Application of Quantum Technology for Generation of Green Solar Hydrogen from Sea Water for Naval Applications

Mr. Shankab J. Phukan, Mr. Suraj Goswami

* *Green Keplerate Laboratory, Department of Chemistry, Banaras Hindu University, Varanasi-221005.*
* Corresponding Author. Email: *shankabphukan@gmail.com, sgoswami1993@bhu.ac.in*

Synopsis

Majority of the present-day technology for production of hydrogen utilizes Electrolysers, which are energy intensive and with a large carbon foot print. In order to provide a cost effective and efficient production process, Green Keplerate Laboratory, at Banaras Hindu University (BHU) in India has developed a novel and sustainable Quantum-derived technology for the bulk production of Solar Green Hydrogen from water through cost-effective photocatalytic based process. This team at BHU, led by Dr. *rer. nat*. Somenath Garai, has designed a Quantum Confinement Technology, wherein the confinement of the reaction systems inside the space with sub-Bohr radius, leads not only an accelerated kinetics but also alters the overall thermodynamics of the reaction. The Quantum Thermodynamics will reign inside the compartmentalized Quantum Containers, also amounting for the unusually high photo-conversion-efficiency.

The authors are effectively simulated the industrial waste material-based electron donor system and through progressive upgradation of the prototypes (from generation-I to generation-III), they have ultimately accomplished the optimum green H_2 generation rate, with a peak production rate of approximately 50 Litres/hr (YouTube Link for Lab-Scale Demonstration: https://youtu.be/uIKdd_5Uzfw). Similarly, they have rigorously tested their technology with saline water, simulated seawater and even artificially polluted water. The authors are confident that with abundance of sea water in the maritime domain, they can cost effectively directly harness sea-water for green hydrogen production, subsequently employing it as a marine and naval fuel, representing a promising and eco-friendly technological endeavour. In addition to the pure solar energy as an input to this process, the authors have also demonstrated production of hydrogen with LED lights as an input, should there be a challenge in availability of direct sunlight in certain circumstances such night time or poor weather conditions or inside closed compartments.

The authors have ensured that the design and assembly of the production unit is carried out in such a manner that they can produce hydrogen with maximum purity, thereby alleviating the need for additional purification. Hydrogen thus produced can be directly injected into the IC Engines, which they have successfully demonstrated in a two-wheeler, portable power generators. They have also successfully adapted the legacy IC Engines, by suitably redesigning the fuel manifold system, adhering to the safety standards, to power a river boat (https://youtu.be/-jLBpJ3GOHk). Notably, the legacy of hydride storage free IC-Engines with minimum modifications have been shown to run on the pure hydrogen produced with this new technology. These engines powered by green hydrogen minimizes energy loss due to heating, thereby elevating performance and durability. In view of the above experiences, the authors feel that this technology can be utilized in the marine and naval sectors.

This paper begins with the general introduction, followed by a brief on the modern Quantum technology application for green routes of energy generation and discusses the challenges likely to be encountered in adapting to the naval /marine environment such as safety, storage, metal-embrittlement etc. and the technologies available for finding solutions.

Keywords: Photocatalytic Green Hydrogen; Hydrogen-fueled Direct IC engine; Hydride Free Hydrogen Storage; Gas Clathrate Hydrates, Maritime Naval Transportation

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Author's Biography

Mr. Shankab J. Phukan is currently pursuing his doctoral research in Banaras Hindu University, Varanasi, under the supervision of Dr. *rer. nat*. Somenath Garai; following his Masters (Chemistry) education in Sikkim Central University, Sikkim. His expertise consists of catalytic composite designing, structural architecture alteration, waste water management and heterogenous catalysis for energy fuel production.

Mr. Suraj Goswami is presently engaged in the pursuit of his doctoral studies at Banaras Hindu University, Varanasi, India, under the esteemed guidance of Dr. *rer. nat*. Somenath Garai. He holds a Master's degree in Chemistry from Chaudhary Charan Singh University, Meerut. His areas of specialization encompass the development of adsorbent materials, the extraction of precious metals and the advanced methodologies pertinent to the adaptation of modern internal combustion engine technologies.

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1. Introduction:

In this today’s shift towards sustainable energy sources, the Quantum Energy Roadmap emerges as a pivotal player amid burgeoning technologies for the sustainable generation of green hydrogen from seawater. This roadmap frameworks an innovative strategy to harness quantum principles and solar energy to directly produce green hydrogen fuel from seawater, offering an eco-friendly alternative to carbon-intensive methods. The depletion of carbon-based non-renewable fuels and subsequent CO_x emissions significantly contribute to global warming and severe climate changes (Cook *et al.* 2010, Chu and Majumdar 2012, Chu *et al.* 2017). Meanwhile, the green hydrogen generation *via* renewable energy resources like solar or wind, proffers a sustainable resolution to curtail carbon emissions and lessen reliance on fossil fuels (Marouani *et al.* 2023).

The vastly expanded global shipping sector contributes around 2-3% of the world’s carbon emission (Sharma *et al.* 2021). The growth of green hydrogen is of paramount importance for global transportation, with a detailed examination of EU regulations and regional nuances highlighting its potential as a cornerstone in Europe's carbon-constrained environment (Bader *et al.* 2008). Researchers indicates that future developments in shipbuilding may be shaped by transformative trends motivated by evolving energy sources and technological innovations. The incorporation of green hydrogen as an eco-friendly fuel corresponds with the industry's transition toward sustainable methodologies and diminished C-footprints (Seppälä 2023). According to the IEA, adopting sustainable methods could annually save 830 million tons of CO_2 emitted from fossil fuel-based hydrogen production. Transitioning all global grey hydrogen production to green hydrogen would necessitate 3,000 TWh/year of new renewable energy. Despite concerns over its production cost, advancements in renewable energy and decarbonization efforts are expected to render green hydrogen more economically viable in the future.

Depending on the extraction method employed, hydrogen is classified into three distinct categories as referred in Figure 1. (Phukan *et al.* 2024)

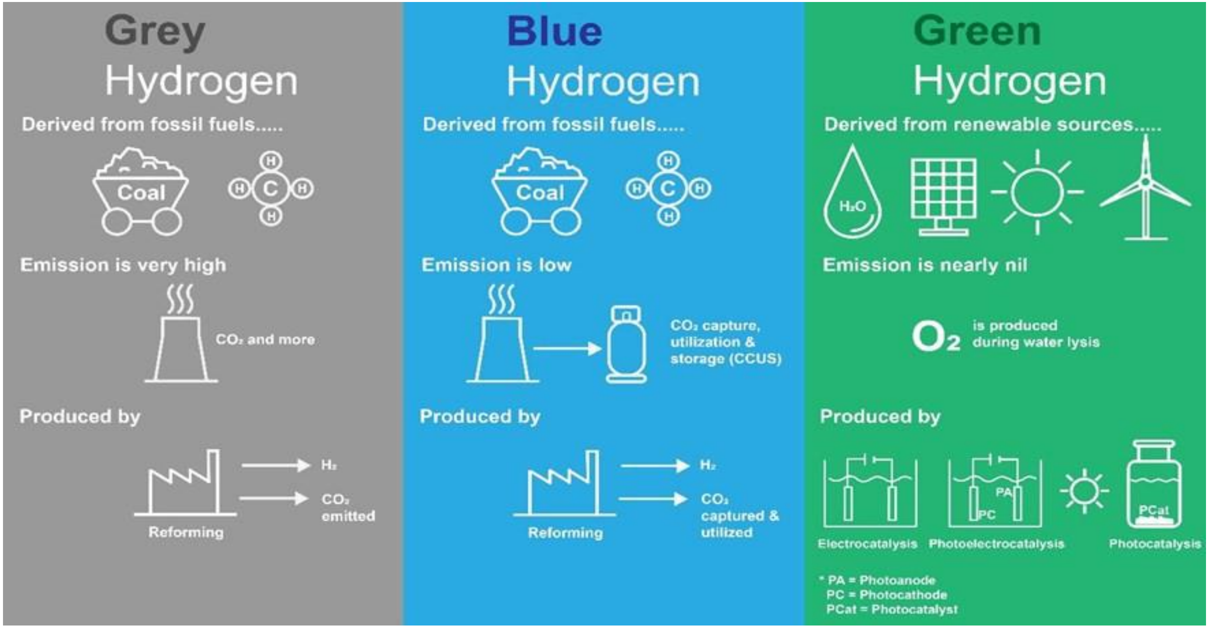


Figure 1: Differentiating by the method of extraction, hydrogen is categorized into three distinct types: Grey, Blue, and Green. Reproduced with permission from *ref.* Phukan *et al. 2024*. Copyright 2024 Elsevier

To address the pollution issues, the Green Keplerate Laboratory (GKL) at Banaras Hindu University (BHU), has pioneered a novel Quantum-derived technology for large-scale Solar Green Hydrogen production. The team has gradually scaled up through three prototype generations to optimize the peak rate of green hydrogen production up to 50 Liters/hour. The technology has been validated with various water sources, envisioning direct seawater utilization for eco-friendly marine and naval fuel production. Adaptability extends to LED-driven hydrogen generation, mitigating sunlight dependency. Production unit design ensures maximum hydrogen purity, obviating additional purification needs.

The succeeding sections explain the Quantum Technology developed for green hydrogen, followed by the progress made in generation and storage of green hydrogen. The redesigning of some parts/sections of the existing legacy IC Engines will then be presented and discuss the challenges (safety, storage, metal-embrittlement *etc.*) before concluding the paper. The graphical roadmap of the technology is depicted in Figure 2.

