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Beyond Silos: A Unified Approach to Decarbonisation through Hydrogen Integration

Perminder Jit Kaur[1], **Pradeep Karuturi**[2*]

[1] *Lal Bahadur Shastri Institute of Management, Delhi*
[2] *Centre for Clean Mobility, OMI Foundation*

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**Corresponding Author Email: Perminder.dua@gmail.com*

Abstract: Renewable sources like hydrogen ignite hope as the world wrestles with surging energy demands, dwindling fossil fuels, and choked skies. Hydrogen fuel, versatile in both gaseous and liquid forms, boasts applications from fuel cells and internal combustion engines to powering industries. Global hydrogen production currently stands at 0.1 gigatonnes, primarily for industrial applications like metal refining. Despite its promise, hydrogen remains a fledgling player in the global energy mix. High production costs, with water electrolysis four times costlier than steam reforming, pose a significant hurdle. Also, hydrogen's low volumetric density necessitates efficient compression, liquefaction, and storage advances. Public awareness of the scope of turquoise and blue hydrogen should be actively pursued. With this background, the present article discusses critical global challenges in detail and suggests recommendations and pathways for enabling a decarbonised future powered by clean, sustainable hydrogen energy.

1. Introduction

The global drive for alternative and renewable energy sources is fuelled by two primary concerns: ensuring energy security by reducing reliance on imported fossil fuels and mitigating climate change through reduced carbon emissions. Global warming due to fossil fuels-led greenhouse gas emissions makes the transition to renewable fuels imperative [1]. Innovation in technologies can facilitate optimal usage of existing resources, protect the environment and promote sustainable development. Challenges remain while significant progress has been made – for instance, global renewable energy capacity surpassed fossil fuel capacity in 2021. These include limitations in large-scale energy infrastructure, underdeveloped ecosystems for electric vehicles, and dependence on critical minerals [2].

With an energy density of 122 MJ/Kg (2.75 times more than gasoline), hydrogen presents a compelling option for future energy systems (Kaur et al. 2024). Some of the significant properties of hydrogen as a fuel are mentioned in Table 1. The lower heating value (LLV) of 120 MJ/Kg and higher heating value (HLV) of 119.9 MJ/Kg compared to diesel's 44.8 MJ/Kg (LLV) and 42.5 MJ/Kg (HLV), positions hydrogen as a strong contender for the title of "ultimate energy source for the 21st century [3–5]. Hydrogen, with abundant reserves, high calorific value and a non-carbon-based energy source, is eco-friendly, renewable and versatile and is important for a smoother transition in the energy sector (Zhou et al. 2022). Based on sources of raw materials, chemical, physical or biological processes can be employed to produce hydrogen. Both chemical and physical processes for hydrogen production require specific reaction conditions and are thus energy-exhaustive processes. Biologically produced hydrogen, though low in cost, carries a long duration of time [9]. To produce Hydrogen, a commonly employed process is steam methane reforming (SMR) or coal gasification without carbon capture (Grey H) [10]. In addition to this, steam methane reforming (SMR) or coal gasification with carbon capture (Blue Hydrogen), methane pyrolysis (Turquoise Hydrogen), and electrolysis of water or biomass pyrolysis (Green Hydrogen) are also alternative routes of hydrogen production [11].

Table 1: Properties of Hydrogen Fuel

Fuel	LLV (MJ/Kg)	HLV (MJ/Kg)	Reference
Hydrogen	120	119.9	[7-8]
Methane	55.5	50	[8]
Ethane	51.9	47.8	[8]
Gasoline	47.5	44.5	[8]
Diesel	44.8	42.5	[8]
Methanol	20	18.1	[8]

Alkaline electrolysers are the most favourable cost-effective, mature technology and most widely used, with reported efficiencies ranging from 63-70%. Proton Exchange Membrane (PEM) electrolyzers, with a slightly lower level of commercial maturity, also exhibit comparable efficiency levels within the same range (63-70%). Solid Oxide Electrolyzer Cells (SOECs), with higher energy conversion efficiency (74-86%) and higher cost, are still at the demonstration stage of development [12].

Hydroelectric cell is an innovative alternate technology to produce clean hydrogen at ambient temperature, eliminating the need for light, acid, or alkali. Laboratory-scale studies on hydroelectric cells have shown encouraging results with the production of large volumes of hydrogen (1.856 mmol/h). The study on the effectiveness of hydroelectric to produce fast hydrogen has shown that zinc anode and silver cathode immersed in deionized water, coupled with a nanoporous lithium-substituted magnesium ferrite catalyst and driven by external voltage, presents a promising pathway for sustainable hydrogen generation [13].

