TC 197) (ISO, 2022)	Standardization in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen
European Committee for Standardization (CEN)—CEN/TC 23; CEN/TC 185; CEN/TC 262; CEN/TC 459/SC 1 (CEN, 2016; CEN/ CENELAC, 2018)	Transportable gas cylinders, their fittings, requirements relating to their design, testing and operation; Fasteners; Metallic and other inorganic coatings, including for corrosion protection and corrosion testing of metals and alloys; Hydrogen embrittlement
Hydrogen and Fuel Cells Codes and Standards Matrix (FCHEA)	Hydrogen and fuel cell technologies
International Partnership for Fuel Cells and Hydrogen in the Economy (IPHE, 2022)	Standing Working Group on Regulations, Codes, Standards and Safety and dedicated task force on hydrogen production analysis

Limited Stakeholder Capacities for Development of Disaster Resilient Hydrogen Infrastructure

A recent study has projected that there could be a shortage of skilled manpower in the renewable energy sector. As many as 43 million jobs are estimated to be created in the sector by 2050 (IRENA & ILO, 2021). with major drivers being technological advancements, changing supply chain structures and evolving policy focus putting renewables at the forefront. It has also been pointed out that there is a critical skills gap arising out of the interconnectedness of the hydrogen energy grid and through the entire hydrogen value chain.

An initial landscape analysis of various energy systems labs from across the world's leading universities (CDRI, 2022) revealed that most of the labs are in advanced economies such as USA, UK, Japan and Australia. Research in these institutes is majorly focused on production aspects of hydrogen including water electrolysis, fuel cells, storage, integration of production with renewable energy sources, grid integration, storage and generation, microgrids and the overall hydrogen economy. Notably, focus on enhancing disaster resilience of hydrogen is missing from the mandate of these labs.

Additionally, capacity gaps for disaster resilient infrastructure have been identified across stakeholders, ranging from policy makers to technical personnel. The gaps identified include little to low levels of awareness on disaster resilient infrastructure-related aspects and risk and resilience assessments.

Need for Disaster Risk Financing for Resilient Hydrogen Assets

At present, the projected investment outlay for global hydrogen is to the tune of US$ 15 trillion by 2050 (Reuters, 2021). As of February 2021, investments of value US$ 300 billion have already been commissioned or are in the final stages of evaluation, with many of these being large-scale projects in Europe, Asia and Australia (S&P, 2021). The investment value of large-scale hydrogen projects globally as of July 2021 is now worth US$ 500 billion through to the year 2030 (Hydrogen Council, 2021).

The transition to resilient infrastructure is imminent in the context of daunting physical risks posed by climate change. From a disaster risk finance point of view, it is important to track these investments, else all these could get locked-in for generations in the form of bad debts, if proper resilience measures are not followed.

Practice

High Dependence on Other Energy Sources

Production of green hydrogen is dependent on renewable energy sources such as the sun or wind, to power the electrolysis process. Thus, the performance of the hydrogen production system is dependent on the resiliency of the renewable energy system that is powering production. For instance, production can be disrupted due to sandstorms or other climate extreme weather events as well as variability and reduction in wind speeds.

Depletion of Critical Natural Resources

a. ***Large quantity of water gets consumed for electrolysis during the production of green hydrogen*** and this requirement will compete with equally critical requirements for water such as irrigation etc. Electrolysis is an intensive process that uses 9 litres of purified water, free from any impurities, to produce 1 kilogramme (kg) of hydrogen (IEA, 2021; Beswick, Oliveira & Yan, 2021). Water use is projected to increase at a rate of 20 to 30 percent above the current consumption rates until 2050 (UN Water, 2019) and many of the green hydrogen production plants are in water stressed areas.

