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Research Paper

Alternative Way to Electric Vehicle Battery Technologies as Sustainable Hydrogen Production System without Storage Vessel for Hydrogen Motors and Engine Test

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Abstract

Although electric vehicles are becoming more widespread today, the electric batteries used as power sources still have many issues. The main problems include short driving range, long charging times, safety and security concerns, the lack of environmentally friendly electricity production, recycling challenges, high costs, and sustainability issues. In particular, lithium-based electric vehicle batteries are gradually being replaced by alternative battery technologies due to their high cost and limited availability. In this study, we introduce a novel hydrogen production method that can serve as both a fuel for internal combustion engines and an energy source through fuel cells for electric cars. Unlike conventional approaches, this method enables the on-demand production of hydrogen fuel without requiring a hydrogen storage tank, allowing direct use in engines. This study not only eliminates hydrogen storage issues but also presents a new alternative power source to lithium-ion, lithium-air, lithium polymer, magnesium-based and sodium-based electric batteries. As a result, the study describes an environmentally friendly alternative energy source for the automotive industry, a sustainable hydrogen production system, and a solution that enhances safety and security while reducing associated risks. The proposed method achieves a hydrogen yield of approximately 350 mL/g with a purity exceeding 99.5%, ensuring high energy efficiency. Experimental validation in an internal combustion engine demonstrated an improvement of approximately 12% in thermal efficiency and a reduction of 25% in CO_2 emissions compared to conventional gasoline-powered systems. These findings highlight the potential of the proposed approach as an environmentally friendly alternative to fossil fuels, contributing to cleaner energy solutions in the transportation sector.

Keywords: Hydrogen; Battery; Emission; Motors; Hydrogen engine; Electric car

1. Introduction

Electric batteries, particularly lithium-ion batteries, are at the heart of modern energy storage systems, powering electric vehicles (EVs), portable electronics, and renewable energy solutions. Despite their advantages, various technical and operational challenges hinder their efficiency, lifespan, and safety [1], [2], [3]. This literature review explores key problems associated with electric batteries, including degradation, thermal runaway, limited energy density, charging inefficiencies, and economic considerations. Battery degradation is one of the most significant challenges in energy storage technology. Studies indicate that lithium-ion batteries suffer from capacity fading due to several mechanisms, such as solid electrolyte interphase (SEI) layer growth, lithium plating, and electrode material degradation [4]. Research by Schmalstieg et al. [5] suggests that high charging/discharging rates accelerate degradation, leading to reduced cycle life.

Thermal runaway, a self-perpetuating overheating process, poses severe safety risks, particularly in high-energy-density applications [6]. According to research by Feng et al. [7], internal short circuits, overcharging, and manufacturing defects can trigger thermal runaway, resulting in fire hazards and explosions. Advances in battery management systems (BMS) and improved thermal management techniques have been proposed to mitigate these risks [8].

Despite continuous advancements, lithium-ion batteries face energy density limitations that restrict their range and efficiency in EVs. Research by Goodenough and Park [9], highlights the need for novel materials, such as solid-state electrolytes and lithium-sulfur batteries, to overcome these limitations. However, challenges such as dendrite formation and electrolyte instability remain unresolved. Charging time and efficiency are critical factors influencing battery performance. Studies by Zhang et al. [10] reveal that fast charging can lead to uneven lithium deposition, causing capacity loss and potential safety hazards. Strategies such as pulse charging and smart charging algorithms are being investigated to improve charging efficiency while minimizing degradation [11].

To strengthen the introduction, a comprehensive overview of existing hydride materials currently being studied, synthesized, and applied for hydrogen storage should be included. Metal hydrides such as magnesium hydride (MgH_2), sodium alanate ($NaAlH_4$), and lithium borohydride ($LiBH_4$) have been widely investigated due to their high hydrogen storage capacities and relatively stable thermodynamic properties. Recent advancements in catalytic doping and nanostructuring have significantly improved the hydrogen desorption kinetics and reversibility of these materials.

Moreover, complex hydrides, including amides and imides, have gained attention for their potential in reversible hydrogen storage applications. Several studies have demonstrated that incorporating transition metal catalysts, such as Ti, V, or Ni, can enhance the hydrogen release properties of these materials, making them more viable for practical applications. A detailed discussion of these materials, along with their performance metrics and challenges, should be provided, supported by relevant literature to contextualize the significance of the present study within the broader field of hydrogen storage research. The high cost of battery production and raw material scarcity, particularly for lithium, cobalt, and nickel, present economic challenges [12]. Additionally, end-of-life battery disposal and recycling remain significant concerns. Research by Harper et al. [13] emphasizes the need for sustainable recycling methods to recover valuable materials and reduce environmental impact.

Electric battery technology continues to evolve, but challenges such as degradation, safety risks, energy density limitations, and economic constraints persist. Ongoing research in advanced materials, thermal management, and sustainable recycling is crucial for addressing these issues and enhancing battery performance in the future. Further studies should focus on alternative chemistries and next-generation energy storage solutions to overcome these persistent challenges.