Globally, about 95 Mt of hydrogen was produced annually in 2022, nearly two-thirds of which is derived from reforming natural gas, with lower environmental benefits. It has been reported that there is a critical need to rapidly scale up green hydrogen production technologies like electrolysis [14].

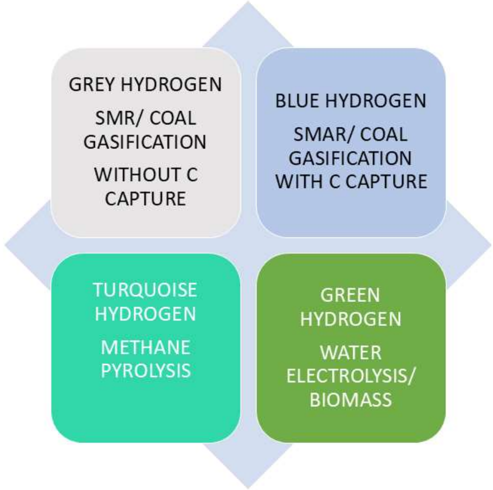

Figure 1: Colour codes for Hydrogen

Debates persist regarding the preferred production method, with the oil, gas, and coal industries favouring "blue" hydrogen. At the same time, wind and solar sectors advocate for "green" hydrogen to expand their markets. Additionally, natural gas-producing countries also lean towards blue hydrogen. Globally, nations have designed strategies to move towards other sources of hydrogen, depending on available national resources and infrastructure, to gain maximum environmental benefits. Thus, the present study delves into the potential and challenges of hydrogen as a clean, alternative, non-carbon fuel. It explores its viability for large-scale deployment and a smooth transition to a net-zero global future.

1. Global Hydrogen Policy Landscape

Driven by a desire for clean energy, countries worldwide are turning to hydrogen and have announced their national hydrogen policies [15]. While Japan was the first to announce its national hydrogen policy, other Asian nations like India are also developing hydrogen programs. Europe, a major hydrogen consumer, is heavily invested in production and storage technologies with a goal of carbon neutrality by 2050. International collaboration between research institutions, industries, and governments is crucial to achieve this ambitious target. Hydrogen valleys, where the entire hydrogen supply chain is clustered, and public-private funded projects like HEAVENN, showcase the promising future of hydrogen in a global clean energy transition [16].

3. Challenges for the Hydrogen Economy

3.1 Transition to Green Hydrogen:

Most hydrogen is produced through fossil fuels, which questions the greening of the whole value chain. To provide long-term solutions, the need of the hour is impetus to Green Hydrogen eco-system development. While solar and wind energy are available widely at competitive prices, it is essential to support the manufacturing of green hydrogen globally.

3.2. Economies of Green Hydrogen Production:

Total cost includes fixed cost like cost of electrolyser, and land procured. The operational cost consists of raw materials like water, utilities (electricity), labour employed, maintenance and repair. The cost depends on the type of technology used, with water electrolysis an expensive

Table 2: Global Nations with Hydrogen Policies [17]

Country	Major Policy Guidelines
Australia	The Australian Clean Hydrogen Trade Program (ACHTP) of AUD 150 million was initiated in 2022 to support the growth of a clean, innovative, safe and competitive Australian hydrogen industry.
Canada	Hydrogen production through electrolysis as well as from natural gas with carbon capture, utilization, and storage (CCUS) receives Investment Tax Credit in 2024
China	State-owned Sinopec Green Hydrogen Plant initiated with an aim to produce 20,000 tonnes of hydrogen through financial investment of 2.6 billion yuan (2022)
EU	Homegrown hydrogen production of 10 GW supported through 17.5 GW by 2025 of electrolysers, storage and port facilities
India	National Green Hydrogen Mission (2023) for annual production of 5 MMT of GH by 2030
Japan	The annual budget 2024, announced the development of hydrogen supply chain through funding of 25 billion yen
UK	Green Industries Growth Accelerator program with financial support of GBP 960 million for net zero sectors through offshore wind, networks, CCUS, hydrogen and nuclear (2024)
USA	Department of Energy has initiated $100 million grant program for low-carbon energy technologies (2021)

technology compared to other technologies (Table 3).

Specifically in Indian scenarios, the report by Department of Science and Technology (DST), India shows that electrolysis of water required for production of GH involves higher cost of production (Rs 433/kg) than steam methane reforming of Rs 150/kg.

