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COMPARATIVE ANALYSIS OF HYDROGEN PRODUCTION, ACCUMULATION, DISTRIBUTION, AND STORAGE SYSTEMS

Abstract. *The global energy demand in the world continues to grow and environmental pollution caused by fossil fuels becomes increasingly serious, the development and utilization of new energy sources has become a hot topic of global concern. The development and utilization of new energy sources is one such possible solution, which can provide clean, renewable energy and thus reduce the impact on the environment. Hydrogen, as a clean, productive, carbon-free secondary energy source, has the potential to be used as a fuel and essential substance for different fields such as heating, transportation, industry, and power generation. As the international community strives to achieve a shift toward a more eco-conscious and sustainable future, hydrogen has received extensive research and attention due to its abundant resources and environmentally friendly properties. The main objective of this study was to describe and comparatively analyze the efficient production, accumulation, distribution and storage of hydrogen. Today the production of hydrogen is centered on the creation or extraction of hydrogen from primary energy sources. The accumulation of hydrogen involves the preservation of surplus hydrogen for subsequent utilization. The distribution of hydrogen encompasses the conveyance and delivery of hydrogen. The storage systems for hydrogen pertain to the technologies and infrastructure employed to retain hydrogen for future deployment. In complex, these constituents establish a comprehensive hydrogen value chain that facilitates the generation, preservation, and distribution of hydrogen as a sustainable and environmentally friendly energy solution.*

Keywords: comparative analysis, hydrogen, production, accumulation, distribution, storage systems.

1. Introduction

As global energy demand continues to grow and environmental pollution caused by fossil fuels becomes increasingly serious, the development and utilization of new energy sources has become a hot topic of global concern. The importance of this issue lies in the need to find a solution that meets the energy needs while reducing the impact on the environment. The development and utilization of new energy sources is one such possible solution, which can provide clean, renewable energy and thus reduce the impact on the environment. Hydrogen, as a clean, productive, carbon-free secondary energy source, has the potential to be used as a fuel and essential substance for different fields such as heating, transportation, industry, and power generation [1]. Hydrogen production, hydrogen accumulation, hydrogen distribution, and storage systems are discrete constituents of the hydrogen value chain, each fulfilling a distinctive function in the creation, retention, and transportation of hydrogen [2–4].

2. Hydrogen Production

Hydrogen is a colorless, odorless, non-toxic gas, and people cannot detect its presence with the naked eye or sense of smell. There are various options for producing hydrogen, and hydrogen is labeled as different colors so people can know which way the hydrogen is produced and whether it is produced in a climate-friendly way. Hydrogen can be classified as black hydrogen, brown hydrogen, gray hydrogen, blue hydrogen, turquoise hydrogen, white hydrogen, orange hydrogen, green hydrogen, pink hydrogen and yellow hydrogen, as shown in Table 1 [5].

Black hydrogen is produced by steam reforming hard coal, and brown hydrogen is based on brown coal. The hydrogen production process produces large amounts of greenhouse gases (CO&CO_2) into the atmosphere, which is harmful to the climate and unsustainable.

Gray hydrogen is produced from natural gas through steam reforming [6]. During this process, exhaust CO_2 is released directly into the atmosphere. Gray hydrogen is currently the most produced hydrogen in the world. It is not considered climate neutral or sustainable due to the large amount of CO_2 it emits directly into the atmosphere.

Blue hydrogen is based on gray hydrogen, but the CO_2 generated during its production process does not directly enter the atmosphere and through the implementation of carbon capture, use and storage to reduce the emissions of CO_2 [7].

Turquoise hydrogen is produced through the pyrolysis of methane [8]. Its principle is to treat natural gas with high-temperature plasma in an oxygen-free container to separate carbon and hydrogen to obtain hydrogen.

White hydrogen refers to naturally occurring hydrogen [9]. This type of hydrogen occurs naturally as a free gas in the continental crust, deep in the ocean crust, in volcanoes, and elsewhere.

Orange hydrogen is hydrogen that occurs naturally in the Earth's crust, but it is not like the white hydrogen. It can be extracted through the process of hydraulic fracturing: Water is forced into the ground, causing the iron oxides in the rock to react, and the hydrogen released in the process is captured by the borehole [10].