Nuclear Energy and Systemic Resilience of Hydrogen Production

Nuclear energy could be one of the production sources of hydrogen. The main risks that climate change poses to the operation and safety of nuclear power plants relate to water: excessive amounts due to intense flooding or a lack of water for cooling. Even though the nuclear power plant operators are well prepared, the dynamic changes in climatic conditions could adversely impact hydrogen production from nuclear sources. Systemic resilience of the production source, therefore, needs strengthening along with investments in emergency preparedness measures to better anticipate future risks.

b. ***Critical minerals such as platinum and iridium are used in the making of electrolysers and their supply is scarce.*** With a significant projected increase in the global installed capacity of electrolysers (IEA, 2021), the demand for these critical minerals is also expected to go up significantly. Further, the supply chain of the critical minerals, including production centres, are in areas of high climate vulnerability. This may likely expose the supply chain to risks from different climate disasters, potentially impeding hydrogen production.

Significant Production Costs

The uptake of green hydrogen costs will be determined by cost of production and the cost remains high in absence of a comprehensive hydrogen ecosystem including lack of scale, high input costs (critical minerals used in electrolysers) and nascent public policies.

Green Hydrogen
Cleanest form of hydrogen, that is produced from renewable energy sources such as solar and wind for electrolysis of water

Grey Hydrogen
Hydrogen is extracted from natural gas using the steam methane reformation process, but carbon emissions are not captured

Blue Hydrogen
Currently the main source of hydrogen; produced from natural gas through steam methane reformation; carbon emissions are captured and stored underground using carbon capture and storage

Pink Hydrogen
Hydrogen is produced from water electrolysis using nuclear power

Black Hydrogen
Hydrogen is extracted through coal; considered to be one of the most environmentally destructive forms of producing hydrogen

Currently, the costs of producing green hydrogen amount to around US$ 4-6 per kg, whereas the cost of producing grey and blue hydrogen is significantly lower at around US$ 1-2 per kg (IRENA, 2021). Another major cost factor is the production cost of electrolysers which involves platinum, with a single troy ounce currently costing US$ 1049 (World Bank, 2022). Platinum is used extensively in proton exchange membrane (PEM) type of electrolysers, while the other critical but expensive mineral, nickel, is used extensively in other types of electrolysers such as alkaline, anion exchange membrane and solid oxide.

However, an analysis by IRENA reveals that by 2030, most major economies could have achieved cost efficiency with respect to green hydrogen production (IRENA, 2021). Production costs using renewable energy sources such as solar and wind will also experience significant cost reductions.

Challenges in Storage and Transport

Hydrogen is characterized by low volumetric and energy density and is highly flammable. Being a light molecule, it is also prone to leaks and is characterized by a high level of diffusivity and permeability. These characteristics create different infrastructural challenges in terms of storage as well as transportation.

Storage

Storage infrastructure of hydrogen currently comprises both liquid and gaseous forms and entails special considerations in conditions of low temperature and high pressure. Hydrogen requires high pressures of over 300 bar in gaseous forms and needs to be cooled to -250 Celsius for storage in liquid forms.

Transport

The current methods of hydrogen transport employ either fixed or movable infrastructure. Fixed infrastructure includes transmission and distribution pipelines and specially built terminals in hydrogen ports. Movable infrastructure includes transport through shipping and truck-based containers. The suitable method of transporting hydrogen is also determined by whether hydrogen is in a gaseous or liquid state (United Nations Economic Commission for Europe, 2021). For short-distance transport of hydrogen through pressurized containers, hydrogen needs to be in a gaseous state. It is projected that about 50 percent of the hydrogen would be transported through pipelines with the other half being transported through long haul ships in the form of ammonia (IRENA, 2022). An IEA scenario of long-term potential hydrogen trade further suggests that by 2050, hydrogen-based fuels will account for 20 percent of the global trade (IEA, 2021).

