RECENT ADVANCEMENTS IN HYDROGEN FUEL TECHNOLOGY

Introduction:

Hydrogen stands firm as an enduring and iconic energy source, with a history intertwined with the evolution of power generation. For example, in 1807, before the first gasoline-powered automobiles, François Isaac de Rivaz introduced hydrogen as a fuel for an experimental automobile in a reciprocating engine with electric ignition1. Since then, hydrogen has been commonly used as a fuel source, albeit in a limited capacity. While hydrogen's historical significance in energy innovation is undeniable, it is important to acknowledge the persistent apprehension surrounding its utilization. This apprehension can be attributed, in part, to the infamous Hindenburg disaster of 1937, in which hydrogen's flammability played a tragic role [2].

Despite a checkered history, hydrogen fuels are experiencing a resurgence driven by the urgency of the climate change crisis. Governments and industries are fervently investing in clean hydrogen fuels due to their lightweight, versatile, and high-energy nature[3]. The versatility of hydrogen production methods has led to the emergence of five distinct "colors" of hydrogen, each tailored to various applications as shown in Figure 1 [4]. This diversity of production methods and applications has catalyzed substantial growth in the hydrogen industry in recent years. Advancements in production and storage techniques as well as the emergence of novel pathways have fueled rapid progress in hydrogen fuel technology over the past half-decade. This article discusses several noteworthy breakthroughs from this period, highlighting their specific contributions to various aspects of the hydrogen fuel sector.

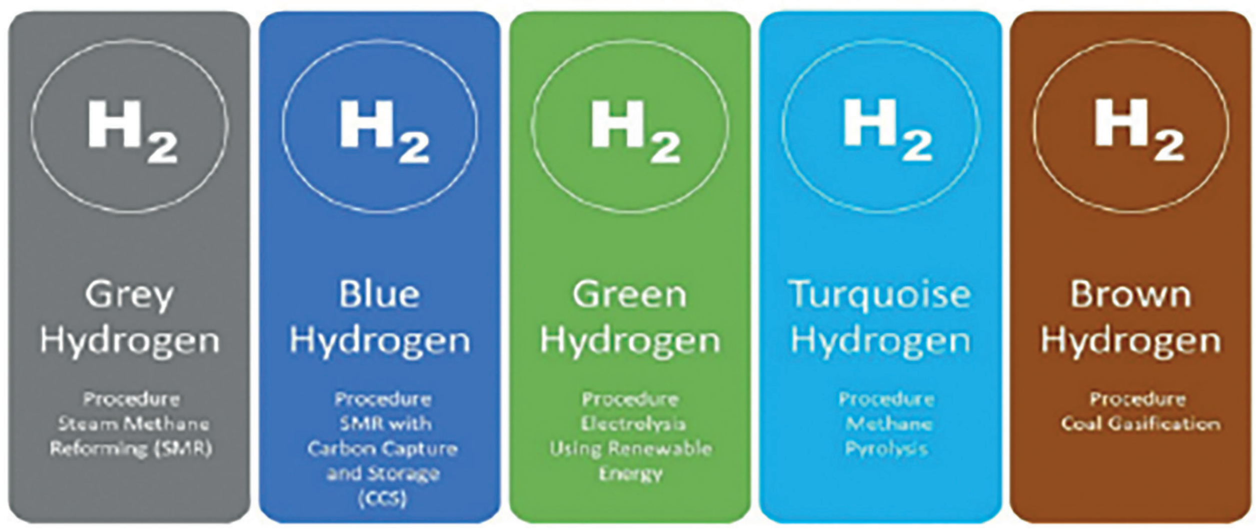

Figure 1: The five primary types of hydrogen, distinguished by their manufacturing process. Grey and blue hydrogen use steam methane reforming (SMR), green hydrogen uses electrolysis, turquoise hydrogen uses methane pyrolysis, and brown hydrogen uses coal gasification[4]