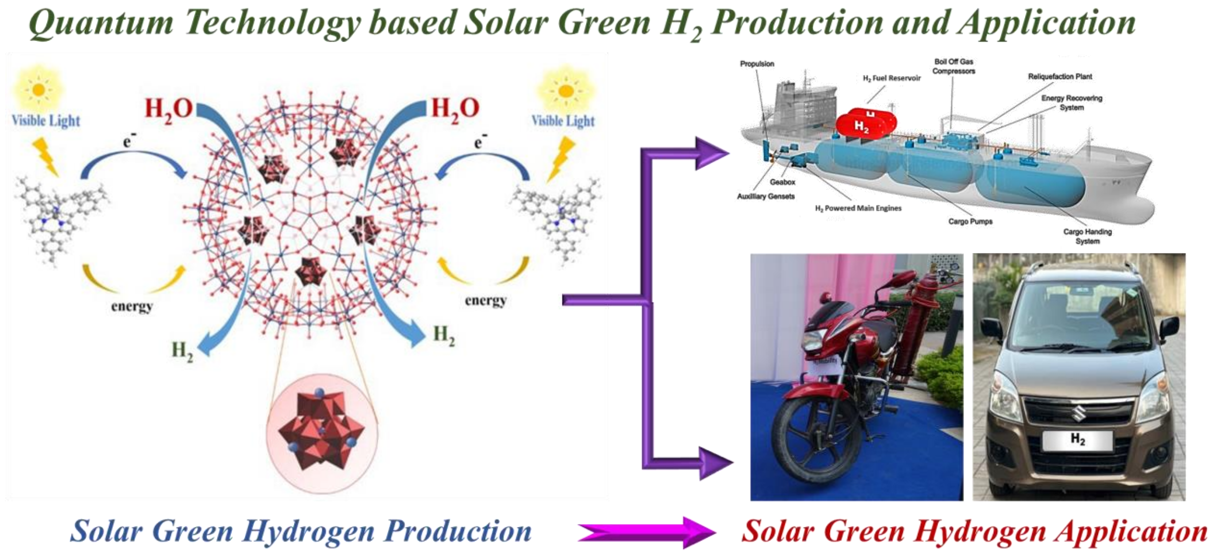


Figure 2: Graphical representation of the technology developed by Green Keplerate Laboratory, BHU, India

Some of the National and International highlights are as shown in Appendix-A. The research group has also demonstrated the "Quantum-confinement powered Bulk-scaled Production of Photocatalytic Green Hydrogen" Technology at the CEM14/MI-8 Ministerial discussions, which took place on 19-22 July, 2023 in Goa University on the side-line of the G20 Energy Transition Ministerial Meeting and also in 9th Smart City India Expo-2024, at New Delhi. The particular links for the above-mentioned events are as follows in the Table 1:

Table 1: YouTube Links for the demonstration of the GKL's Technologies (Solar Green H_2 production and H_2-Mobility) at different Events.

Particulars	**Link**
Solar Hydrogen Production Technology Demonstration Set-Up in the G-20 Ministerial Meeting, Goa	**https://youtu.be/dkF3Q-FoJNY** **https://youtu.be/mua3E5yUbGk**
Demonstration by GKL at the 9th Smart Cities INDIA Expo	**https://youtu.be/La9nwOIAnuM**

2. Modern Quantum Technologies for Green Hydrogen Generation

In the paradigm of solar energy transformation, the deployment of Quantum Dots (QDs) has materialized as a promising route for enhancing the efficacy of photocatalytic reactor systems. These nanoscale semiconductor systems demonstrate unique photonic and electronic properties, which can be finely tuned through size, composition, and structure variations (Bajorowicz *et al.* 2018, Mehta *et al.* 2019). The QDs demonstrated high efficiency in solar energy conversion, leveraging quantum confinement to considerably augment photovoltaic performance (Kundu and Patra 2017). Furthermore, the inclusiveness of QDs within solar panels possesses the capability to revolutionize the field of sustainable energy production, leading to an orientation towards increased sustainability and efficiency (Xu *et al.* 2021). Recent investigations manifest advantageous outcomes with optimal photo-harvesting and improved charge carrier separation in QD-based catalyst systems. As the domain of QDs grows, integrating this technology into solar-powered frameworks holds notable potential for systematic renewable energy production.

The conventional photocatalysts exhibits reduced H_2 production rates relatively to the quantum effect powered catalytic systems due to insufficiently accessible active sites. In 2021, Jia *et al.* (Jia *et al.* 2021) proposed leveraging surface autocatalytic effects and quantum confinement of ultrasmall SiC-nanocrystals to augment active site approachability. By anchoring these nanocrystals onto carbon nitride nanosheets, they advanced a non-metallic photocatalyst that substantially enhanced and sustained H_2 generation. The heterojunction band alignment, enabled by quantum confinement, optimized photo-harvesting in the visible range and facilitated optimal exciton pair separation. Meanwhile, Sanjay Apte *et al.* (Apte *et al.* 2014) has also verified the satisfactory functionals of $CdS_{0.5}Se_{0.5}$ and CdSe QD-glass nano-systems induced with quantum confinement characteristics for solar hydrogen production phenomena. Through the alteration in dimensions of $CdS_{0.5}Se_{0.5}$ QDs, the band gap of glass nano-system was adapted from 3.6 to 1.8 eV, and further to 1.68 eV with the growth of CdSe QDs. The facile tunability of band gaps improves light harvesting, boosting the photocatalytic hydrogen generation, with maximum rates attaining 8164.53 and 7257.36 $\mu\text{mol}\cdot\text{h}^{-1}\cdot\text{g}^{-1}$ for $CdS_{0.5}Se_{0.5}$ and CdSe quantum dot-glass nano-systems, respectively.

Quantum materials, owing to quantum confinement and tunnelling effects, shows the competence to produce multiple excitons, enabling up to three electrons per absorbed photon, contrary to conventional semiconductors that predominantly yield a single electron. Additionally, doping QDs with wide-bandgap semiconductors further improves light absorption and photocatalytic hydrogen production (Rao *et al.* 2019). For instance, the co-condensed amorphous carbon/g-C_3N_4 photocatalytic composites was able to demonstrate hydrogen production rate attaining 212.8 $\mu\text{mol}\cdot\text{h}^{-1}\cdot\text{g}^{-1}$ (Xu *et al.* 2017). Whereas, g-C_3N_4 nanotubes embedded with carbon QDs displayed a significantly heightened rate of 3538.3 $\mu\text{mol}\cdot\text{h}^{-1}\cdot\text{g}^{-1}$ (Wang *et al.* 2018), referable to the quantum effects rooted within the latter catalytic system. Advancements in quantum mechanics principles, such as confinement and tunnelling, are being leveraged to augment materials with advanced catalytic performance for water splitting (Attia and Samer 2017). Innovative integration techniques and custom nano-structuring are undergoing assessment to address existing hurdles and encourage the broader application of quantum materials in green hydrogen production.

3. Achievements of GKL in *state-of-the-art* Quantum Confinement (QC) Technology

The Quantum Confinement Technology has been devised by the authors of the GKL to enhance the utilization of renewable energy sources to yield green energy fuels. This technology involves confining reaction systems within spaces smaller than the Bohr exciton radius of given system, which relates to the significant effect in the reduction of the distances over which an excited electron and an ensuing hole are attracted to each other, as depicted in Figure 3. This reduction in radius enhances the kinetics of the reactions, meaning they occur more rapidly. Moreover, the confinement alters the kinetic as well as the thermodynamic properties of the reactions. Quantum Thermodynamics, which governs the behaviour of energy at the quantum level, becomes significant within these Quantum Containers (QCs). This alteration in thermodynamic properties further contributes to the efficiency of processes like photo-conversion, where light energy is converted into other forms of energy with remarkable efficiency.

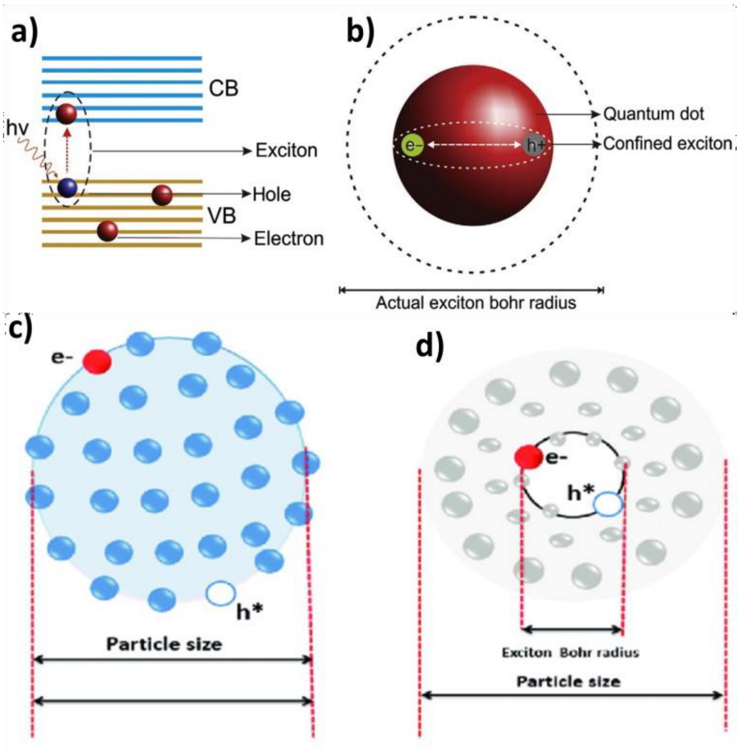


Figure 3: Graphical description of (a) formation of photo-excitons in quantum confined energy band. (b) comparison of exciton radius and quantum dot size. Comparison of (c) excited electron and hole position of conventional particle system and (d) Exciton Bohr radius in quantum dots. Reproduced with permission from *ref.*(Ramalingam *et al.* 2020). Copyright Intechopen.