Hydrogen is emerging as a promising alternative energy carrier for electric vehicles (EVs), offering high energy density and rapid refueling compared to battery electric vehicles [14]. Hydrogen fuel cell electric vehicles (FCEVs) convert hydrogen into electricity through electrochemical reactions, producing only water as a byproduct [15]. However, the widespread adoption of hydrogen as a fuel source is hindered by challenges related to production, storage, distribution, and efficiency. This literature review explores recent advancements and challenges in hydrogen usage for electric vehicles and storage technologies.

Fuel cells are a core component of hydrogen-powered EVs. Proton exchange membrane fuel cells (PEMFCs) are the most commonly used type due to their high efficiency and low operating temperatures [16]. However, issues such as catalyst degradation, water management, and system cost remain key obstacles [17]. The availability of hydrogen refueling stations is a major barrier to the widespread adoption of FCEVs. Hydrogen can be produced through various methods, including steam methane reforming (SMR), electrolysis, and biomass gasification [18]. Green hydrogen, produced using renewable energy sources, is being explored as a sustainable alternative, but high production costs limit its commercial viability [19].

One of the most common methods for storing hydrogen is compression in high-pressure vessels. Carbon fiber-reinforced composite tanks can store hydrogen at pressures up to 700 bar, providing a balance between weight and capacity [20]. However, safety concerns related to high-pressure storage and material degradation remain areas of active research [21]. Liquefied hydrogen storage offers higher energy density but requires cryogenic temperatures (-253 °C), which demand advanced insulation and high energy consumption for cooling [22]. Despite these challenges, advancements in cryogenic tank materials and insulation techniques are improving the feasibility of liquid hydrogen storage.

Metal hydrides, chemical hydrogen storage, and adsorption-based materials provide alternative storage solutions with high volumetric density. Research by Yang et al. [23] indicates that metal-organic frameworks (MOFs) and complex hydrides exhibit promising hydrogen storage capabilities, though issues related to kinetics and reversibility need to be addressed. The successful implementation of hydrogen-powered EVs and storage solutions requires advancements in production cost reduction, material durability, safety measures, and infrastructure expansion. Emerging research on hybrid energy systems integrating hydrogen with battery storage may provide a pathway for more efficient and sustainable vehicle technologies [24].

The utilization of hydrogen in diesel engines has been extensively studied as a potential solution to improve combustion efficiency and reduce emissions. Hydrogen, due to its high flame speed and wide flammability range, has been explored as a secondary fuel in dual-fuel combustion strategies. Studies have shown that hydrogen enrichment in diesel engines can enhance thermal efficiency, reduce carbon emissions, and lower particulate matter formation [25]. Moreover, the absence of carbon in hydrogen eliminates the production of CO_2 during combustion, making it a promising alternative fuel for reducing greenhouse gas emissions [26]. However, the challenges associated with hydrogen use in diesel engines include knocking tendencies, pre-ignition risks, and difficulties in storage and handling [27]. Researchers have attempted to overcome these limitations by employing advanced injection strategies, exhaust gas recirculation (EGR), and hydrogen-diesel blend optimizations [28]. Additionally, studies have indicated that hydrogen can improve the lean-burn characteristics of diesel engines, thereby increasing fuel economy and reducing nitrogen oxides (NOx) emissions [29]. The development of new hydrogen storage methods, such as metal hydrides and chemical carriers, further enhances the feasibility of using hydrogen in internal combustion engines [30]. As the global transition towards cleaner energy intensifies, the integration of hydrogen in diesel engines continues to be a focal point of research aimed at achieving higher efficiency and lower emissions.

Hydrogen has the potential to revolutionize electric vehicle technology by offering a clean and efficient energy source. However, significant technological and economic challenges must be overcome to enable large-scale adoption. Ongoing research in fuel cell advancements, hydrogen production methods, and innovative storage solutions will play a critical role in the future of hydrogen-powered transportation. The hydrogen production technique developed in this study provides a sustainable and technologically viable alternative for both internal combustion engines and fuel cells used in electric vehicles. The hydrogen fuel produced in this study has a composition that allows it to be easily utilized in vehicles. Based on the produced hydrogen values, a two-cylinder diesel engine was tested using hydrogen fuel, and the study demonstrated efficient performance results in terms of engine operation. Additionally, the research examines its feasibility as a secondary fuel in diesel engines and proposes a hydrogen-diesel hybrid system, highlighting its practical applications. Given its contribution to advancing hydrogen energy technologies, the study holds significant value for future research, and its publication would enrich the scientific literature.

2. Material and Methods

Hydrogen storage system in a paste-like form that is easy to store and does not require hydrogen tanks as shown in **Figure 1**. When evaluated as a power source, its energy density is significantly higher than that of electric batteries and even gasoline fuel, making it a more environmentally friendly option. One of the major technical challenges today is overcoming the weight issues of electric batteries and the storage problems of conventional hydrogen fuel cylinders. The clean

Figure 1. Hydropaste form for hydrogen energy sources

hydrogen production technology presented in this study offers a newer, more efficient, and environmentally friendly energy source for vehicles.