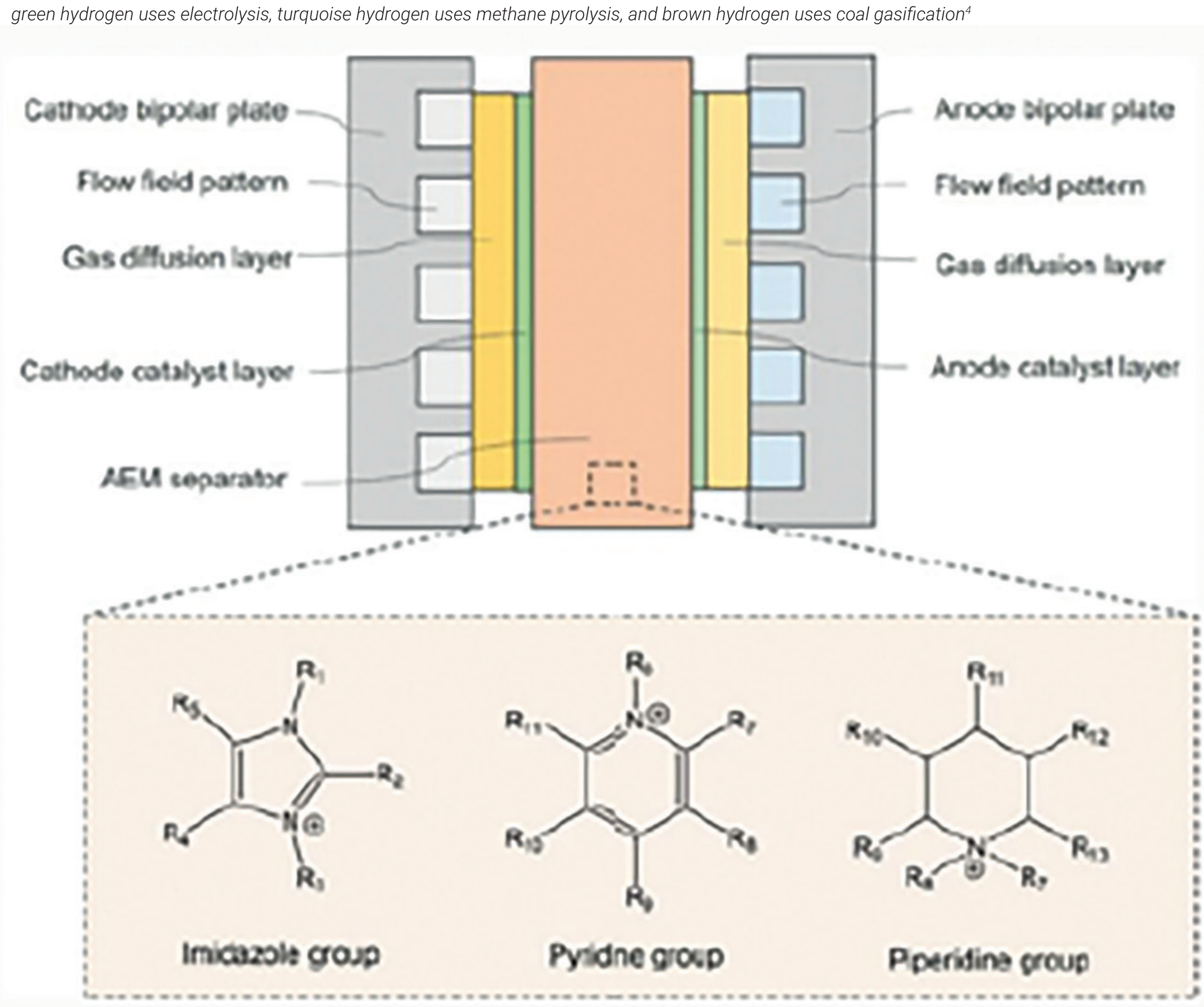

Figure 2: The structure of an Alchemr AEM cell[5].