3.1. Scientific Merits

Recent interest has growing in developing QCs with designed geometries and pore structures to host catalytically active molecules, integrating the properties of diverse nanomaterials for expanded applications. Beyond integrating Keplerates or QCs with metal or semiconducting nanoparticles, assessing their viability in fields such as solar cells and fuel cells needs a deep dive into optimizing charge separation (electron and hole dynamics), modifying valence and conduction bands, enhancing proton conductivity, facilitating electron transport and stabilizing active centers for hydrogen evolution. A. Mueller *et al.* reported the synthesis of Quantum enabled spherical capsules (Figure 4; Size 3.0-3.5 nm as opposed to the Bohr radius of 7.0 nm for molybdenum sub-oxides) based on the robust fundamental skeleton $[\{(Mo)Mo_5O_{21}(H_2O)_6\}_{12}\{Mo_2O_4(ligand)\}_{30}]$ which has sizeable pores, finely sculpturable interiors with Quantum Gating (inner diameter 2.5 to 3.0 nm) and in between, tuneable functionalized channels with unprecedented molecular-scale filter properties (Müller *et al.* 2003). B. Nohra *et al.* has highlighted the synthesis of Polyoxometalate-based metal organic frameworks where they grafted the triangular 1,3,5-benzene tricarboxylate linkers on tetrahedral ε-Keggin polyoxometalates (POMs) capped by Zn (II) ions, formed in situ under hydrothermal conditions. These POMOFs demonstrate potential for an effective electrocatalysts for H_2 generation (Nohra *et al.* 2011). A recent progress in this area is construction of polytantalotungstates by using tri-vacant Dawson- or Keggin-type POTs as supporting and protecting ligands by Shujun Li *et al*. In their work they achieved a higher rate of H_2 evolution by modulating the electronic structure by way of mixing the W5*d* and Ta5*d* orbitals and specifically raising the LUMO level of the polytantalotungstates with respect to Ta-free POTs (Li *et al.* 2012). Another advance in this area is made by Jaramillo *et al*. from Stanford University, to develop surface structure of MoS_2 to preferentially expose edge sites to improve the electrocatalytic hydrogen evolution (Kibsgaard *et al.* 2012). Prof. Lee Cronin, Univ. of Glasgow has been working profoundly on polyoxometalates for oxygen evaluation (Rausch *et al.* 2014, Martin-Sabi *et al.* 2018). The enhanced electrocatalytic activity of this catalyst is mainly due to its high surface curvature, which enhances the exposure of edge sites. This study underlines the significance of polyoxometalates as next-generation hybrid materials.

Although not yet commercialized, the growing interest in these multifunctional materials highlights their potential to address challenges related to cost, design and performance in advanced applications.

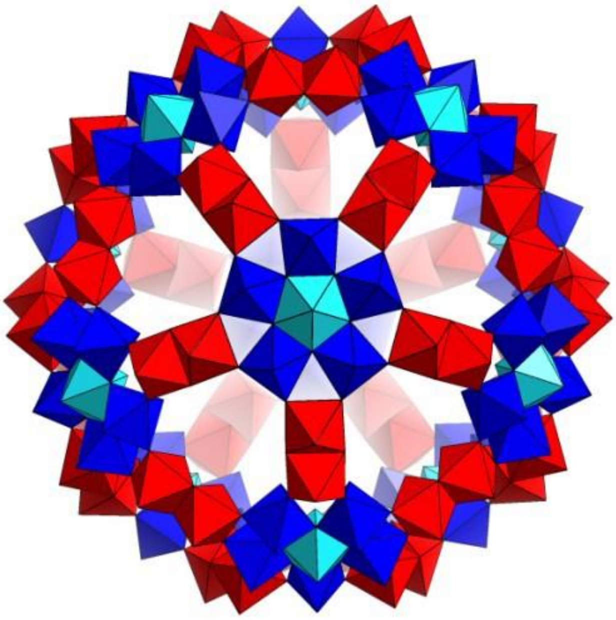


Figure 4: Polyhedral representation of the crystal structure of Mo_{132}-type QC. Reproduced with permission from *ref.* (Lodh *et al.* 2018). Copyright Royal Society of Chemistry.

3.2. Production Technology

By the culmination of the calendar year 2021, the esteemed research cohort hailing from the illustrious GKL, BHU has adeptly pioneered and meticulously engineered sophisticated photochemical energy production methodologies. The authors have designed and fabricated a laboratory-scale photocatalytic reactor possessing the capacity to yield approximately 50 liters/hour of photochemical green hydrogen, leveraging a 200-watt LED illumination source, till *May 2022*. Notably, they have also obtained the peak throughput of their laboratory demonstrator for the evolution of green hydrogen stands at approximately 1.0 liter/minute, even when utilizing saltwater as the feedstock, till *September 2022*. The GKL team has also designed, assembled and fabricated a lab-scaled solar powered-green energy production reactor, installed with concaved solar reflectors for maximum solar light utilization. The solar reactor's development was finalized by *March 2023*. The reactor was assessed in *May 2023*, demonstrating a green hydrogen production rate of ~50 liters/hour (Figure 5). The attached gas chromatography (GC) report is shown in Figure 6, which illustrates the purity analysis of the green hydrogen sample.

Keeping the '*Waste-to-Wealth*' approach in mind, the authors has designed the Quantum Confinement Technology with maximum utilization of the waste materials. The confinement of the reaction systems accelerates the kinetics but also alters the overall thermodynamics of the reaction as Quantum Thermodynamics will reign inside the compartmentalized Quantum Containers, also amounting for the unusually high photo-conversion-efficiency as depicted in Figure 7. The Z-scheme charge transfer pathway for advanced photocatalytic green hydrogen production has been enhanced using quantum confinement technology, which is integrated to a two-dimensional hybrid photocatalytic composite, as shown in Figure 8. The GKL team has successfully simulated an electron donor system originated from industrial waste, attaining an optimized green hydrogen generation rate. They are currently developing a solar-powered salt water-based photocatalytic reactor, which will be able to use both solar and LED lighting depending on solar availability. The reactor is designed to make maximum use of solar radiation and achieves a green hydrogen production rate of around 50 litres/hour with over 95% purity, eliminating the need for further purification and increasing cost-effectiveness.

The authors demonstrate the development of three successive prototypes (as shown in Figure 9) dedicated to green energy production, concluding in the successful development of a lab-scale green hydrogen fuel production unit. This system represents a significant development over existing photocatalytic hydrogen generation technologies, particularly through its direct utilization of seawater. This approach circumvents the need for ultrapure milli-Q water and delivers robust performance across saline, simulated seawater, and polluted water samples. Even under these conditions, consistent and efficient green hydrogen production establishes this technology as a promising, sustainable solution for marine and naval fuel applications.