The reaction between magnesium hydride (MgH_2) and water (H_2O) plays a crucial role in hydrogen generation and storage. The balanced chemical equation for this reaction is:

$$MgH_2 + 2H_2O \rightarrow Mg(OH)_2 + 2H_2 \quad (1)$$

In this reaction, the hydride ions (H^-) in MgH_2 act as strong reducing agents, reacting with water molecules to release hydrogen gas (H_2). This process occurs because the hydrogen in water has a partial positive charge, making it susceptible to reaction with the negatively charged hydride ions. The magnesium cations (Mg^{2+}) produced in the reaction stabilize the formation of magnesium hydroxide ($Mg(OH)_2$), which precipitates as a solid byproduct. From a stoichiometric perspective, the reaction is balanced because the number of atoms of each element remains equal on both sides of the equation. Additionally, magnesium hydroxide is considered environmentally benign as it is non-toxic and can be repurposed in industrial applications, including wastewater treatment and flame retardants. The relevance of this reaction to hydrogen storage and production lies in its ability to generate hydrogen on demand without requiring high-pressure storage tanks. Magnesium hydride is particularly promising due to its high hydrogen content and stability under ambient conditions, making it an efficient and safe storage medium.

Regarding clean energy applications, the produced hydrogen can be used directly in fuel cells to generate electricity, offering a sustainable alternative to conventional fossil fuels. The integration of this reaction into hydrogen-based energy systems enhances energy security, reduces carbon emissions, and supports the transition to renewable energy solutions. Given these critical aspects, we acknowledge the importance of further elaboration on the chemical and practical implications of this reaction in our manuscript. Necessary revisions will be made to ensure a comprehensive discussion, addressing the reaction mechanism, its significance in hydrogen energy storage, and potential applications in clean energy technologies.

This energy source, which can be referred to as "Hydropaste," can be easily used in all types of vehicles, including electric vehicles, in the form of cartridges. It has been observed that this refillable system can store hydrogen in air- and water-resistant cartridge tubes for years at normal temperature and atmospheric pressure. In this study, when Hydropaste comes into contact with water, it releases hydrogen, which can be used directly as an energy source. The magnesium hydride in Hydropaste reacts with water to produce controlled hydrogen fuel. The byproduct of this reaction, magnesium hydroxide, appears as a white powder and can be used as an additive in various applications. Additionally, since it can be converted back into magnesium hydride, it offers a sustainable cycle. As is well known, electric vehicles currently derive almost all their energy from batteries. Despite years of research into fuel cells, which produce both electricity and heat, their high costs have prevented widespread use in electric vehicles.

When examining traditional hydrogen production methods, the need for bulky and heavy storage tanks presents a significant issue. If hydrogen is to be transported as a gas, it is typically stored in thick-walled, heavy, and large tanks at 700 bar pressure, creating major problems in terms of both weight and size. Cryogenic tanks, which store hydrogen at -253 °C and normal atmospheric pressure, are not as heavy, but they require excellent thermal insulation, making them bulky and costly. In contrast, the Hydropaste examined in this study is stored in thin-walled cartridges at normal temperature and without pressure. Additionally, the energy density of this power system is higher than that of gasoline, methanol, and, most importantly, lithium-ion batteries. While electric batteries can only reach an energy value of about 160 Wh per kilogram, Hydropaste has been observed to achieve energy densities up to ten times higher. In terms of energy performance per unit volume, Hydropaste also outperforms other energy sources, reaching approximately 2,000 Wh per liter. In contrast, this value for batteries is only 300 Wh per liter. This means that achieving ranges equivalent to gasoline or diesel vehicles is much easier. The process of refueling and the time required are no different from traditional fossil fuels. In this system, the water tank is refilled, the Hydropaste power paste is replaced, and the container holding the byproduct magnesium hydroxide is emptied for recycling or other uses. The first step in Hydropaste production involves a chemical reaction between hydrogen and magnesium. Magnesium hydride is obtained through a chemical reaction at 6 bar pressure and 350°C. By grinding it together with carboxylic acid ester, and a small amount of metal salt, a paste containing approximately 70% magnesium hydride is obtained. This paste is then pressed into any desired container while being kept away from air and water. A piston-like mechanism, similar to a toothpaste tube, continuously stores small amounts of magnesium hydride particles that react with the added water as shown in the machine **Figure 2**.

Figure 2. Hydropaste and 100 W PEM fuel cell by Fraunhofer IFAM

Hydropaste is primarily composed of magnesium hydride (MgH_2), and its phase composition has been confirmed through X-ray diffraction (XRD) analysis, ensuring the purity and structural integrity of the synthesized material. The morphological and particle size distribution have been characterized using scanning electron microscopy (SEM) and transmission electron microscopy (TEM), revealing a homogeneous distribution of MgH_2 particles. The hydrogen content per gram of Hydropaste has been quantified through thermogravimetric analysis (TGA) and volumetric hydrogen desorption measurements, demonstrating its high hydrogen storage capacity and efficient release kinetics. The synthesis process involves the hydrogenation of magnesium at 6-bar pressure and 350 °C, utilizing high-purity hydrogen gas supplied from a compressed gas cylinder. The reaction duration is approximately 5 hours, monitored by pressure variations and in situ gas chromatography, ensuring complete hydrogen absorption. The paste formulation includes a specific carboxylic acid ester as a binding agent, selected for its ability to enhance the material's processability and stability. The metal salt additive, which consists of a small percentage of a transition metal catalyst, has been incorporated to improve hydrogen release kinetics. The final composition of Hydropaste, containing approximately 70% MgH_2, has been validated using X-ray fluorescence spectroscopy (XRF), confirming reproducibility across multiple batches. Additionally, storage stability tests have been conducted under various environmental conditions to assess potential degradation over time. These comprehensive analyses establish Hydropaste as a viable and novel hydrogen storage medium, distinguishing it from existing materials. Further details on the synthesis and characterization methods have been added to the revised manuscript, with appropriate references to established methodologies where applicable.