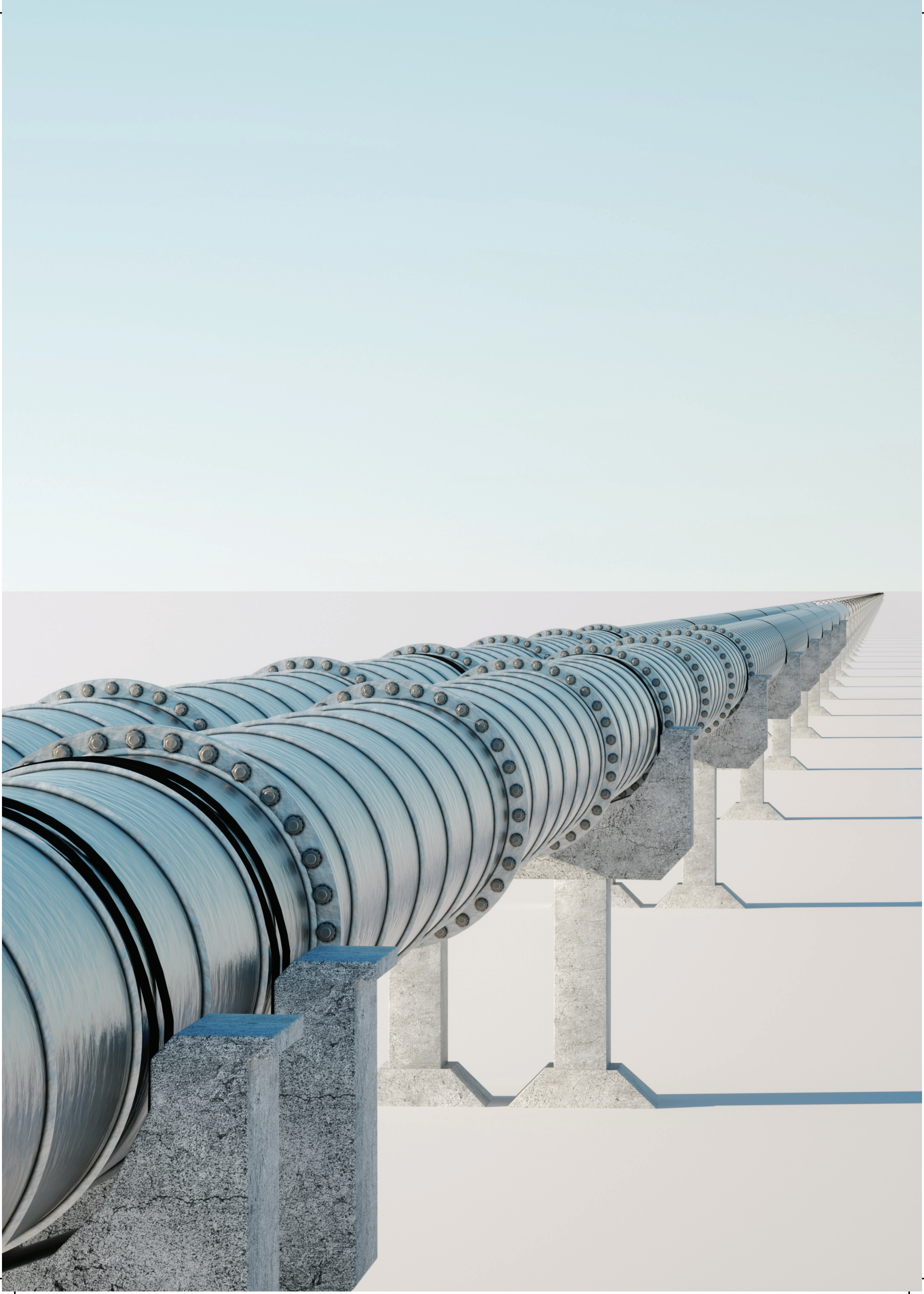
Using natural gas pipelines is a preferred way to transport hydrogen, in contrast to building dedicated pipelines and shipping containers (IRENA, 2022) because of significant cost savings. However, repurposing existing natural gas pipelines will require decommissioning of existing operations, replacement of specific fittings and dismantling of old connections at an approximate cost of around 10 to 15 percent of that of constructing new, dedicated hydrogen pipelines (European Hydrogen Backbone, 2021). Repurposing also saves pipelines from becoming stranded assets.