AEM Electrolyzers:

The advancement of electrolysis technology holds great promise in significantly reducing the cost of producing green hydrogen, a crucial component in the transition to renewable energy and achieving net-zero emissions[6]. Green hydrogen is generated through electrolysis, a process that splits water into hydrogen and oxygen using excess renewable energy. While this method is environmentally friendly, it has its challenges. Currently, there are several electrolysis methods in use, with alkaline electrolyzers being a prominent choice. These electrolyzers employ an aqueous electrolyte and a porous membrane, creating a reliable but relatively slow system that doesn't readily adapt to different renewable energy sources[7].

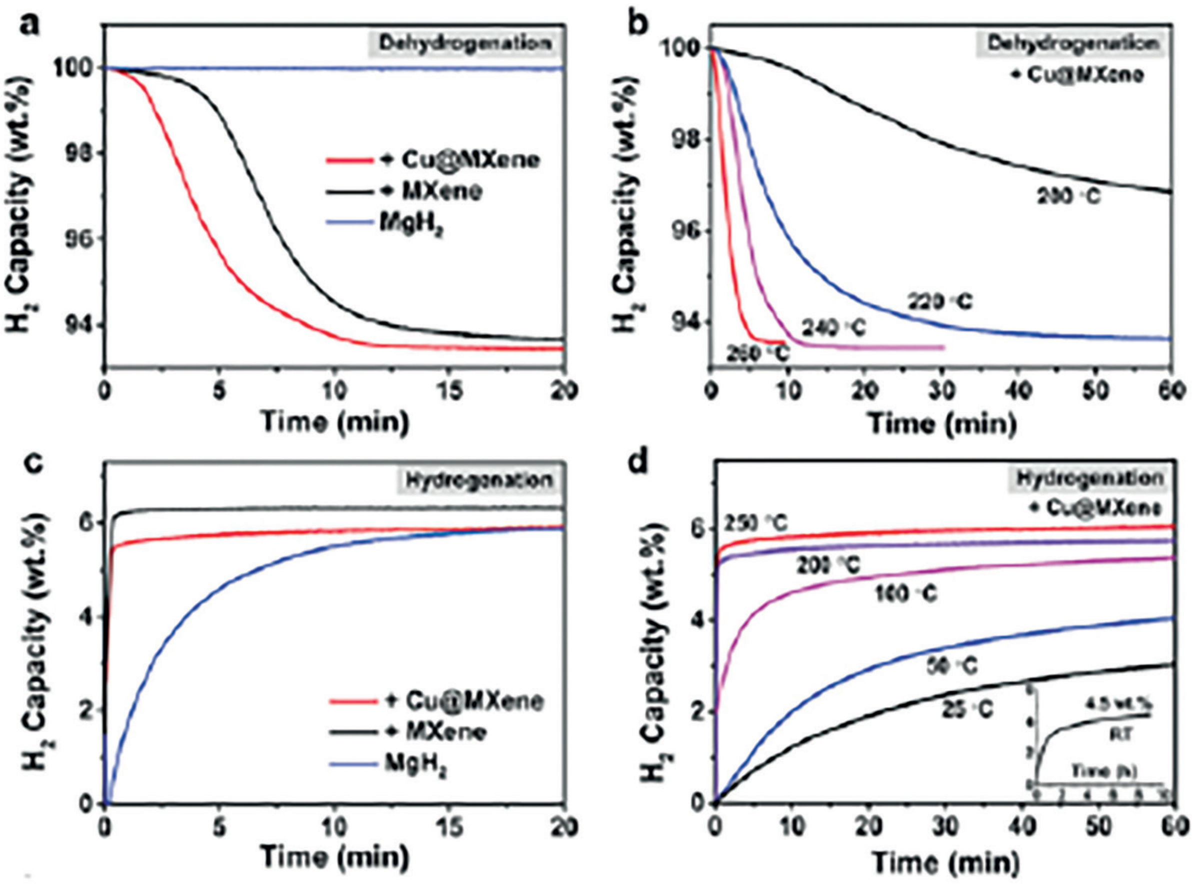

Figure 3: The isothermic hydrogenation and dehydrogenation curves of MgH_2 at 240℃ under the catalysis of: Cu@MXene and MXene, respectively (a,c), or Cu@MXene at varying temperatures (b,d)[9].