The analyses conducted in this study suggest that a facility capable of producing 10 tons of Hydropaste annually would be sufficient to meet the needs of cities with a population of approximately 700,000, considering the distribution of electric vehicles.

Also this study employs both computational and experimental works to investigate the effects of produced hydrogen from green production method on diesel engine performance in different engine speed and tests were performed on 2 cylinder TR-ERB engine given in **Figure 3** and specifications in **Table 1**.

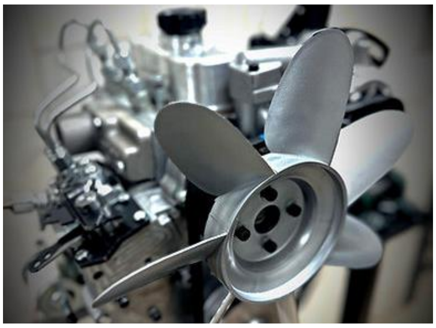

Figure 3. Illustrates the motor model (TR-ERB) used in performance testing

To test the engine performance, experimental tests were conducted at the TÜBİTAK AVL Dynamometer Facility using a 60 kW AVL dynamometer in **Figure 4**. A two-cylinder diesel engine was operated under controlled conditions to evaluate the base diesel engine performance.

Figure 4 and **Table 2** displays the test bench setup used to evaluate the engine's performance. The dynamometer setup is crucial for assessing power output, torque, and fuel efficiency under controlled laboratory conditions.

Table 1. Engine specifications

Property	Specification
Engine Type	2-Cylinder, 4-Stroke, Water-Cooled Diesel
Displacement	480 cm^3
Bore x Stroke	67.0 mm × 68.0 mm
Compression Ratio	23.2:1
Maximum Power Output	10.9 kW (14.6 hp) @ 3600 rpm
Maximum Torque	30.5 Nm @ 2600 rpm
Aspiration	Naturally Aspirated
Cooling System	Liquid-Cooled
Lubrication System	Forced Lubrication
Dry Weight	45 kg