Transporting through natural gas pipelines also creates challenges. The higher volumetric flow and relatively lower energy density in comparison to natural gas means that there needs to be a higher amount of hydrogen which needs to be pumped through the pipelines. This blending of hydrogen into natural gas pipelines also requires the installation of compression pumps and the replacement of valves for the refurbishment of the pipelines.

Near Absent Early Warning Systems in Hydrogen Infrastructure

The chemical properties of hydrogen mean that it diffuses and burns at a faster rate, which increases flammability risks. There is, therefore, a need for the installation of sensors that can detect flames, ahead of the events. For transport through purpose-built containers, valves need to be resilient accounting for pressure difference between 350 bar and 700 bar under various conditions. Hydrogen gas leakages into confined spaces will also pose a potential safety risk, especially when the pipelines run through major urban agglomerations. Piping and sealing will, therefore, need to be focused upon to prevent the leakages. This also calls for the requirement of sensors and leak detectors, involving early warning systems (EWS) for hydrogen infrastructure.

In the past, EWS have been developed and implemented for different types of geological and hydrometeorological hazards. There is a definite need to build dedicated EWS and customize these to focus on hydrogen-related hazards such as low-temperature hydrogen release that causes cryogenic burns, boiling liquid expanding vapour explosion and explosions occurring due to uncontrolled release of hydrogen (Rusin & Stolecka, 2017).



03 Recommendations

The challenges highlighted in this paper require a paradigm shift in the approach towards development of hydrogen infrastructure. Recommendations on taking a systemic perspective towards resilience of hydrogen infrastructure are described in the following sub-sections.

Policy

Systemic Resilience of Renewable Energy

It is beyond doubt that renewable energy will dominate the energy mix in the coming years (IEA, 2021; IRENA, 2020). The transition towards such sources and the adoption of increased decarbonization targets would also mean that the demand for critical minerals is expected to rise by at least six times the current global demand levels of 7.1 metric tonnes in 2020 to about 42.3 metric tonnes by the year 2050 (IEA, 2021). With climate extreme weather events only expected to further increase in both frequency and magnitude (IPCC, 2021), the supply chain complexities are likely to exacerbate further. Furthermore, resilience of the renewable energy system used will depend on the production source in addition to the electrolysers used for splitting water into hydrogen and oxygen.

A potential solution to tide over the crisis should be the usage of principles of circular economy for potential recycling of platinum from discarded electrolysers. Research should equally focus on finding alternatives to platinum-based electrolysers for which few solutions exist as of date. Additionally, the efficiency rates of current electrolyser technology will need to improve.

Hydrogen Policies to Support Energy Transition

Current global hydrogen policies emphasize the potential energy transition pathways that the energy can crucially provide. These include the avoidance of stranded assets in existing natural gas infrastructure, by means of repurposing some of the existing infrastructure assets in natural gas, with most of the oil and gas producing nations across the world making the transition to producing green hydrogen by 2050 (IRENA, 2022). Countries are also focused on using policy to drive down the costs of hydrogen - through either reduction of production costs or by providing incentives and subsidies to promote cost efficiency in the storage and transmission of hydrogen.

Incentives and Subsidies

The US government has put in place several federal and state-level incentives for hydrogen fuel cell projects. Federal incentives include a fuelling facility tax credit, grants for energy property (in lieu of tax credit), manufacturing credit of 30 percent and residential energy efficiency credit. The Infrastructure and Investment Jobs Act signed into law in November 2021 authorizes spending to the tune of US$ 1.2 billion in hard infrastructures such as transport, power, internet and drinking water facilities with emphasis on climate change mitigation. The law has expanded the scope of the US Department of Energy's (DOE) hydrogen research and development programme to advance research and development for purposes of demonstration and commercialization of clean hydrogen production, processing, delivery and end-use application technologies (DOE, 2022).

The DOE launched the Energy Earthshot initiative to encourage abundant, affordable and reliable clean energy solutions. It aims to address the challenges of climate change and reach the goal of net zero carbon emissions by 2050 (DOE, 2021). The first Energy Earthshot, called the Hydrogen Shot, was launched in June 2021 to reduce the cost of clean hydrogen by 80 percent from US$ 1 per 1 kg in 1 decade (DOE, 2021). It has only implicitly focused on disaster resilience to some extent.