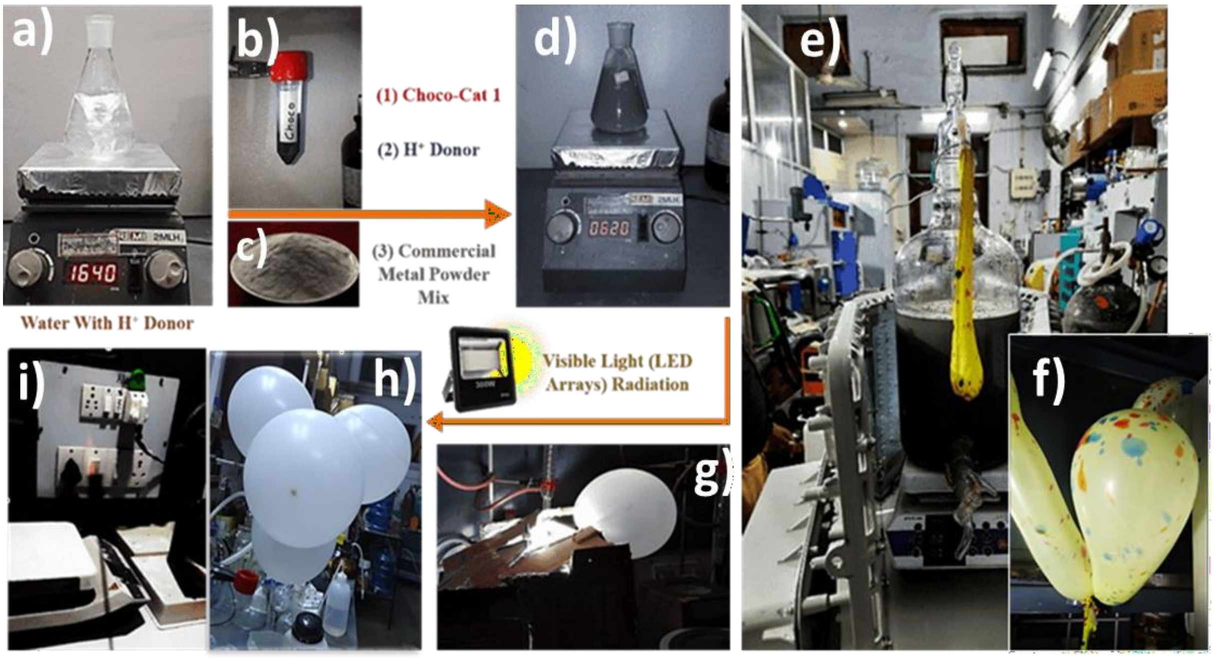
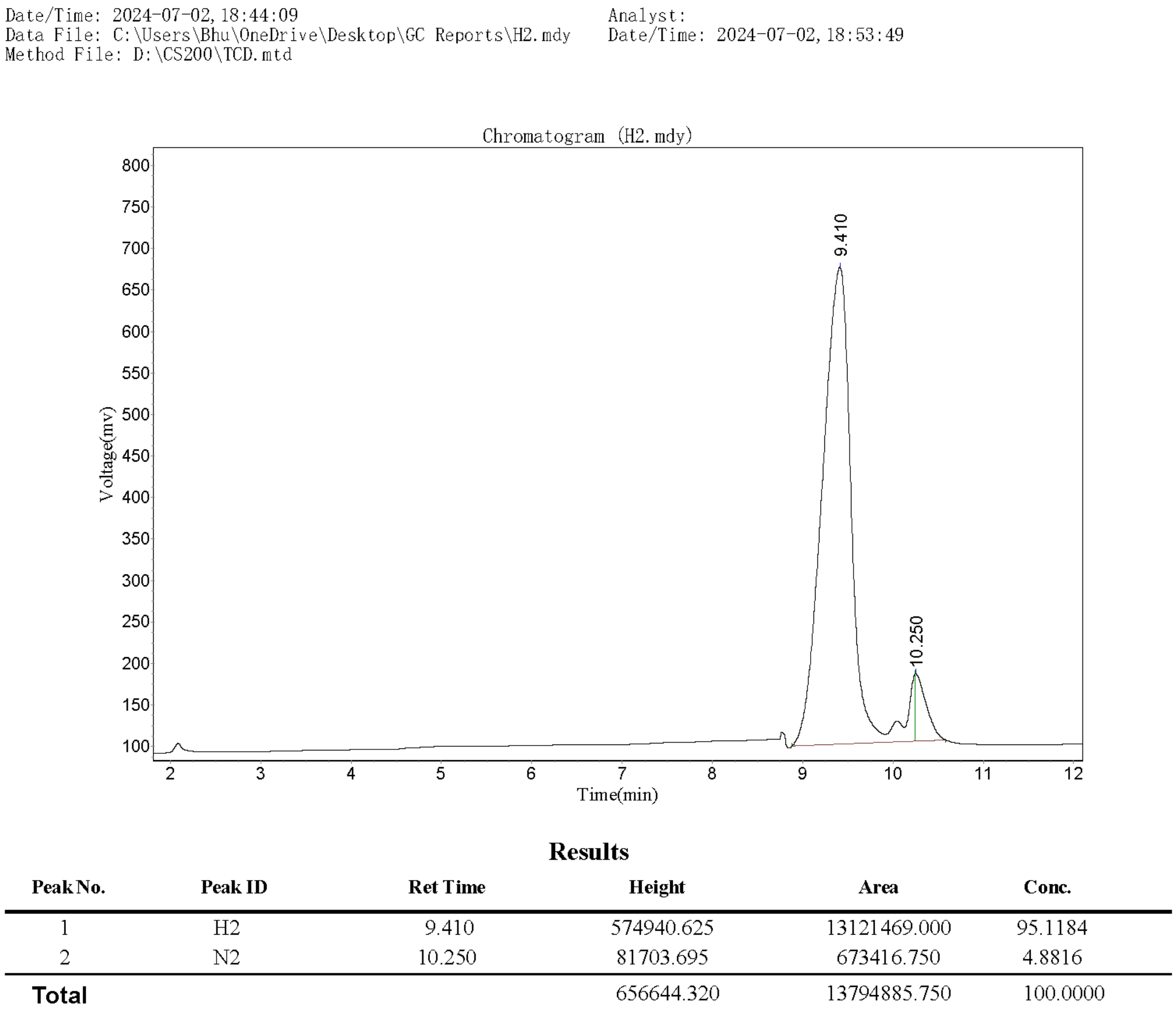


Figure 5: Internal methodology and assembly of the lab-scaled photochemical reactor for bulk Green H_2 production. ((a) Reaction flask containing ground water; (b) Quantum photocatalyst; (c) Mixed metal waste powder; (d) Reaction flask at mixing stage; (e) Lab-scale Green H_2 production reactor; (f) Ballons filled with as produced Green H_2 gas; (g) Execution of Photochemical reaction; (h)Yield of Green H_2 gas from reaction vessel shown in (e); (i) Flame test for H_2 gas.)



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Date/Time: 2024-07-02,18:44:09                                   Analyst:
Data File: C:\Users\Bhu\OneDrive\Desktop\GC Reports\H2.mdy       Date/Time: 2024-07-02,18:53:49
Method File: D:\CS200\TCD.mtd
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Results

Peak No.	Peak ID	Ret Time	Height	Area	Conc.
1	H2	9.410	574940.625	13121469.000	95.1184
2	N2	10.250	81703.695	673416.750	4.8816
Total			656644.320	13794885.750	100.0000

Figure 6: Gas Chromatography (GC) Report of Produced Green Hydrogen Purity.

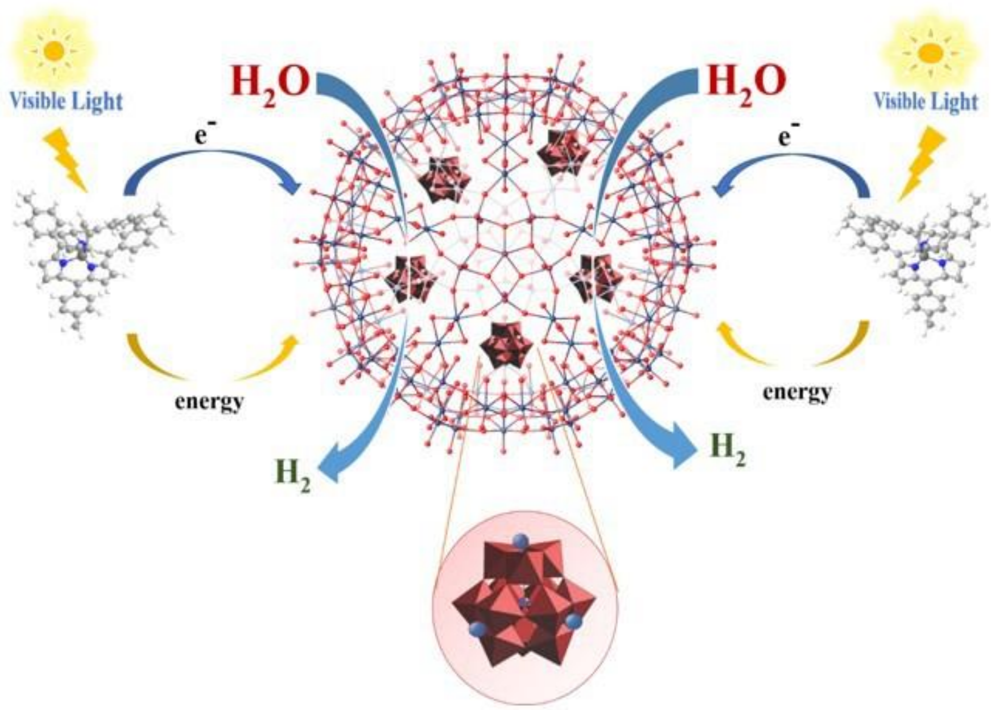

Figure 7: An overall pictorial description of photocatalytic Green H2 production strategy induced with charge transfer route.

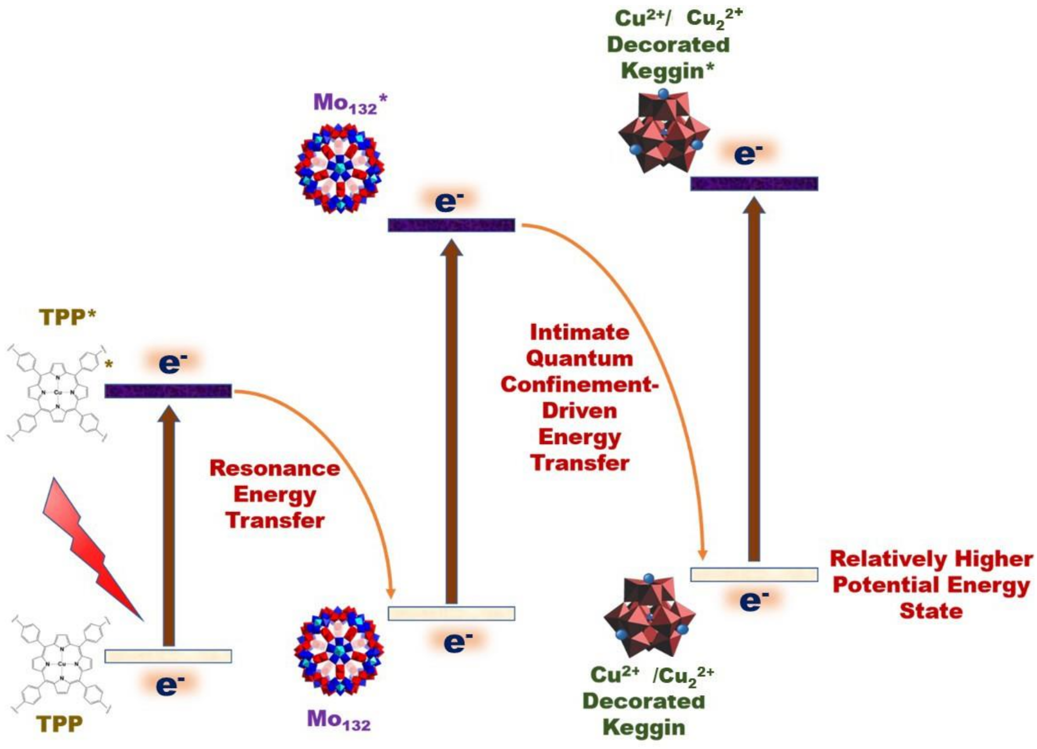

Figure 8: Schematic representation of proposed Z-scheme charges transfer route for effective photocatalytic activities, as a consequence of restrained recombination of photo-excited charge carriers.