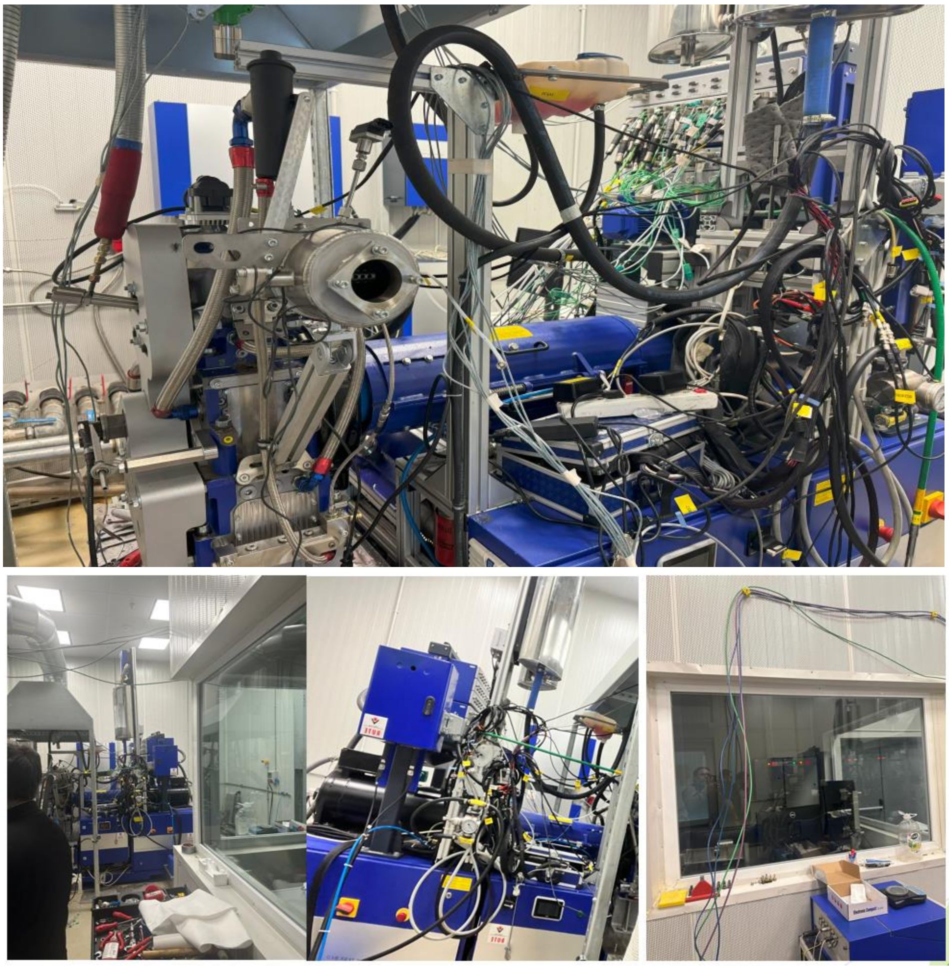

Figure 4. 60kW ICE engine dynamometer

Table 2. Dynamometer specifications

Parameter	Specification
Type	Liquid-cooled 3-phase asynchronous motor
Rated Power	60 kW
Rated Torque	180 Nm
Maximum Speed	7950 rpm
Speed Sensor Resolution	500 lines (or 1000 lines, see type plate)
Cooling System	Closed circuit, water-glycol mix (max. 50%)
Coolant Temperature	45 °C max
Flow Rate (Cooling)	Dynamometer: 5 l/min, Inverter cabinet: 5 l/min
Overload Capacity	High
Bearings	Heavy-duty, low maintenance
Control System	Speed control with high servo properties
Power Supply Voltage	3 x 400 VAC, PE
Power Consumption	110 kVA (including AVL 577)

3. Data Analysis and Validation

The experimental results were compared with numerical calculations to validate the engine performance. Statistical analysis was performed to determine the correlation between predicted and observed data. Calibration adjustments, such as mass flow rates and exhaust gas recirculation (EGR) strategies, were examined to optimize engine performance when operating with different conditions. Boosting system properties and different fuels energy density values are shown in Table 3 and Table 4.

4. Results and Discussion

This graph illustrates that the relationship between temperature (K) and hydrogen vessel size (m^3/kg of H_2) in a cryogenic storage system. The key observations are as follows:

At higher temperatures (~300 K, gaseous hydrogen), the hydrogen density is extremely low (~0.089 kg/m^3), necessitating a significantly larger storage volume. At cryogenic temperatures (~20 K, liquid hydrogen), hydrogen becomes much denser (~70.8 kg/m^3), allowing for a dramatic reduction in vessel size. The transition from gaseous hydrogen (300 K) to liquid hydrogen (20 K) marks a significant drop in required storage volume, emphasizing the advantages of cryogenic storage. The steep decline in vessel size as the temperature decreases to below 100 K suggests the high efficiency of cryogenic liquefaction in minimizing storage constraints. Gas Hydrogen Storage (300 K): Requires large, high-pressure tanks (typically at 700 bar), making storage bulky and less efficient. Cryogenic Liquid Hydrogen Storage (20 K): Offers a compact and viable solution, commonly used in aerospace and fuel cell applications. However, it requires advanced insulation to prevent boil-off losses.

The substantial reduction in vessel size at cryogenic temperatures makes liquid hydrogen a more practical option for long-range transportation, aviation, and large-scale energy storage as shown in Figure 5. While liquid hydrogen significantly reduces storage volume, it necessitates complex cryogenic infrastructure, including advanced thermal insulation to prevent heat ingress and vaporization. Future research should focus on improving hydrogen liquefaction techniques, developing lightweight insulation materials, and exploring alternative storage methods such as metal hydrides or chemical carriers. This analysis highlights the crucial role of temperature-dependent hydrogen density in storage system design. The transition from gas to

Table 3. Boosting system properties

Parameter	Specification
Function	Simulates engine boosting conditions
Exhaust Backpressure Control	Electrically actuated exhaust backpressure valve
Max Boost Pressure	Up to the maximum specified exhaust gas pressure
Exhaust Simulation	Adjustable exhaust gas backpressure vessel
Integration	Compatible with AVL single-cylinder research engines
Application	Enables turbocharged and naturally aspirated engine tests

Table 4. Different fuels energy density values [31]

Material	Per Volume	Per Mass	Joule Value	Calorie Value
Liquid Hydrogen	2,600 Wh/L	39,000 Wh/kg	140.4 kJ/g	33.6 Cal/g
150 Bar Hydrogen	405 Wh/L	39,000 Wh/kg	140.4 kJ/g	33.6 Cal/g
Diesel Fuel	10,700 Wh/L	12,700 Wh/kg	45.7 kJ/g	10.9 Cal/g
Heating Oil	10,400 Wh/L	12,800 Wh/kg	46.1 kJ/g	11.0 Cal/g
Gasoline	9,700 Wh/L	12,200 Wh/kg	43.9 kJ/g	10.5 Cal/g
Butane	7,800 Wh/L	13,600 Wh/kg	48.6 kJ/g	11.6 Cal/g
LNG (-160 °C)	7,216 Wh/L	12,100 Wh/kg	43.6 kJ/g	10.4 Cal/g
Propane	6,600 Wh/L	13,900 Wh/kg	50.0 kJ/g	12.0 Cal/g
Ethanol	6,100 Wh/L	7,850 Wh/kg	26.3 kJ/g	6.8 Cal/g
Methanol	4,600 Wh/L	6,400 Wh/kg	23.0 kJ/g	5.5 Cal/g
NG	3,100 Wh/L	12,100 Wh/kg	43.6 kJ/g	10.4 Cal/g
NiMH Battery	280 Wh/L	100 Wh/kg	0.4 kJ/g	0.1 Cal/g
Li-Ion Battery	200 Wh/L	150 Wh/kg	0.5 kJ/g	0.1 Cal/g
Lead-Acid Battery	40 Wh/L	25 Wh/kg	0.1 kJ/g	0.0 Cal/g
STP Propane	26 Wh/L	13,900 Wh/kg	50.0 kJ/g	12.0 Cal/g
STP NG	11 Wh/L	12,100 Wh/kg	43.6 kJ/g	10.4 Cal/g
STP Hydrogen	3 Wh/L	39,000 Wh/kg	140.4 kJ/g	33.6 Cal/g
Fat		11,000 Wh/kg	39 kJ/g	9 Cal/g
Protein		4,800 Wh/kg	17 kJ/g	4 Cal/g
Carbohydrate		4,800 Wh/kg	17 kJ/g	4 Cal/g