The Australian strategy focuses on supporting the safety of users through means of guidelines on storage, transport and refuelling. Crucially, the explicit emphasis on disaster resilient infrastructure is missing. Future versions of policy must address these gaps.

Policymaking must be informed by priorities of resilience of infrastructure for a sustainable hydrogen energy transition. A holistic approach will ideally focus on both market and climate and disaster risk resilience at all stages of the value chain including downstream (production), midstream (storage and transport) and upstream (end-user). The policy should emphasize transitioning energy infrastructure as a critical pathway to building infrastructure resilience and ensuring net zero simultaneously.

Policies should focus on allocation of research and development (R&D) budgets in hydrogen infrastructure towards disaster risk reduction. Policies that enable the creation of specialized curricula around capacity building on disaster resilience of infrastructure must also be prioritized. Climate-specific aspects - more importantly, those relating to the challenges emerging from rising seawaters, the ensuing water stress and the rise in climate extreme weather events - are missing. These aspects need to be reinforced in addition to also incorporating principles of circular economy, so that issues of resource intensiveness are addressed.

Standards and Certifications for Ensuring Disaster Resilience of Hydrogen Infrastructure

Current standards and certification systems in hydrogen focus on its handling. An explicit focus on the disaster resilience of the hydrogen infrastructure is essential while framing standards and certifications. This will lead to establishment of long-term pathways for investments for hydrogen infrastructure within energy standards. Institutionalized standards pave the way for future infrastructure characteristics within a sector. Typically, governments play a key role in defining this pathway through approved standards as reliable references for investors and developers.

Investment in infrastructure is guided by proper regulatory mechanisms of supply chain. Initiatives may also involve supporting R&D and setting mechanisms for regular updating of standards. Standard developing agencies will need additional R&D support, evidence-based mechanisms and a pool of professionals. The systems for these are yet not developed, so regular updating mechanisms are necessary to stay at par with innovation and incorporating focus on disaster resilience of infrastructure.

Transition to hydrogen would require building new infrastructure and retrofitting it into existing infrastructure. This will further necessitate new standards for the harmonization of resilience aspects across sectors in critical infrastructure. Development of standards and certification programmes to regularize the resilience of upcoming infrastructure is equally important.

Codes and standards are critical for establishing a market-receptive environment for commercializing hydrogen-based products and systems. While most critical standards, such as those related to production of hydrogen supply and end-use equipment, technology deployment, etc., are in place, these need improvement and advancement.

National standardization institutions and international bodies such as the ISO, CEN, etc., can play a key role in this process. Also, regulatory bodies need to be on board for implementation of these standards. Given that developing and obtaining consensus on revised standards is a long-drawn process, immediate and intermediate steps may also be taken.

Capacity Strengthening to Bridge Knowledge Gaps

The green hydrogen sector is estimated to create about 2 million jobs by the year 2050, with another study projecting that there could be as many as 3.4 million jobs that could be created by 2050 (Fuel Cell and Hydrogen Energy Association, 2021). Another study pegs the total number of jobs to be created at around 5.4 million in Europe by 2050 across all hydrogen allied industries (Europa, 2020). The rate of jobs being created in the hydrogen sector is expected to outpace jobs created in the other renewable energy sectors such as carbon capture and storage, solar and wind. There is a perceived need for creating a skilled workforce comprising project managers, technicians, electricians, welders, pipefitters, truck drivers, crane operators, etc. for meeting the demands of the hydrogen economy. There is also a clear need to focus on vocational aspects as well as high-end research.

The above can be facilitated through capacity building initiatives, development of specialized skillsets in individuals, policy support and commitment to operationalize capacity development issues in the hydrogen sector.

Additionally, capacity development inputs (through awareness sessions, webinars, Training of Trainers, workshops, guidelines, SoPs, deployment etc.) to strengthen and sustain the capacities of various stakeholder groups may also be provided.