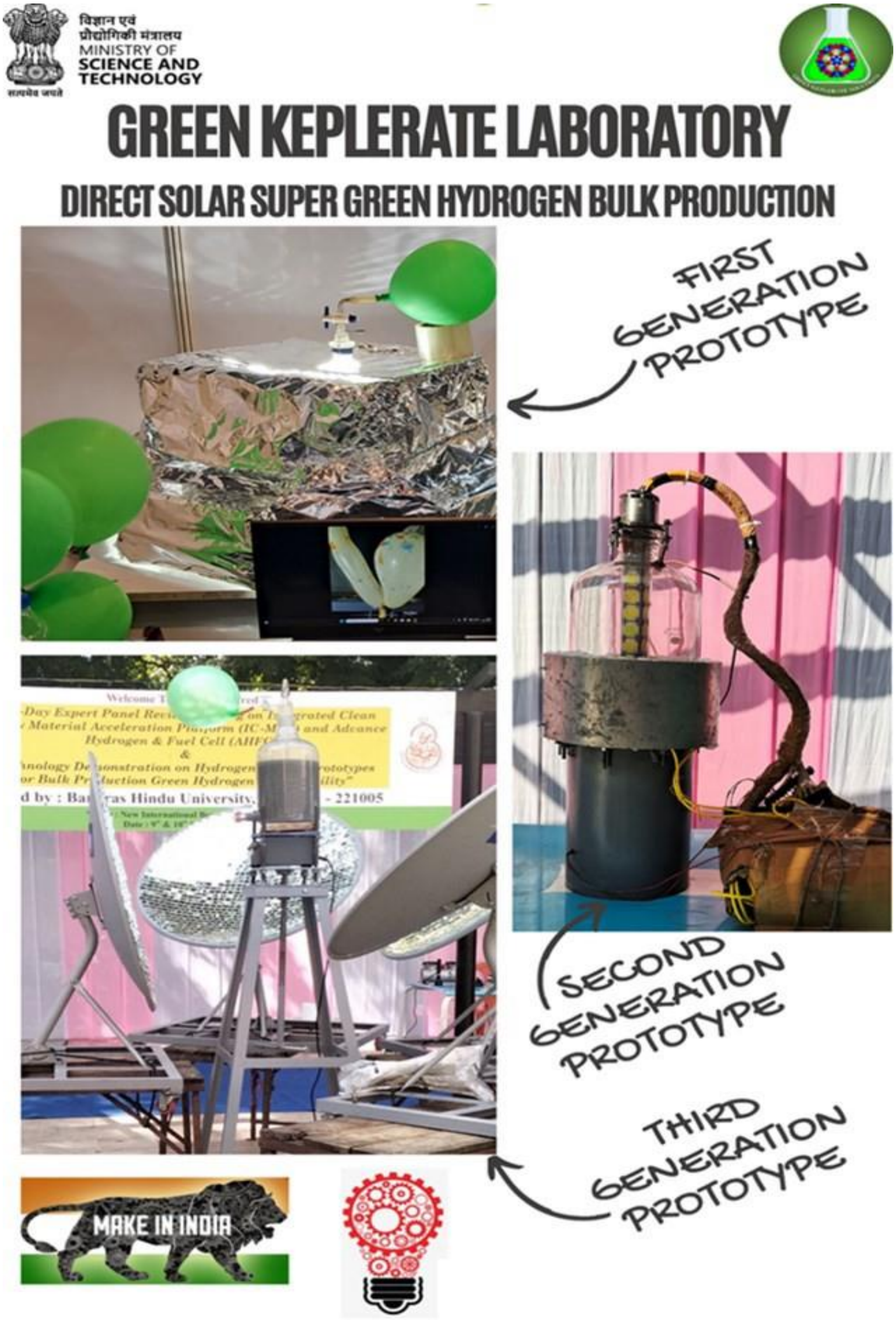

Figure 9: Illustration of the three generation prototypes for green energy generation.

3.3. Green Hydrogen Storage Technology: A Future Idea

The research group at the Green Keplerate Laboratory plans to improve energy efficiency by forming clathrate hydrates by employing a hydrogen natural gas blend (HNGB)-based approach for hydride-free H_2 storage. This approach takes advantage of carefully structured, strong hydrogen bonding shells, similar to those observed in clathrate structures, such as the water shells contained within $\{Mo_{132}\}$-Keplerates. The validation behind this method lies in the structural resemblance between water shells in clathrates and the encapsulated water shells within $\{Mo_{132}\}$-Keplerates (Figure 10). Extending this concept for green hydrogen gas storage, the team aims to exploit the beneficial properties of the well-defined hydrogen bonding shell to confine hydrogen gas within the clathrate in the future.

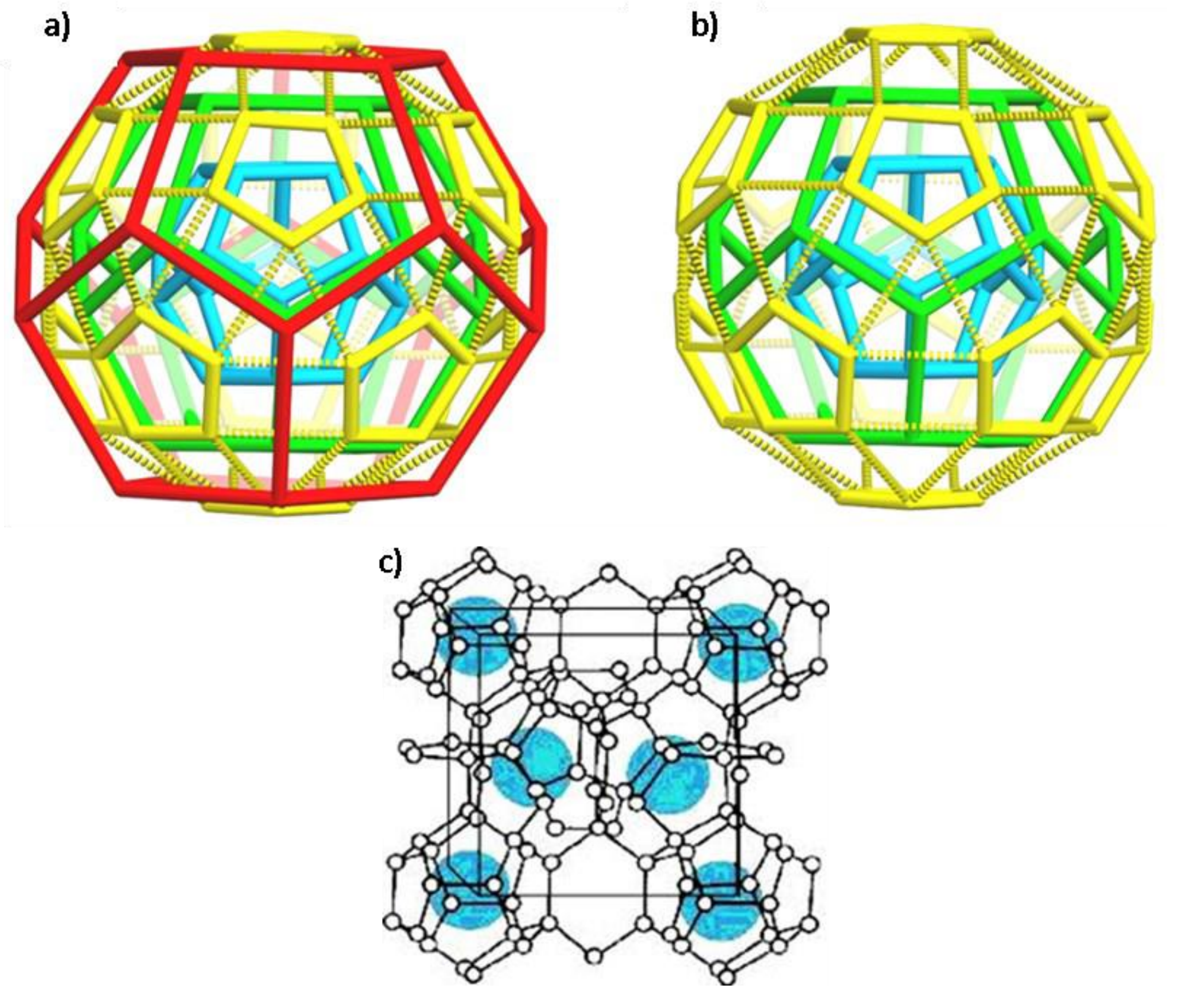

Figure 10: The pictorial diagram of encapsulated $(H_2O)_{100}$ inside the $\{Mo_{132}\}$-Keplerate. Reproduced with permission from *ref.*(Mitra *et al.* 2009). Copyright John Wiley and Sons.

This method takes advantage of the stabilization of hydrogen gas within a clathrate encapsulated by metal oxide clusters, significantly increasing stability and reducing cost and risk. The tunability of clathrate structures and gas encapsulation properties provide a prominent solution for hydrogen storage, especially for direct H_2 ICE-based vehicles. This approach addresses key challenges in hydrogen storage and increases the efficiency and safety of hydrogen-powered transportation.