In response to these limitations, scientists introduced the proton exchange membrane (PEM) electrolyzer in the 1960s[5]. This technology, utilizing a PEM separator and pure water feed, significantly increases production rates and adapts more rapidly to various power sources. The technology is well established, since many commercial fuel cells use similar technologies. However, PEM electrolyzers have a downside: they operate in a highly corrosive environment and require rare and expensive noble metal catalysts, driving up the initial costs of green hydrogen production.

To address this challenge, Alchemr, an American-based company, developed an anion exchange membrane (AEM) electrolyzer, as shown in Figure 2. Combining features from both alkaline and PEM designs, this machine features a thin AEM layer that separates the electrodes while facilitating the exchange of hydroxide ions[5]. This innovation transforms the environment from acidic to alkaline[5], allowing the use of more affordable and readily available materials without sacrificing efficiency. Alchemr's AEM electrolyzers have the potential to enable large-scale hydrogen production, which, if adopted in the market, could significantly lower the overall cost of green hydrogen production.

Portable Paper-Based Hydrogen Fuel Cells:

In a noteworthy development on a smaller scale, a group of researchers recently conducted a study showcasing the viability of microscale fuel cells powered by hydrogen. These microscale fuel cells are constructed using cost-effective materials compared to their traditional counterparts[8]. Hydrogen's remarkable fuel conversion efficiency and absence of emissions make it an ideal choice for micro applications, ensuring prolonged power supply for such devices. Furthermore, the inherent advantages of microtechnologies, including simplified refueling processes and reduced reliance on noble metal catalysts, mitigate the typical challenges associated with hydrogen fuel cells[8]. However, despite the advantages of microscale hydrogen fuel cells, there has been limited exploration into the use of low-cost fabrication materials for their construction.

A 2022 study presented microscale hydrogen fuel cells developed through readily available materials. Leveraging cellulose paper as a base, along with graphite pencil electrodes and food-grade aluminum foil, the research team successfully crafted a durable, affordable, and compact fuel cell capable of powering portable electronic devices[8]. This device is astonishingly simple and cost-effective, with all materials costing less than $1. Moreover, the research team incorporated various substrates and catalysts to enhance the fuel cell's efficiency. While traditional fuel cells remain effective, this experiment underscores the potential for microscale hydrogen fuel cells to become cost-effective and accessible, with the ability to rival the efficiency of their larger counterparts.

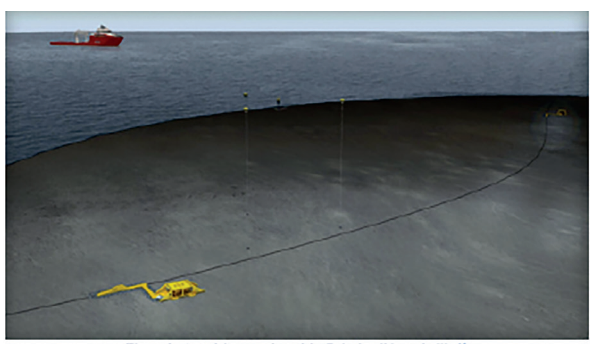

Figure 4: A model recreation of the Polaris offshore facility[15].

Solar-driven Reversible Hydrogen Storage:

In 2022, a groundbreaking study introduced an innovative approach to hydrogen storage by combining photothermal conversion and catalysis to facilitate the storage and release of hydrogen within metal hydrides[9]. One of the significant hurdles in hydrogen energy adoption lies in the effective and safe storage of high-density hydrogen sources, given that storage options for lower-energy hydrogen are less practical and more costly than their high-density counterparts10. Recently, there has been growing interest in storing hydrogen in solid-state metal hydrides. However, the high kinetic barrier of these hydrides necessitates intense external heating before hydrogen extraction, which compromises system efficiency and relies on fossil fuels[11].