Disaster Risk Financing

Mobilizing public and private finance to embed resilience in new infrastructure and to phase out all activities that adversely affect climate will be essential in the transition for hydrogen energy. The following disaster risk finance strategies may be useful for infrastructure resilience:

- Assessment of hydrogen energy infrastructure vulnerabilities to climate-related disasters is useful to gauge damage costs. Resilience measures include upfront investments in mitigation and adaptation measures e.g., elevated plants and structures, aerodynamic structures etc. Switching to low-carbon technologies as a mitigation step, building financial resilience, ensuring sustainability through risk transfer and financing mechanisms may also help in tackling expected damages.

- Inducting infrastructure resilience measures at contract design stage may help in setting a clear layout for implementation. The practice may further be aided with insurance agreements with offers of resilience dividend at lower premium rates.

- Carbon pricing mechanism to provision funds for resilient recovery may help in offsetting the carbon footprint of hydrogen energy production. The environmental and climate costs reflected in the hydrogen energy prices can be used for the development of low-carbon hydrogen energy infrastructure and to build financial resilience.

Practice

Circular Economy to Reduce Depletion of Critical Resources

Addressing challenges regarding depleting critical resources (water, minerals etc.) could include integrating the principles of circular economy through policy interventions. For example, the US is launching a US$ 140 million facility to address critical minerals extraction and separation refinery (DOE, 2022). In addition to these, dedicated R&D budgets specially earmarked to produce electrolysers using critical minerals-free materials and technologies may also be promoted. Future iterations to policy and regulatory mechanisms may also advocate for the inclusion of such criteria for safeguarding the critical infrastructures of the mining supply chains.

Subsidy/ Innovation to Reduce Production Costs

For successful reduction of production costs for hydrogen energy, the cost of electrolyser technologies needs to go down. A major cost factor impacting production of electrolysers is platinum, with a single troy ounce currently costing US$ 1049 (World Bank, 2022).

Storage and Transportation

Assessment of physical risks and impact for each site in the storage and transportation network can prove useful. The assessment may be based on the comprehensive analysis of climate hazards, exposure and vulnerabilities to significantly enhance climate change and disaster resilience. It is hoped that the assessments will lead to development of issue/ challenge-specific guidelines.

Salt Caverns as Long-Term Storage Options

From a large-scale storage point of view, underground, geologic storage of hydrogen in salt caverns, aquifers, porous rock reservoirs, and depleted oil and gas reservoirs are viable long-term options. Storage of hydrogen will have cost implications through purity aspects. Salt caverns are naturally occurring storage sites that can hold large volumes of hydrogen. Currently, only a few operational sites in the world exist at Teesside, United Kingdom, and Clemens Dome, Spindletop, and Moss Bluff in the United States. Other potential underground storage sites are being explored in areas in Australia and parts of Europe including Poland, Germany, Romania and Portugal (Gilhaus & Horvath, 2008).

Other forms of storage will include repurposing the existing seaport infrastructure that many ports are currently lacking. To withstand higher storage pressures, specially constructed vessels that are polymer lined and are many times heavier need to be constructed that can also withstand the various types of climate extreme weather events. The issue becomes crucial given the projected increase in frequency and magnitude of extreme weather events and the impacts on the low-lying islands and coastal regions and SIDS (IPCC, 2019; IPCC, 2021).

Additionally, long distance transport using liquified hydrogen is one of the options. However, the liquefaction of hydrogen for transporting presents some challenges.

Transportation through dedicated shipping containers using ammonia is also a possible avenue. There is major worldwide momentum towards using green ammonia as a new approach to storing and transporting hydrogen in an inherently safer chemical form. Hydrogen can be converted into a much denser form of storage as ammonia, thus, addressing many problems and risks inherent in hydrogen infrastructure. These include safely compressing, storing and transporting ammonia as a liquefied gas. As a result, the explosive hazard of hydrogen is mitigated since ammonia does not cause the same corrosive deterioration to containment that results from storing elemental hydrogen (H_2). This, therefore, greatly improves resiliency and mitigates any catastrophic risk.