Table 3: Cost of Hydrogen Production through different technologies [18]

Hydrogen production method	Cost (USD/ kg hydrogen produced)
Photobiolysis	1.84-2.27
Dark fermentation	1.02-2.70
Gasification	0.93-2.83
Pyrolysis	1.47-2.57
Steam reforming	1.25-3.50
Water electrolysis	3.01-4.51

Table 4: Cost for Hydrogen production in India [19]

Hydrogen production method	Cost (Rs/ Kg)
Steam methane reforming	150
Coal gasification	245
Biomass Gasification	258
Biomass microbial	813
Electrolyser	433

3.3 **Standards for Hydrogen**:

The development of the hydrogen economy hinges on the establishment of clear standards that guarantee reliability, safety, and traceability and foster a robust global market, translating into significant economic benefits. While ISOTC197 deals with standards for hydrogen, PESCO (Petroleum Explosives Safety Organisation) has established Static & Mobile Pressure Vessels Rates 1981, Explosive Act 1854, 2008, and Gas Cylinder Rules 2004.

The establishment of ISO/TS 19870, which provides a methodology for evaluating greenhouse emissions from the production, condition, and transport of hydrogen, is a step towards evaluating the environmental impacts of the hydrogen economy. However, since hydrogen can be produced from various sources and finds applications in multiple fields, evaluation of overall emissions and carbon foot printing under different scopes is a complex task and needs detailed international guidelines (Figure 2).

However, hydrogen-specific rules and regulations pertaining to gas refilling, storage, and transport vary from country to country. More integration among global certifications is needed. Revised globally acceptable regulations, codes, and standards for the hydrogen sector need to be formulated. Certification methods for cross-border certificates for hydrogen trades are yet to be available. While future regulatory frameworks are uncertain, there are inconsistencies in certification and standardization, posing significant barriers to investment.

3.4 Infrastructure for Sustainable Green Hydrogen Deployment

Electrolyzers, the workhorses of green hydrogen production, account for 40% of the total cost and are crucial to unlocking this clean fuel's potential. Securing a reliable and affordable supply is crucial, particularly in developing nations like India, where most electrolyzers are imported (often with in-house assembly). Raw materials are concentrated in just a few countries. This limited geographic spread throws a wrench into efforts to build robust electrolyser manufacturing capabilities worldwide. The widespread adoption of green hydrogen hinges on overcoming this supply chain bottleneck.

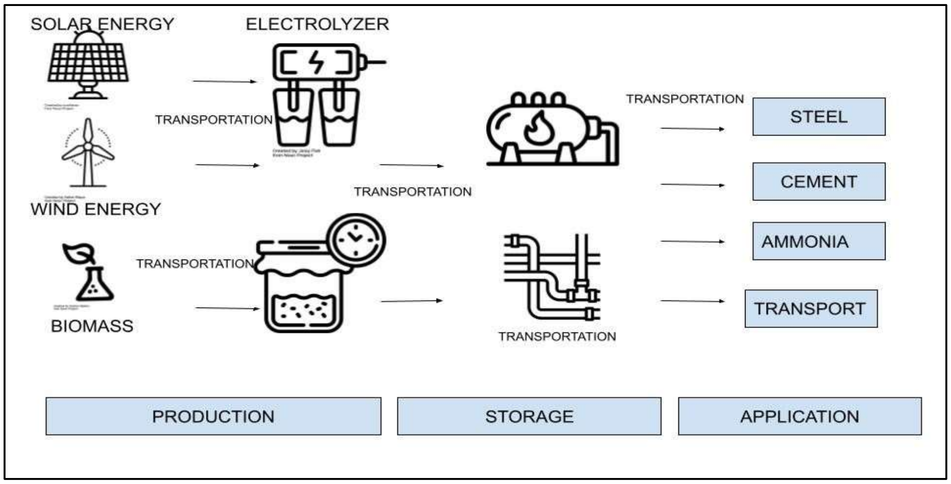

Figure 2: Different Segments of Hydrogen Eco-system

Pipelines, cryogenic storage facilities, trucks, and export ports must be strengthened globally. Presently, hydrogen can be stored in cylinders with 350 bar capacity in India, which needs to be developed to type 4 cylinders with 700 bar capacity. There is a strong need for research for the development of hydrogen storage materials as well as systems development. Storage of hydrogen composite tanks is found to be the most viable option. Companies like Hexagon are the world's largest manufacturers of composite tanks. The size of hydrogen tanks allowed internally, and face issues with hydraulic retest every 3 years. Global standards that should be followed should be well-established. Also, rules and regulations related to safety systems should be documented. Hydrogen purification systems and heating and cooling applications for Hydrogen compression are in the stages of development.