To address this challenge, a team of researchers published a study presenting a method to alleviate the difficulty of hydrogen extraction. Leveraging magnesium hydride (MgH_2) as the storage medium, the team incorporated copper (Cu) nanoparticles supported on an MXene base. The incorporation of Cu nanoparticles weakened the Mg-H bonds within the compound, reducing the temperature requirements for both hydrogenation and dehydrogenation of MgH_2[9]. Additionally, the low thermal conductivity of MgH_2 further decreased the temperature demand, expediting both hydrogen absorption and hydrogen desorption processes. By harnessing solar energy as the sole energy source, the team achieved a stable and reversible hydrogen desorption and adsorption process for MgH_2, promising increased storage capacity and more efficient hydrogen extraction[9].

The results of their experiments validated their hypothesis, as shown in Figure 3. Adding Cu and MXene to the storage method substantially reduced the time needed for hydrogenation and dehydrogenation, resulting in a storage capacity of approximately 5.9 weight percent for MgH_2, all powered by sunlight. Spectral analysis revealed that the Cu@MXene compound exhibited stronger absorption characteristics than the standard MXene base alone, signifying greater storage potential for MgH_2. Moreover, the Cu@MXene compound demonstrated superior thermal characteristics compared to MXene, allowing it to reach ultrahigh temperatures and return to stability more rapidly than the MXene sheet. These findings are highly significant, as they demonstrate an effective means of catalyzing hydrogen transport and storage, increasing storage capacity while accelerating the dehydrogenation process, all reliant solely on solar energy. If widely adopted, this Cu nanoparticle-supported MXene approach could revolutionize hydrogen transport and storage industries by significantly reducing costs and making large quantities of hydrogen more accessible.

Blue Hydrogen Carbon Storage Systems:

In the realm of blue hydrogen, a Norwegian startup is poised to revolutionize carbon capture technology. Presently, the predominant source of hydrogen production is grey hydrogen, derived from natural gases or methane through steam reformation[12]. Unfortunately, this process generates carbon dioxide and is unsustainable in the long run. Researchers, however, have chosen a different path, opting to mitigate the emissions rather than entirely phase out steam reformation. The result is blue hydrogen, which shares the same production method but incorporates carbon capture and storage techniques to reduce its carbon footprint[12]. While this distinction may appear minor, carbon capture systems play a pivotal role in mitigating global carbon emissions, and one company has been at the forefront of this initiative since 2022.

Established in 2019, Horisont Energi dedicates itself to producing and storing blue hydrogen and clean ammonia[13]. Notably, in 2021, the company forged a strategic partnership with industry giant Baker Hughes, outlining their collaboration on the "Polaris Carbon Storage Project[14]." The Polaris project is an integrated offshore carbon storage facility poised to boast a total carbon storage capacity of 100 million tons[14], as shown in Figure 5. It aspires to become a global leader in carbon storage, aiming for the lowest