For the H_2 fuel storing purpose, treating the Keplerate-based Quantum Container assemblies with ammonium sulfate solutions and utilizing the resulting nano-capsules containing the $\{Mo^{V}_2O_4(SO_4)\}$ type linker (Müller *et al.* 2003) as containers offers a promising approach to address the challenge. Upon examination, the authors observed that the significant alteration is undergone by the central water assembly structure within the obtained capsule. The icosahedral supramolecular $\{H_2O\}_{100}$ water nanodroplet (Müller *et al.* 2002) confined within the carefully engineered quantum container mentioned earlier. The structure of this nanodroplet may be derived either by enclosing the two nested $\{H_2O\}_{20}$ dodecahedra within a strongly distorted $\{H_2O\}_{60}$ rhombicosidodecahedron or by inserting an $\{H_2O\}_{20}$ dodecahedron within the two-shell $\{H_2O\}_{80}$ assembly. This geometric arrangement is characterized by relatively short hydrogen bonds, with an average hydrogen bond energy calculated to be 28 kJ/mol and significant anisotropy across the three concentric water molecule shells. Moreover, due to the substantial negative charge of the Quantum Containers, ammonium ions are absorbed into the cavity along with the water molecules. This water-based assembly presents a unique opportunity for direct observation of how its hydrogen-bonding network is perturbed by the presence of foreign cations.

3.4. Integration with the Existing Engines Technology

The endeavors have culminated in the proficient adaptation and integration of H_2-ICE (Hydrogen—Internal Combustion Engine) across a diverse spectrum of automotive platforms- 4-wheeler (Figure 11), two-wheeler (Figure 12) as well as a 7.5 HP diesel engine-based generator (Figure 13), and the Honda ep 2500 CXS petrol-based generator. The adaptive modification for direct hydrogen combustion, on the ICEs of the vehicles was completed by end of year 2023. Additionally, the propulsion systems, tailored for Ganges River boats (as shown in Figure 14), showcased hydrogen power in October 2023.

A standard hydrogen gas cylinder, which has a capacity of 50 liters and is pressurized to 200 bars, is capable of delivering energy equivalent to 10 kWh. This implies that the cylinder can sustain a fuel cell producing 1 kW of electrical power for a duration of 10 hours (Cellkraft Fuel Cell Products: Factsheets_Fuelcells n.d.). To supply a 50-kW fuel cell for one hour, you would need around 4,900 liters (4.9×10^3 liters) or approximately 4.375 kilograms of hydrogen gas. For a fuel cell of this capacity, the hydrogen feed rate would be roughly 102 liters per minute (LPM). Therefore, the hydrogen fuel consumption rate can be approximated to be 2 liters per minute per kilowatt (LPM/kW). The authors conducted a test ride using a hydrogen-powered maritime boat, revealing important insights into the fuel requirements for such scaled vessel. This test involved a maritime boat equipped with a 7.5 horsepower (5.6 kW) Honda IC motor, which had a weight of approximately 50-60 quintals. During the test, the maritime vessel achieved speeds of about 8-12 knots. To maintain this speed, the boat required a hydrogen fuel flow rate of approximately 12 LPM.

The experimental results indicated that the hydrogen consumption rate of the maritime boat during the test ride closely matched the theoretical values typically expected from a traditional fuel cell system. This alignment between experimental and theoretical values suggests that the fuel consumption behavior of the hydrogen-powered maritime boat is predictable and consistent with established models. Based on these findings, it is concluded that in order to efficiently power a boat equipped with a 7.5 horsepower Honda internal combustion motor using a high-quality fuel cell system, a hydrogen fuel feed rate of approximately 11-12 liters per minute would be necessary. This rate ensures that the boat operates optimally, providing the necessary power while maintaining efficiency and consistency with theoretical predictions. Meanwhile, the statistics and optimization parameters derived from the testing of hydrogen-powered maritime vessels will be methodically evaluated for potential application in larger-scale naval ships. The implementation of this environmentally sustainable waterborne mobility technology in naval-based operations will necessitate procurement of appropriate regulatory endorsements at both national and international levels. Additionally, it will necessitate access to suitable certified testing facilities and supervision by competent authorities. In spite of the prerequisites, the acquired valuable insights from maritime testing and optimization are decidedly advantageous for advancing to the next phase of scaled-up trials. These exertions are contributory in driving the integration of next-generation IC engine technologies into the naval sector, paving the route for a transformative alteration in naval propulsion systems.

This visionary project integrates green hydrogen gas through a methodically advanced manifold piping system, adhering to stringent safety standards. The modified H_2-ICEs significantly decrease internal acoustic emissions, improving auditory comfort. The major modifications include the inclusion of fuel cylinders with established safety protocols, secure mounting mechanisms, a custom manifold-based hydrogen fuel transition assembly, industrial-grade one-way valves, and hydrogen-compatible fuel control systems. To prevent the accumulation of gas, a special gas injection system secures continuous air flow inside the engine section, thereby preventing the accumulation of hydrogen. Innovating with customized fire-retardant, hydrogen-grade non-return valves using indigenous technology, the system ensures fire and leakage resistance, strategically integrated at junctions and chamber inlets. Figure 13 schematically shows the restructuring of a conventional maritime boat or naval ship engine into a direct H_2-ICE. Relevant technological links are provided in Appendix-B.

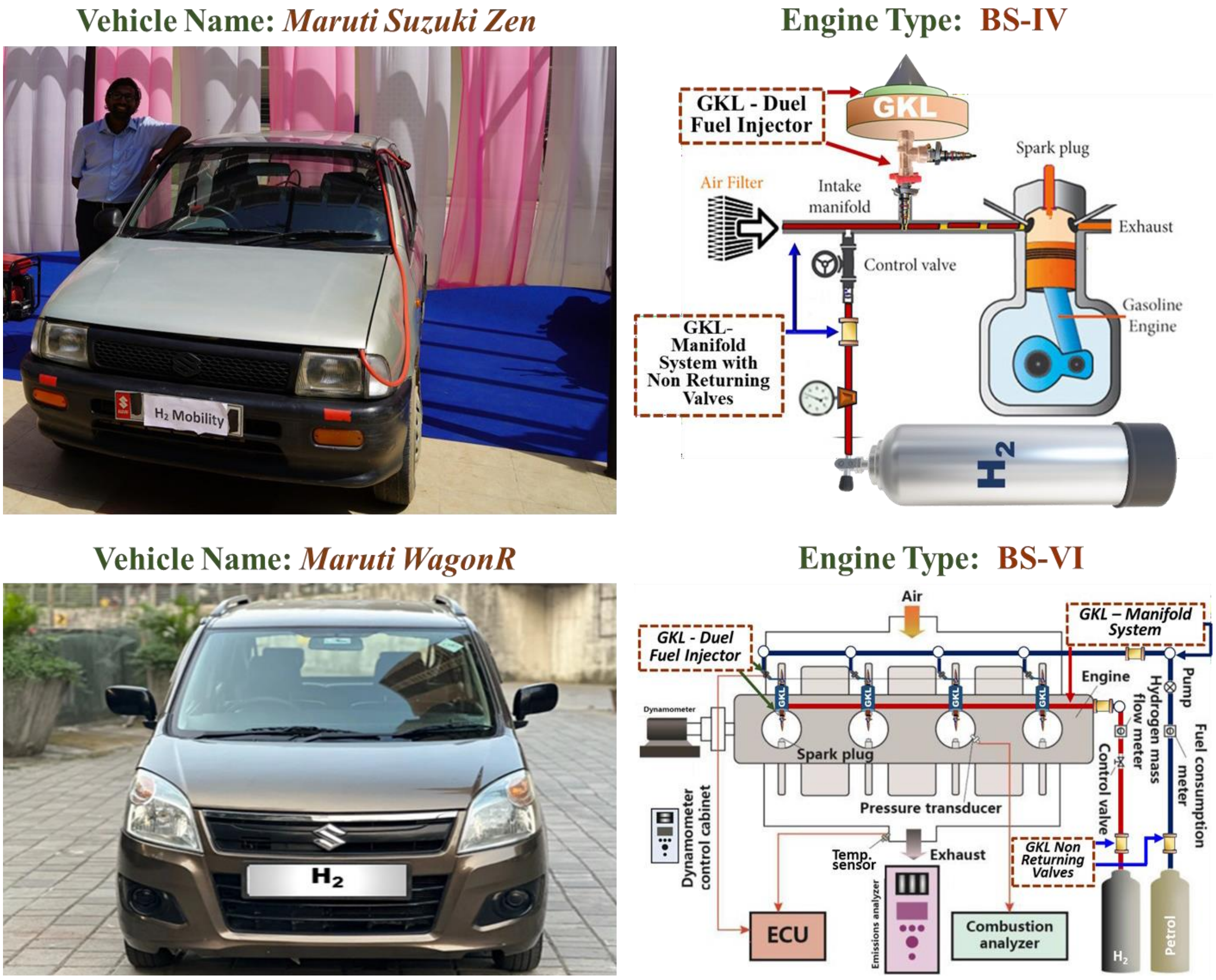

Figure 11: The engine schematic design powering the H_2 fueled four-wheeler vehicles.