3.5 Hydrogen Application Development

There are ample green hydrogen offtake possibilities in industrial sectors such as Mobility, Fine chemicals, Steel, and Fertilizers as well as in other sectors such as Data Centers, Cold Storage, Gated Communities, etc. Hydrogen can be used in vehicles to power fuel cells in zero-emission cars with a potential for high-efficiency [20].

Industrial applications of hydrogen are already well-established. Hydrogen is widely used in the synthesis of ammonia and nitrogenous fertilisers [21]. Petroleum refineries use hydrogen to lower the sulfur content of fuels [22]. The modern steel industry is leaning on hydrogen to become environment-friendly and its decrabonisation goals through phasing out coal with hydrogen in processes such as direct reduction of iron (DRI) for conversion of iron oxides to metallic iron. The application of ammonia-blended hydrogen-fuelled engines is still in the pilot stages, which can further broaden and adaptation of hydrogen [23]. Hydrogen also finds application in the hydrogenation of the food and oil industry to enhance their stability and avoid spoilage [24].

Some of the potential uses of hydrogen include its application in powerplants where hydrogen can also be converted into electricity in a conventional fuel cell [25].

Further, to meet high energy demand and reduce intermittency in the solar and wind energy sector, hydrogen is also considered as a medium of additional storage [24].

Furthermore, with higher energy efficiency and lower environmental impacts, the mobility sector has shown keen interest in integrating hydrogen as a fuel source, on a global scale. Some of the commercially launched projects have shown promising results, propelling further research in the domain [26]. However, the adoption of hydrogen in the transport sector needs simultaneous development in multiple sectors. First, the infrastructure for hydrogen refuelling is underdeveloped and costly, hindering widespread adoption. Fuel cell vehicles (FCVs) have higher initial costs due to expensive materials and low production volumes, making them less competitive with battery electric vehicles (BEVs). Process development to lower energy losses during production, compression, storage, and conversion needs detailed investigation.

3.6. Capacity Building

The hydrogen sector is experiencing explosive growth, with new production plants and applications developing rapidly. Research and development is also flourishing, fuelled by the promise of clean energy. However, the workforce must gain the specialised knowledge and experience required for these cutting-edge hydrogen production technologies. This skills gap threatens to stall the sector's momentum, creating a bottleneck between innovation and large-scale implementation. The availability of a skilled workforce equipped with the latest hydrogen technologies is paramount for the sector's continued success.

4. Conclusions

To strengthen the GH sector, we need a continuous supply of Solar and wind energy, which is already available at enough and competitive cost. Taking examples from the solar PC sector, establishing large-scale GH production plants will help reduce overall costs in the long term. Joint research ventures to share resources and expertise are needed to accelerate innovation across every aspect of hydrogen production, storage, transportation, and application. JRVs will help in avoiding duplication of effort and maximizing resource utilization. Innovations like hydrogen-powered vehicles and infrastructure, such as hydrogen refuelling stations and pipelines, will accelerate widespread adoption. Converting waste biomass into green hydrogen holds immense potential that demands further exploration. Biohydrogen offers a promising approach to tackling climate change by reducing greenhouse gas emissions (GHG) and boasting an energy efficient process. However, research on improving the strains of microorganisms used in the conversion is crucial to make this method truly competitive with conventional methods. Global funds dedicated to technological breakthroughs are essential to fuel these collaborative efforts. These funds should prioritize research in critical areas like seawater electrolysis, wastewater electrolysis, advanced storage materials, and transportation. The ambitious global hydrogen economy requires a robust knowledge base. To achieve this, fostering partnerships for data recording and sharing is crucial. The whole value chain can be validated by pooling data from various stakeholders from cradle to grave, i.e., renewable energy producers to run electrolysers to end-users. The digitalisation of every step in the form of a hydrogen passport will serve as a valuable tool to evaluate carbon foot printing and assist in identifying challenges, accelerating the global journey towards a hydrogen-powered future.

To develop trained manpower, bridging the gap between educational institutes and industries is essential. There are some positive examples. For instance, industries like Greenzo are establishing electrolyser and GH production capacity near Ahmedabad (India). The industry is collaborating with nearby universities to provide students with invaluable hands-on experience in cutting-edge hydrogen production technologies. In addition, they are working with educational institutions to develop comprehensive theoretical courses specifically focused on green hydrogen technology. This will ensure a well-rounded understanding for future industry leaders.

Therefore, a multi-dimensional approach focusing on infrastructure development is essential for boosting the ecosystem for hydrogen deployment. Scaling up green hydrogen production and utilising existing turquoise and blue hydrogen will help explore more avenues for hydrogen utilization. Different strategies for hydrogen, production, storage and applications can be devised and implemented depending on local resources.

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