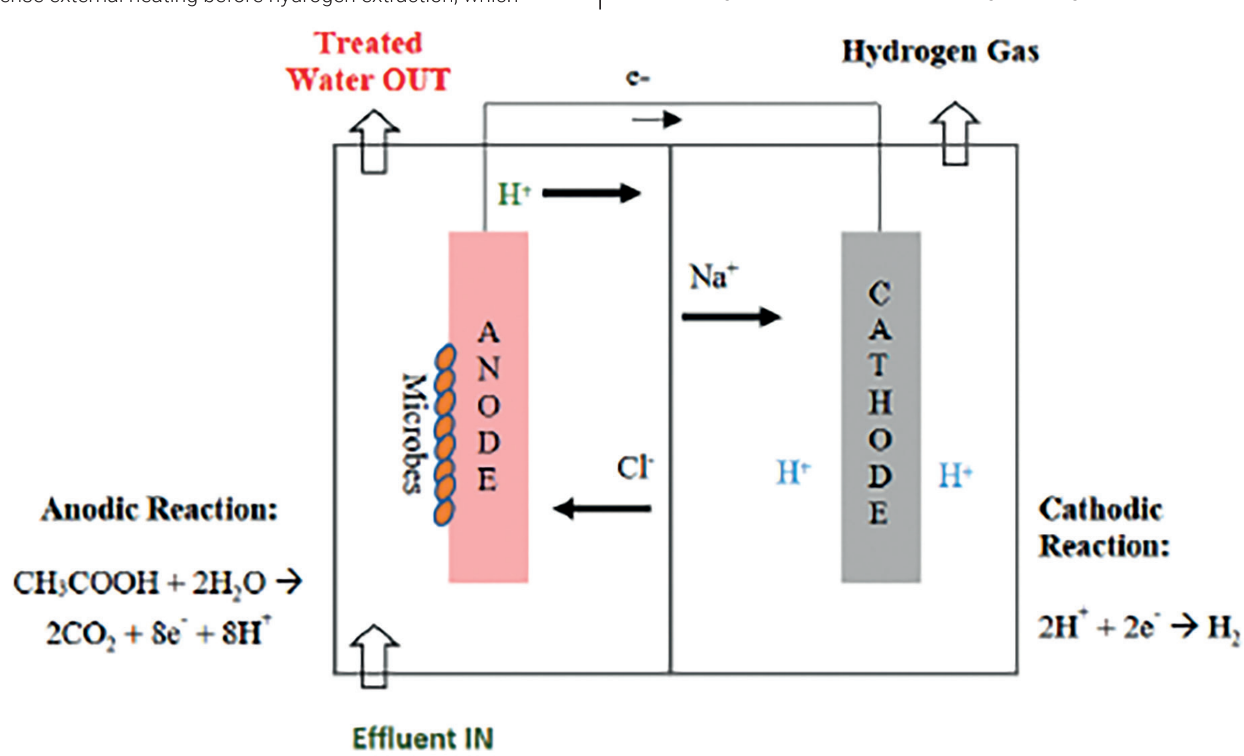

Figure 5: A diagram of the chemistry behind hydrogen generation in the OB Hydracel[20].

carbon storage costs worldwide, all while maintaining its status as a self-sustaining carbon capture, transport, and storage facility, independent of government support.

Furthermore, the Polaris project aligns with Horisont Energi's "Barents Blue" initiative, a separate full-scale production plant focused on manufacturing blue ammonia[16]. Blue ammonia is produced using a similar steam methane reformation process and serves as an efficient means of storing blue hydrogen[17]. Once the ammonia reaches its destination, it is easily reconverted to blue hydrogen and used as fuel[17]. This integrated approach allows the company to utilize its carbon capture facility to produce blue hydrogen and transport it with minimal environmental impact. Any excess carbon dioxide can be conveniently stored in saline aquifers beneath the Barents Sea facility[18].

The Polaris Carbon Storage Project is an ambitious undertaking that has garnered global support during its construction phase. In a recent development, PGNiG Upstream Norway (PUN), a subsidiary of Poland's state-controlled petroleum refinery group ORLEN, announced its intention to join the project as a partner on September 5th of this year[19]. This partnership underscores the sustained interest in the facility's potential. If completed, the Polaris Carbon Storage Project has the potential to significantly reduce greenhouse gas emissions while simultaneously providing a substantial supply of renewable hydrogen fuel to facilities worldwide.

Hydrogen From Wastewater

In a pioneering move, the Indian startup Ossus Biorenewables has introduced a device known as the OB Hydracel, designed to harness intelligent microbial communities for synthesizing green hydrogen from wastewater[20]. This innovation is set to be self-sustaining, non-intrusive, and retrofit-friendly, meant to be directly attached to effluent pipelines for maximum efficiency. To produce hydrogen, the Hydracel leverages microbes present in wastewater as catalysts, targeting specific chemical compounds within the waste and converting them into hydrogen gas through electrodes, as shown in Figure 5[20].

To showcase the capabilities of the Hydracel, the startup conducted a notable study in 2020. In this study, the team retrofitted an Indian naval vessel with the Hydracel to facilitate onboard hydrogen gas production as an auxiliary fuel source. The experiment proved highly successful, with measurements of anticipated wastewater content aligning well with energy generation. The vessel maintained efficient operation without compromising maneuverability or safety. The researchers extended their findings to discuss the potential for retrofitting commercial ships with the Hydracel, recognizing that the quality of effluents in wastewater can vary significantly depending on vessel types and conditions.