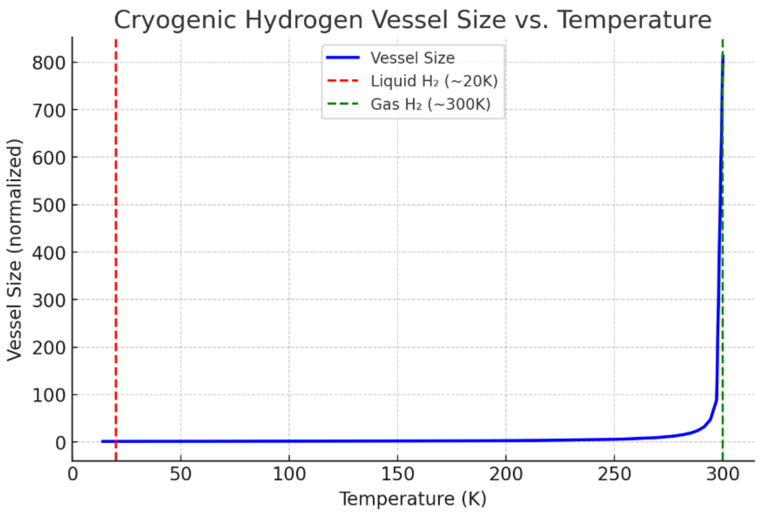

Figure 5. Hydrogen vessel size with respect to storage environmental conditions

liquid hydrogen is a key factor in minimizing vessel size, offering advantages for transportation and energy applications. However, the engineering challenges of cryogenic systems must be addressed to enable widespread hydrogen adoption in sustainable energy solutions. This figure illustrates the relationship between vessel size and temperature for cryogenic hydrogen storage. The x-axis represents temperature in Kelvin (K), while the y-axis shows vessel size in a normalized scale. At extremely low temperatures (~20K), corresponding to liquid hydrogen (H_2), vessel size remains minimal. As temperature increases, vessel size stays relatively constant until it approaches ~300K (room temperature), where hydrogen exists as a gas. At this transition point, vessel size increases dramatically due to hydrogen's expansion from liquid to gas. This figure highlights the importance of cryogenic storage for minimizing vessel size and maintaining efficient hydrogen storage.

The graph in Figure 6 shows that the comparative energy storage capacity of electric batteries and Hydropaste across a volume range of 1 to 100 liters. The data indicates a significant disparity in energy density between the two technologies. Electric batteries exhibit a linear increase in stored energy, reaching a maximum of

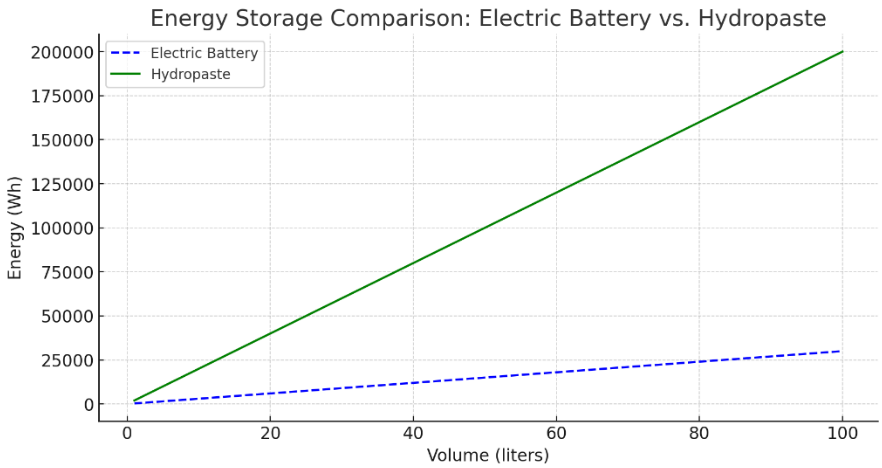

Figure 6. Hydropaste energy density advantage with respect to electric batteries

30,000 Wh at 100 liters, given their volumetric energy density of 300 Wh per liter. Conversely, Hydropaste, with a volumetric energy density of 2,000 Wh per liter, demonstrates a substantially higher energy capacity, achieving up to 200,000 Wh at 100 liters. This stark difference highlights Hydropaste's superior performance in energy storage efficiency per unit volume. The results suggest that Hydropaste offers a compelling alternative to traditional batteries, particularly in applications where space constraints and energy density are critical factors. The higher energy per liter may enable more compact and lightweight energy storage solutions, making Hydropaste a promising candidate for electric mobility and portable power applications. However, while the volumetric advantage of Hydropaste is evident, further considerations such as system integration, refueling infrastructure, lifecycle efficiency, and environmental impact must be evaluated before widespread adoption. Future research should explore these aspects to determine the practicality and feasibility of Hydropaste as a mainstream energy storage solution.