Vehicle Name: ***Bajaj Pulsar 180 cc*** **Engine Type: BS-VI**

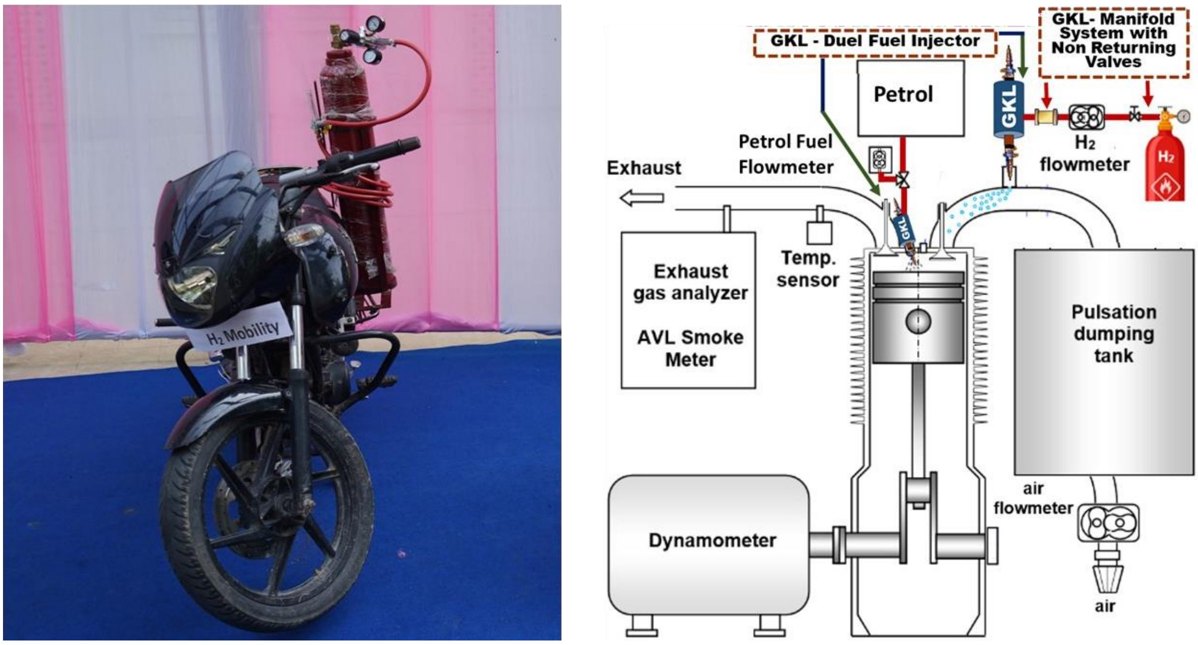

Figure 12: The engine schematic alongside a captivating showcase of the H_2 fueled two-wheeler vehicle.

Vehicle Name: ***Diesel-based Motor Generator (7.5 kW)*** **Engine Type:** **AVR type**

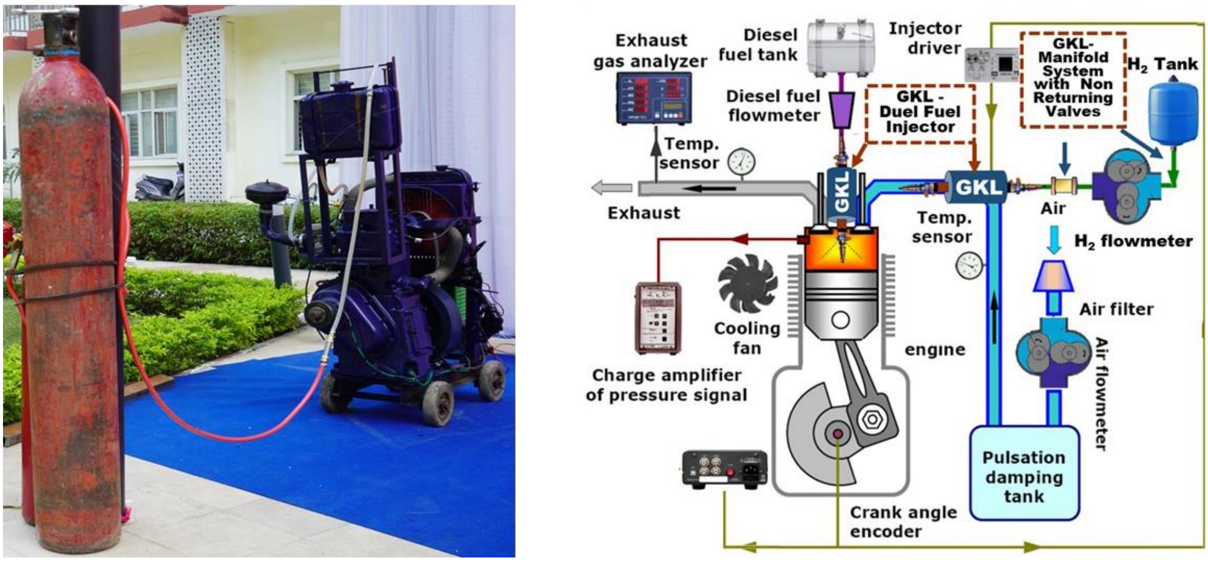

Figure 13: The detailed engine schematic alongside a demonstration of the hydrogen-powered diesel engine

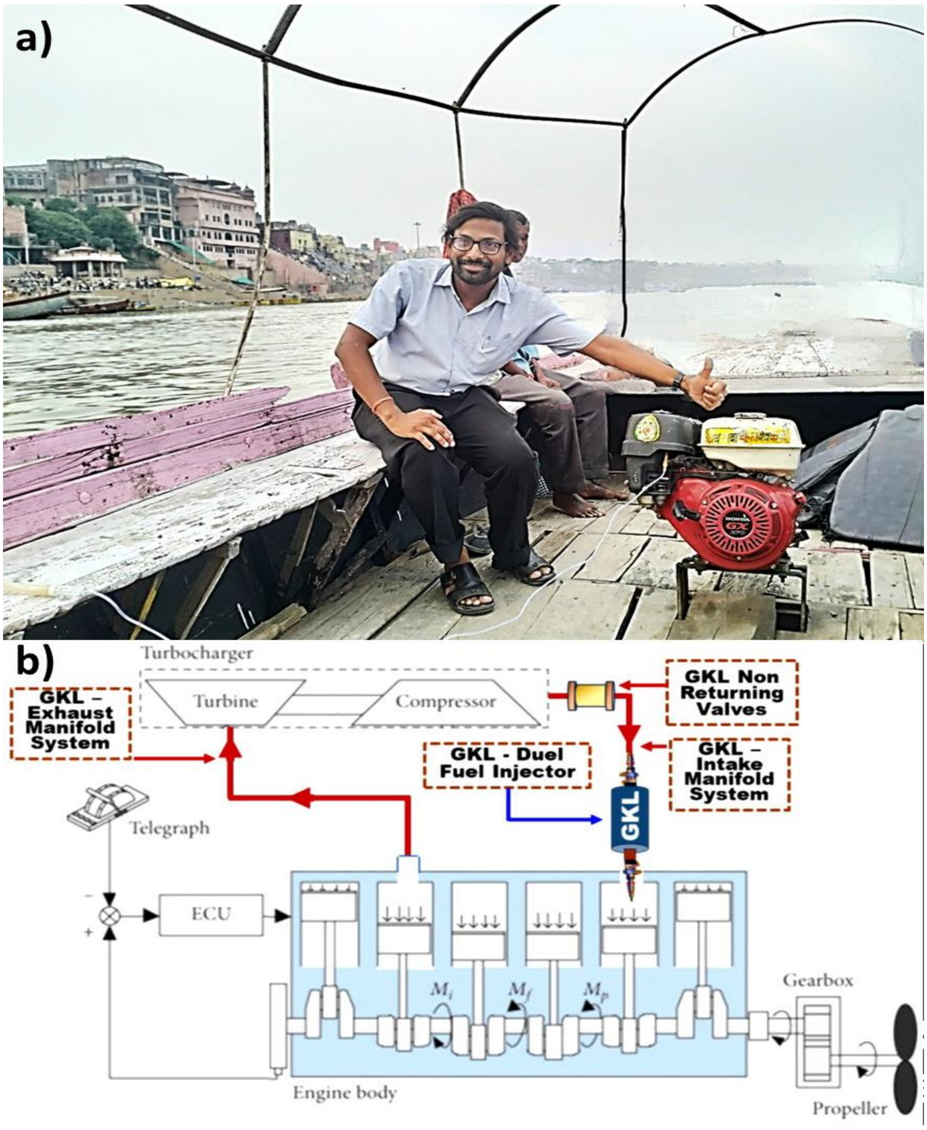

Figure 14: (a) Block diagram of Strategical reconfiguration and assembly of conventional propulsion-based boat engine into direct H_2 –IC Engine; (b) Revolutionizing Waterways: H_2-Powered Boat Navigation on the **Ganges** River.

4. Challenges

4.1. Safety

Liquid hydrogen, with its minuscule molecular structure and high expansion coefficient, undergoes rapid expansion, intensifying its combustible nature. This rapid expansion serves to dilute the concentration of hydrogen in the surrounding air, reducing the potential for danger while increasing the size of flammable clouds. With a surprisingly low energy barrier to combustion in air (0.017 mJ) and wide flammability range (4-74%), hydrogen stands as a prime candidate for being ignited by even the slightest spark (Ratnakar *et al.* 2021). Furthermore, once ignited, extinguishing hydrogen flames proves to be a very difficult task. For safety, the GKL team had implement a specialized gas injection system designed specifically to efficiently disperse any hydrogen gas that might accumulate in the engine chamber (*viz.* section 3.4). This system confirms an unceasing airflow, preventing hydrogen build-up. The GKL team is also using custom-made non-returning valves that are fireproof and leak-resistant, tactically positioned in crucial junctions and chamber inlets.

4.2. Storage

The shift towards green hydrogen for sustainable energy introduces complex storage challenges that must be addressed for widespread adoption. Effective storage methods are vital, particularly in overwhelming limitations like reactor efficiency and catalyst advancement in solar-driven photocatalytic hydrogen production. Figure 15 structures various hydrogen storage technologies, predominantly remain economically and safely unviable for naval applications. Recent studies have emphasized the need to increase storage capacity through technological advancements, including the enhancement of batteries and capacitors using nanomaterials (Ahmad *et al.* 2023). These revelations elucidate the pivotal role of storage in streamlining the utilization of green hydrogen, notably within domains like maritime and naval applications. Through the incorporation of quantum technology in storage frameworks, remedies can be formulated to counteract safety apprehensions, metal embrittlement predicaments, and heighten overall efficacy in harnessing green hydrogen sourced from marine environments. This comprehensive methodology tackles the multifaceted obstacles linked with hydrogen storage, laying the groundwork for a more sustainable energy terrain.