Following this study, Ossus Biorenewables garnered substantial recognition and funding. On April 5th, 2023, the company secured $2.4 million in funding from Gruhas Proptech and Rainmatter Climate[21]. This infusion of capital will further propel the development of the Hydracel, enabling its broader application across various sectors, including the food, brewing, and pharmaceutical industries. The realization of a fully functional OB Hydracel could revolutionize traditional production methods by harnessing waste and refuse as catalysts for green hydrogen production. This advancement promises to make hydrogen production more sustainable and accessible, paving the way for a greener and more efficient future.

Conclusion:

From new electrolysis methods to innovative hydrogen storage solutions to entirely novel pathways for synthesizing hydrogen, it is clear that the development of hydrogen fuels is as rapid as it is branching. Discoveries are constantly breaking new ground in this field; however, more work must be done to integrate these findings into workable technologies. Still, the future of hydrogen fuels is very bright, and every color of hydrogen will undoubtedly find many new advancements and innovations in the years to come.

References:

1. Auto Body Review. "Innovator of the Combustion Engine: François Isaac de Rivaz." [Online]. Available: https://www.autobody-review.com/shop/i14490/auto-fx/article/3865/innovator-of-the-combustion-engine-franois-isaac-de-rivaz
2. Benson, Claire. "The Legacy of the Hindenburg Disaster." [Online]. Available: https://www.chemistryworld.com/news/the-legacy-of-the-hindenburg-disaster/3007067.article
3. International Energy Agency. "The Future of Hydrogen." [Online]. Available: https://www.iea.org/reports/the-future-of-hydrogen
4. Azlan, Farazuddin. "Exploring the Different Types of Hydrogen: From Grey to Green, Turquoise, and Brown - A Comprehensive Guide to Clean Energy Sources." [Online]. Available: https://www.linkedin.com/pulse/exploring-different-types-hydrogen-from-grey-green-turquoise-azlan
5. Technology Wealth. "Alchemr (World's First 50 kW AEM Electrolysis.)" [Online]. Available: https://technologywealth.com/startups/alchemr/
6. World Economic Forum. "What is Green Hydrogen and Why do We Need It? An Expert Explains." [Online]. Available: https://www.weforum.org/agenda/2021/12/what-is-green-hydrogen-expert-explains-benefits/
7. Grigoriev, Sergey A. "Alkaline Electrolysers," [Online]. Available: https://www.sciencedirect.com/topics/engineering/alkaline-electrolysers
8. Rao LT, et al. "Portable Paper-Based Hydrogen Fuel Cell with Automated Pencil-Stroked Electrodes: Development, Analysis, and Performance Investigation." International Journal of Energy Research. 2022;46(15):24008-24020. doi:10.1002/er.8699. [Online]. Available: https://onlinelibrary-wiley-com.proxy.library.stonybrook.edu/doi/full/10.1002/er.8699
9. Zhang X, et al. "Solar-Driven Reversible Hydrogen Storage." Advanced Materials (Weinheim). 2023;35(2):e2206946-n/a. doi:10.1002/adma.202206946. [Online]. Available: https://onlinelibrary-wiley-com.proxy.library.stonybrook.edu/doi/full/10.1002/adma.202206946
10. Eberle U, et al. "Chemical and Physical Solutions for Hydrogen Storage." Angewandte Chemie (International ed). 2009;48(36):6608-6630. doi:10.1002/anie.200806293. [Online]. Available: https://onlinelibrary-wiley-com.proxy.library.stonybrook.edu/doi/10.1002/anie.200806293
11. H. Wang, et al. "Tuning kinetics and thermodynamics of hydrogen storage in light metal element based systems – A review of recent progress." [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0925838815313463?pes=vor
12. National Grid. "The Hydrogen Colour Spectrum." [Online]. Available: https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum
13. Horisont Energi. "Our Projects." [Online]. Available: https://horisontenergi.no/
14. Baker Hughes. "Baker Hughes and Horisont Energi Sign MoU for Groundbreaking Offshore Barents Sea Carbon Capture, Transport and Storage Project." [Online]. Available: https://investors.bakerhughes.com/news-releases/news-release-details/baker-hughes-and-horisont-energi-sign-mou-groundbreaking
15. Horisont Energi. "Polaris." [Online]. Available: https://horisontenergi.no/projects/polaris/
16. Horisont Energi. "Barents Blue." [Online]. Available: https://horisontenergi.no/projects/barents-blue/
17. Gnana, Jennifer. "What is Blue Ammonia?" [Online]. Available: https://www.thenationalnews.com/business/energy/what-is-blue-ammonia-1.1229125
18. Baker Hughes. "Update on Collaboration Efforts with Horisont Energi." [Online]. Available: https://www.bakerhughes.com/update-collaboration-efforts-horisont-energi
19. Energy-Pedia. "Norway: Horisont Energi Intends to Partner With PGNiG Upstream Norway as Operator in The Barents Sea CO2 Licence – Polaris." [Online]. Available: https://www.energy-pedia.com/news/norway/horisont-energi-intends-to-partner-with-pgnig-upstream-norway-as-operator-in-the-barents-sea-co2-licence-%E2%80%93-polaris-192570
20. Suhail Basha, K, Swaroop Sinduluri, S, & Rao,. (2020, October 5). OB HydraCel Bioelectrolyzer: Retrofittable device for hydrogen generation as auxiliary power onboard ships. https://doi.org/10.24868/issn.2515-818X.2020.031. [Online]. Available: https://zenodo.org/record/4486836
21. The Economic Times. "Ossus Biorenewables raises $2.4 million in funding from Nikhil Kamath's Gruhas, Rainmatter Climate." [Online]. Available: https://economictimes.indiatimes.com/tech/funding/ossus-biorenewables-raises-2-4-million-in-funding-from-nikhil-kamaths-gruhas-rainmatter-climate/articleshow/99269809.cms?from=mdr