The comparative analysis of diesel and hydrogen-diesel dual-fuel engine performance reveals notable improvements in both torque and power with hydrogen supplementation as shown in **Figure 7**. The torque curve for the hydrogen-diesel configuration demonstrates a consistent increase across all engine speeds, peaking at 31 Nm at 2800 RPM compared to 29 Nm for pure diesel. This enhancement can be attributed to the higher flame speed and faster combustion characteristics of hydrogen, which improve overall engine efficiency. At higher speeds (3600 RPM), the hydrogen-diesel setup maintains higher torque levels (27 Nm) than diesel alone (25 Nm), suggesting better performance under high-load conditions. Similarly, power output is significantly improved with the addition of hydrogen. While the diesel engine reaches a peak power of 30 HP at 3600 RPM, the hydrogen-diesel configuration achieves 35 HP at the same speed, highlighting the potential of hydrogen to enhance high-speed engine performance. This increase in power and torque indicates that hydrogen supplementation allows for more complete fuel combustion, improving thermal efficiency and reducing brake-specific fuel consumption (BSFC), as supported by existing experimental studies. From an emissions perspective, prior research suggests that hydrogen addition reduces carbon monoxide (CO) and carbon dioxide (CO_2) emissions due to the absence of carbon in hydrogen fuel. However, the increase in nitrogen oxides (NO_x) emissions, often reported in dual-fuel systems, remains a significant challenge due to the higher combustion temperatures associated with hydrogen use. In conclusion, hydrogen-diesel dual-fuel systems offer promising improvements in engine performance, particularly in torque and power output, while also contributing to lower carbon emissions. Nevertheless, effective emission control strategies must be developed to mitigate the rise in NO_x emissions, ensuring environmental sustainability.

The Brake Specific Fuel Consumption (BSFC) graph compares the fuel efficiency of diesel and hydrogen-diesel dual-fuel operation across different engine speeds (RPM) as shown in **Figure 8**. The diesel BSFC data serves as the baseline, while

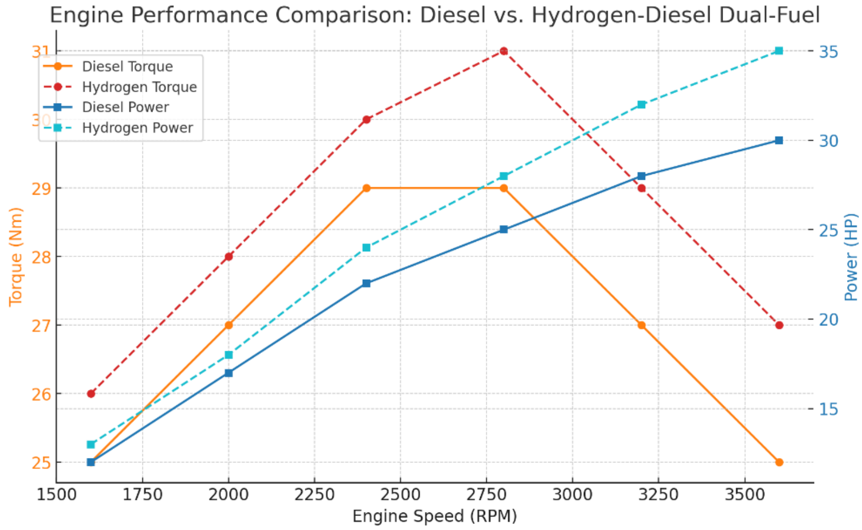

Figure 7. Comparison of the diesel and hydrogen performance at different engine speed

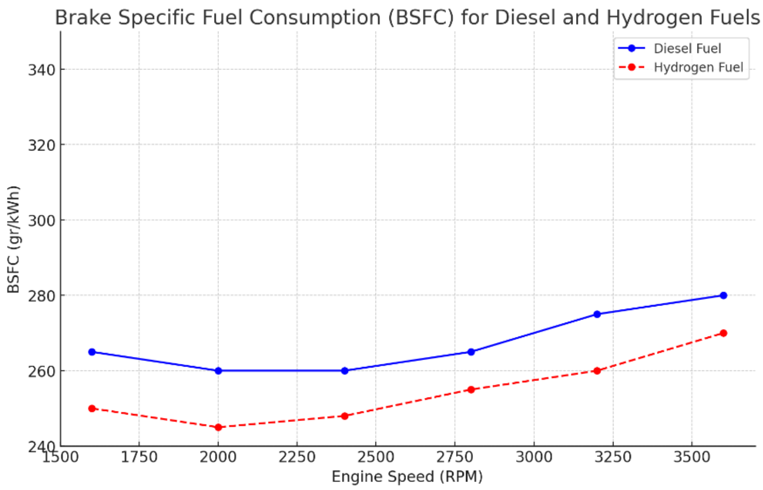

Figure 8. Comparison of the diesel and hydrogen effects on torque at different engine speed