Liquefaction of Hydrogen

Liquefaction of hydrogen refers to the process where gaseous hydrogen is converted to a liquid form by cooling it to below −253°C (−423°F) (US DOE, 2022). Transporting liquid hydrogen for distances greater than 1500 km can assume the form of ammonia or liquid organic hydrogen carriers since these are cost-effective measures.

The hydrogen pipelines infrastructures share many similarities with that of the natural gas infrastructure. Sea level rise could demand realignment of the networks while extreme conditions such as drought may lead to faster ageing of pipelines above ground. In the case of import/export terminals and shipping routes, the associated climate impacts could be similar. For efficient transfer, hydrogen liquefaction may be used, which requires much lower temperatures than liquified natural gas. Additionally, the impact of higher ambient temperatures on cooling energy needs is also observed, which implies that variabilities in handling hydrogen at different temperatures should be duly accounted for. Given the similarity with gas and oil infrastructure, similar EWS can be used for floods, storms, droughts and all the extreme events that negatively affect hydrogen infrastructure.

Green Ammonia

Green ammonia is being envisaged globally as a new approach to store and transport hydrogen in an inherently safer chemical form. Converting hydrogen to ammonia (NH_3 vs H_2), a much denser form of storage, addresses many problems and risks inherent in hydrogen infrastructure:

- Ammonia can be easily and safely compressed, stored and transported as liquefied gas.
- The explosive hazard of hydrogen is mitigated by storing it in the form of ammonia.
- Ammonia does not cause the same corrosive deterioration to containment that results from storing elemental hydrogen, thus, improving resiliency and mitigating the risk of a catastrophic release.

Building Resilience In Hydrogen Infrastructure

In absence of a comprehensive, holistic approach to disaster resilience of hydrogen infrastructure, a comprehensive framework is necessary to:

- Develop a formal, integrated approach to overcoming uncertainty
- Ensure that disaster resilience of infrastructure percolates through various components of the value chain
- Help in better adaptation to tackle the complex risks from climate change

The focus on disaster resilient infrastructure may be made explicit and visible with relationships that are woven into interdependent aspects such as value chain and the policy framework. Such a focus will help in objectively quantifying the contribution and in reducing ambiguities and uncertainties concerning disaster resilience.

European Hydrogen Backbone

The European Hydrogen Backbone is the initiative for a pan-European Union hydrogen transport infrastructure. It is a consortium of gas grid operators in Europe, envisions 39,700 km of pipelines across 21 countries by 2040 and 69 percent would repurpose natural gas networks. The project involves repurposing existing gas infrastructure combined with targeted investments in new hydrogen pipelines and compressor stations for affordable transport of hydrogen over long distances. It is planned to connect industrial clusters in Europe to a 6800 km length hydrogen highway that will gradually expand its network covering more countries. This will enable gas infrastructure companies to scale up hydrogen supply and demand and thus contribute to support the European Commission's Hydrogen Strategy (European Hydrogen Backbone, 2021).

Way Forward

The existing frameworks and emerging policies need to be comprehensive and tackle vulnerabilities of hydrogen infrastructure. The policies will have varying levels of interactivity among various aspects including governance, standards and certifications, and capacity building. This becomes all the more crucial from the viewpoint of disaster resilience of infrastructure, since a systems thinking perspective will help in anticipating disasters and building suitable buffers.

Further, as resilience percolates down to the various components of the hydrogen value chain, one may need to factor in both anticipated and unanticipated risks. The focus may therefore be on adaptation pathways to address long-term uncertainties that translate into interventions. Such approach may help in addressing any risk cascades that emerge.

This paper is an initial effort to promote disaster resilience of hydrogen infrastructure. There is an urgent need to explore the challenges in greater detail for gaining a deeper understanding of the actions from the viewpoint of future programmatic offerings. Future work in this direction may also examine the policy-specific aspects of disaster resilience of hydrogen infrastructure to understand the focus of different national strategies in addition to the different risks and vulnerabilities.

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