Authors

Dr. Raj Shah is a Director at Koehler Instrument Company in New York, where he has worked for the last 28 years. He is an elected Fellow by his peers at IChemE, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute and The Royal Society of Chemistry. An ASTM Eagle award recipient, Dr. Shah recently coedited the bestseller, "Fuels and Lubricants handbook", details of which are available at ASTM's Long-Awaited Fuels and Lubricants Handbook 2nd Edition Now Available (https://bit.ly/3u2e6GY). He earned his doctorate in Chemical Engineering from The Pennsylvania State University and is a Fellow from The Chartered Management Institute, London. Dr. Shah is also a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute and a Chartered Engineer with the Engineering council, UK. Dr. Shah was recently granted the honourific of "Eminent engineer" with Tau beta Pi, the largest engineering society in the USA. He is on the Advisory board of directors at Farmingdale university (Mechanical Technology) , Auburn Univ (Tribology), SUNY, Farmingdale, (Engineering Management) and State university of NY, Stony Brook (Chemical engineering/ Material Science and engineering). An Adjunct Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical engineering, Raj also has over 575 publications and has been active in the energy industry for over 3 decades. More information on Raj can be found at https://bit.ly/3QvfaLX

Contact: rshah@koehlerinstrument.com

Mr. Beau Eng is part of a thriving internship program at Koehler Instrument company in Holtsville, and is a student of Chemical Engineering at Stony Brook university, Long island, where Dr.'s Shah and Mittal are on the External Advisory Board of Directors.

Beau Eng

Vikram Mittal

Dr. Vikram Mittal, is an Associate Professor at the United States Military Academy in the Department of Systems Engineering. He earned his doctorate in Mechanical Engineering at the Massachusetts Institute of Technology where he researched the relevancy of the octane number in modern engines. His current research interests include various energy technologies, system design, model-based systems engineering and modern engine technologies. He has numerous publications in various peer reviewed journals

Author Contact Details

Dr. Raj Shah, Koehler Instrument Company • Holtsville, NY11742 USA • Email: rshah@koehlerinstrument.com • Web: www.koehlerinstrument.com