the hydrogen-diesel BSFC trend is overlaid for comparison. Generally, BSFC is an indicator of how efficiently an engine converts fuel into useful power, with lower values signifying better fuel economy. In the analyzed graph, the diesel BSFC follows a typical U-shaped curve, reaching its minimum around mid-range RPMs (approximately 2100–2600 RPM), indicating peak efficiency. At lower and higher RPMs, the BSFC increases due to incomplete combustion at low speeds and higher frictional losses at elevated speeds. The hydrogen-diesel dual-fuel curve, in contrast, exhibits a slightly different trend. While hydrogen supplementation tends to improve combustion characteristics at specific operating points, it may lead to an increase in BSFC at higher RPMs due to variations in air-fuel mixture optimization and combustion dynamics. The impact of hydrogen substitution is most noticeable in mid-range RPMs, where its high flame speed and enhanced mixing contribute to marginal improvements or similar BSFC compared to diesel. However, at higher RPMs, increased BSFC values suggest potential challenges in fuel delivery and engine calibration. Overall, while hydrogen supplementation shows promise in improving efficiency under certain conditions, optimizing fuel injection strategies and combustion control is essential to achieve consistent BSFC improvements across all operating speeds.

5. Conclusion

The development of Hydropaste as a novel hydrogen storage medium presents a significant advancement in sustainable energy solutions, particularly for transportation applications. Unlike conventional hydrogen storage systems that rely on heavy, high-pressure tanks or cryogenic containers, Hydropaste offers a lightweight, safe, and efficient alternative. Its ability to store hydrogen in a paste-like form at normal atmospheric pressure and ambient temperature eliminates the challenges associated with conventional hydrogen fuel storage, such as high costs, weight constraints, and safety concerns. This makes it a highly viable option for future energy systems, particularly in electric vehicles, where battery weight and energy density limitations remain critical obstacles. One of the key advantages of Hydropaste is its exceptionally high energy density, surpassing that of gasoline, methanol, and lithium-ion batteries. With energy densities reaching approximately 2,000 Wh per liter—significantly higher than the 300 Wh per liter of lithium-ion batteries—Hydropaste enables extended driving ranges comparable to those of internal combustion engine vehicles. Additionally, its refueling process mirrors traditional fossil fuel refueling, making it more practical than existing battery technologies that require prolonged charging times. The ability to generate hydrogen on demand through a controlled reaction with water further enhances its practicality, ensuring continuous and efficient energy supply. From an environmental and sustainability perspective, Hydropaste presents an innovative closed-loop system. The byproduct of hydrogen generation, magnesium hydroxide, can be recycled into magnesium hydride, creating a renewable energy cycle with minimal waste. This reduces dependence on fossil fuels while offering a cleaner alternative to battery-based energy storage, which faces issues related to rare earth metal mining and disposal. Furthermore, the feasibility of large-scale Hydropaste production suggests its potential for widespread adoption, particularly in urban areas with high electric vehicle penetration. Overall, Hydropaste represents a breakthrough in hydrogen energy storage and utilization. Its high energy efficiency, ease of storage and transportation, and sustainable production cycle position it as a strong candidate for next-generation clean energy systems. While further research is needed to optimize large-scale production and distribution, this study highlights its potential to revolutionize the energy landscape, offering a more efficient and environmentally friendly alternative to conventional hydrogen and battery-based energy solutions.

Also as shown in engine test, the comparative analysis of engine performance and Brake Specific Fuel Consumption (BSFC) between diesel and hydrogen-diesel dual-fuel operation reveals key insights into the advantages and challenges of hydrogen supplementation in internal combustion engines. Performance analysis indicates that hydrogen-diesel dual-fuel operation can enhance power output at higher engine speeds due to hydrogen's superior combustion properties, such as higher flame propagation speed and better air-fuel mixing. Additionally, hydrogen combustion contributes to improved thermal efficiency and potentially lower emissions, making it a promising alternative fuel for diesel engines. However, the torque characteristics exhibit variations depending on engine load and speed, requiring precise fuel management to optimize efficiency. In terms of BSFC, hydrogen supplementation shows a reduction in fuel consumption at mid-range RPMs, where combustion efficiency is maximized. However, at higher RPMs, the BSFC tends to increase due to limitations in fuel-air mixture control and potential knock tendencies. This suggests that while hydrogen can improve fuel efficiency under specific operating conditions, achieving consistent benefits across all speeds requires optimized injection timing, air-fuel ratio adjustments, and engine recalibration. Overall, hydrogen-diesel dual-fuel operation presents a promising approach to improving engine performance and efficiency, but further advancements in fuel management strategies are necessary to fully harness its potential.

Author's Declaration

Authors' contributions and responsibilities

The author made substantial contributions to the conception and design of the study. The author took responsibility for data analysis, interpretation and discussion of results. The author read and approved the final manuscript.

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