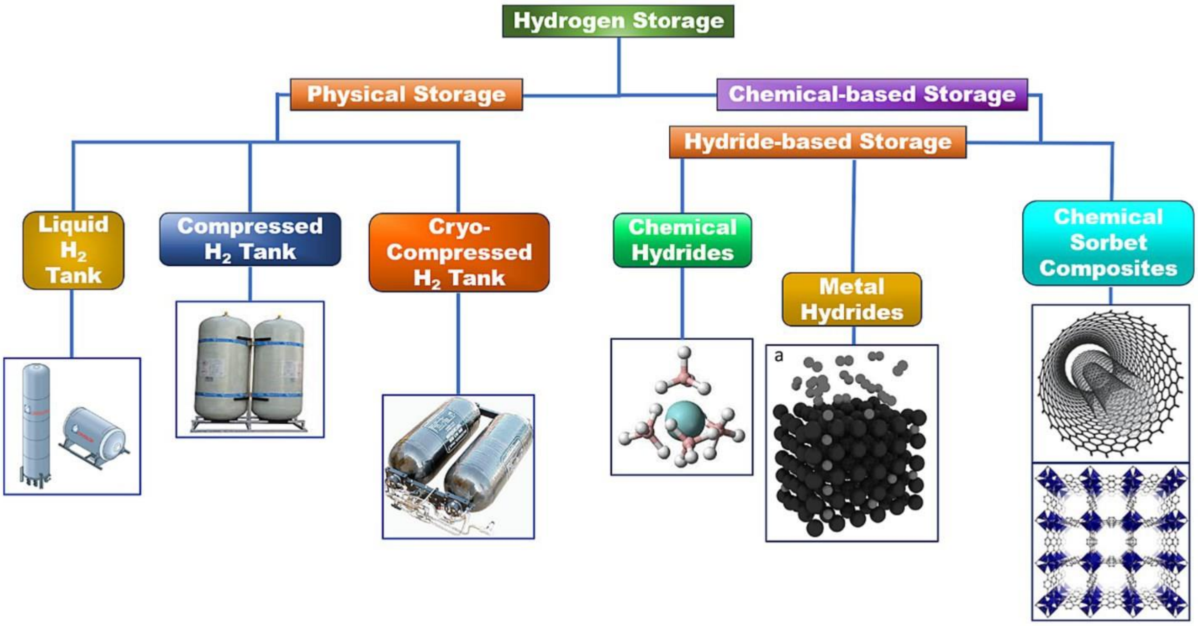

Figure 15: Currently available various methodologies for safe and efficient hydrogen fuel storage. Reprinted with permission from *ref.* Phukan *et al. 2024*. Copyright 2024 Elsevier

The challenge of storing natural gases, encompassing hydrogen, methane, and higher analogues like propane to pentane, persists due to various risk factors. Gas clathrates, a natural storage mechanism, have emerged as a significant methodology, inherently designed by nature. However, replicating these conditions for gas storage presents challenges, requiring lower temperatures and several bars of pressure. Instead of attempting to form clathrate hydrates solely from pure H_2, previous researchers have proposed blending hydrogen with natural gases. This approach has been experimentally validated to facilitate clathrate formation under milder conditions (Ahn *et al.* 2020) and also under Quantum Encapsulation of the QCs as mentioned in the section 3.3.

4.3. Metal Embrittlement

In the field of green hydrogen generation, the issue of metal embrittlement within hydrogen domains emerges as a daunting challenge that requires solutions to maintain the safety and stability of the infrastructure. The invasion of hydrogen atoms into the metal structure causes the metal embrittlement, leading to hydrogen-induced cracks and subsequent breakdown of the material (Sun *et al.* 2024). The maximum embrittlement of metals occurs at the 20 and 100 bar of the partial pressure of H_2 (Barthélémy 2006)). This phenomenon is of utmost significance in the marine and naval sectors where constructions endure ongoing being exposed to extreme environmental conditions. Measures to alleviate this predicament encompass incorporating alloys with elements capable of capturing hydrogen atoms, adopting surface modifications to establish shielding barriers, and enforcing stringent examination and upkeep procedures essential for forestalling catastrophic breakdowns in hydrogen systems. By grasping the intricacies of metal embrittlement mechanisms and carrying out pre-emptive actions, the marine and naval sectors can efficaciously leverage the potential of Quantum technology for sustainable green energy generation while safeguarding operational safety and dependability (*cf.* section 3.3).

4.4. Transportation

Transporting hydrogen is concerned with challenges due to its low density and flammability. Currently, it is mainly transported as a liquid in pipelines or super-insulated tanker trucks, which require cryogenic temperatures (Di Nardo *et al.* 2023). Liquefaction costs more than 30% of the energy content of hydrogen and is expensive (Osman *et al.* 2022). Losses from evaporation during storage are further exacerbated. Another method is to compress gaseous hydrogen to high pressure for transport in tube trailers, which are limited by regulations to 250 bar, but exemptions allow for higher pressures. Recent advances in composite storage vessels have increased carrying capacity. The GKL has also derived a newer Hydrogen injection system for efficient use of the fuel gas used as illustrated in section 3.4.

4.5. Other Naval Challenges

The above sections have discussed, the important challenges that are common to all the domains, However, when one thinks of marine environment one has to factor in many other challenges as enumerated, which will be factored in when one moves from the Pilot Plant to Industrial Scale deployment.

(a) Marine corrosion
(b) Shock
(c) Vibration
(d) Noise
(e) EMI/EMC
(f) Ship motions
(g) Redundancy
(h) Reliability.

Multiple parameters of these factors have been significantly improved by the newer gas injection methodology as derived by the GKL scientists, mentioned in section 3.4; however, further improvements are indispensable to increase the engine agility and operational robustness.

5. Way Ahead and Conclusions

As part of the way ahead strategy, the authors and the respective GKL team feel that they have achieved Technology Readiness Level of 5, and are now planning to build a Pilot Plant that will qualify them to move into producing Green Hydrogen at the industrial scale.

In conclusion, the efforts in sustainable energy production, especially solar and green hydrogen development, represent a significant step forward in addressing the pressing global issues of environmental degradation and energy in the management of sustainability. By integrating cutting-edge quantum mechanics with other engineering techniques, the authors have overcome challenges in various aspects related to safety concerns, storage limitations and metal fragility issues to produce energy-efficient a durable and environmentally friendly technology. The research efforts have yielded promising results, as evidenced from the successful lab-scale demonstrations and real-world applications on various automotive and river platforms.

By integrating solar green hydrogen technology into the maritime industry, the authors want to provide a relatively more efficient system for the running of the naval facilities, emphasizing sustainability and reducing C-emissions. The successfully proven technologies in national and international forums highlight the potential for transformation across sectors, promoting economic growth and environmental stewardship. In essence, the journey exemplifies the power of innovation, collaboration and a strong commitment to meet complex global challenges. As the authors continue to refine and expand the technology infrastructure, their unwavering commitment is destined to build a sustainable and resilient future.

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Appendix-A

This technology has received numerous praises, with one of the most significant recognitions from HPCL. The technological innovations garnered significant acclaim during these events, as the authors unveiled avant-garde green mobility solutions to a discerning audience. Some of the technology highlights are as follows:

National Highlights

- https://ddnews.gov.in/sci-tech/quantum-technology-promises-green-hydrogen-revolution
- https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1966488
- https://timesofindia.indiatimes.com/city/varanasi/experts-discuss-green-h2-fuels-production-utilisation/articleshow/104358063.cms
- https://government.economictimes.indiatimes.com/news/technology/cutting-edge-quantum-tech-backed-green-hydrogen-production-unveiled-to-power-green-future/104336121
- https://sputniknews.in/20231011/india-unveils-cutting-edge-quantum-technology-to-boost-usage-of-green-hydrogen-4737808.html
- https://newsstation.media/latest-news/cutting-edge-quantum-technology-unveiled-for-green- hydrogen-production-paving-the-way-for-a-sustainable-future/
- https://mysuruinfrahub.com/quantum-backed-technology-for-green-hydrogen-production/

International Highlights

- https://www.chronicleindia.in/current-affairs/9805-quantum-technology-promises-a-revolution-in-green-hydrogen-production
- https://opengovasia.com/indias-quantum-powered-green-hydrogen/
- https://carbon-pulse.com/228388/
- https://bwsustainabilityworld.com/bhu-develops-tech-that-can-boost-green-hydrogen-production/

Appendix-B

YouTube Links for the showcasing of the Green H_2 production and H_2-Mobility technologies.

Particulars	Link
Lab-Scale Green H_2 Production Demonstration	https://youtu.be/uIKdd_5Uzfw
Green H_2 Fueled WagonR (BS6 engine) in the Campus of B.H.U.	https://youtu.be/y59XDwvWWZw
Green H_2 Fueled Boat (BS4 engine) in the Holy River Ganges	https://youtu.be/-jLBpJ3GOHk
Green H_2 fueled Diesel Generator	https://youtu.be/s6aamtAgGXg
Green H_2-Powered Maruti Zen (BS4 engine) car	https://youtu.be/WQJsCqH-7_4
Green H_2 Fueled Bajaj CT100 (BS4 engine)	https://youtu.be/6sjd101fheE
Green H_2 Fueled Bajaj Pulsar 160cc (BS6 engine)	https://youtu.be/Hvqr-pcKh48
Technology Demonstration & Recognition Snapshots	https://tinyurl.com/ysf95nbj
Some Important Technological Details	https://tinyurl.com/meu2xz3w

Driving the Hydrogen Fuelled Boat in the River Ganges

https://www.youtube.com/watch?v=-jLBpJ3GOHk