Green hydrogen is primarily produced by splitting water using electricity generated from renewable energy sources such as solar or wind power, with no associated carbon emissions in the process. When used in fuel cells, the only byproduct of using green hydrogen is water [11].

Pink hydrogen is just like the green hydrogen, but it is produced through electrolysis powered by nuclear energy.

Yellow hydrogen refers to hydrogen produced by electrolysis using the grind electricity (a mixture of renewable energy and fossil fuels).

Table 1. Comparison of different sourced hydrogen

Hydrogen	**Technology**	**Source**	**Products**	**CO_2 emissions**
Black Hydrogen	Gasification	Black coal	H_2&CO_2	High
Brown Hydrogen	Gasification	Brown coal	H_2&CO_2	High
Gray Hydrogen	Reforming	Natural gas	H_2&CO_2	Medium
Blue Hydrogen	Reforming & CCUS	Natural gas	H_2&CO_2	Low
Turquoise Hydrogen	Pyrolysis	Natural gas	H_2&CO_2	Negligible
White Hydrogen	Borehole	Natural hydrogen	H_2	Negligible
Orange Hydrogen	Borehole	Iron oxides & water	H_2&Fe_2O_3	Negligible
Green Hydrogen	Electrolysis	Water	H_2&O_2	Negligible
Pink Hydrogen	Electrolysis	Water	H_2&O_2	Negligible
Yellow Hydrogen	Electrolysis	Water	H_2&O_2	Negligible

With the development of the water electrolysis, there are four typical water electrolysis technologies: (1) Alkaline water electrolysis; (2) AEM water electrolysis; (3) PEM water electrolysis and (4) Solid oxide water electrolysis. The working principles of four typical water electrolysis technologies are shown in Fig. 1 [5]. Comparison of 4 types of water electrolysis technology are shown in Table 2 [5, 11].

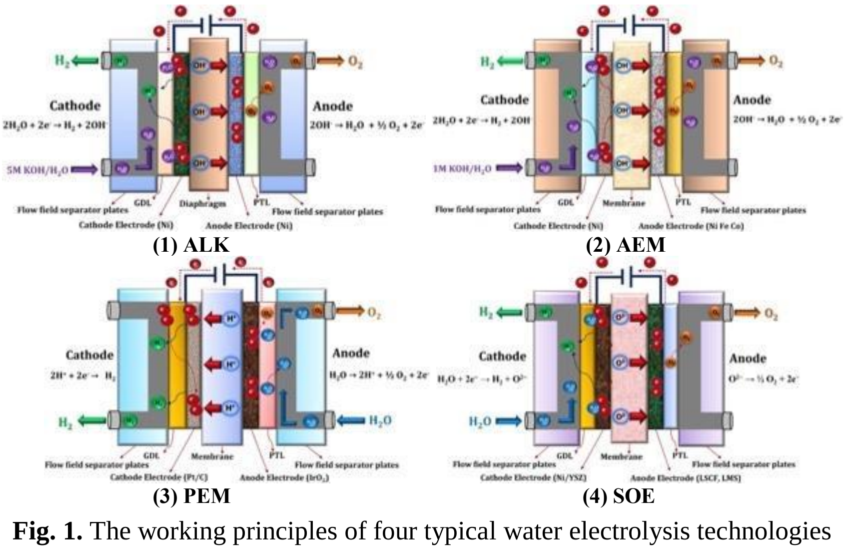

Fig. 1. The working principles of four typical water electrolysis technologies

Table 2. Comparison of 4 types of water electrolysis technology

	ALK	AEM	PEM	SOE
Electrolyte membrane	Asbestos membrane	Proton exchange membrane	Anion exchange membrane	Solid oxide
Current density/($A \cdot cm^{-2}$)	0.2~0.8	0.2~2	1~2	0.3~1
Efficiency/%	50~78	57~59	50~83	89 %(Laboratory)
Operation temperature /℃	70~90	40~60	50~80	700~850
Hydrogen production purity	≥ 99.8 %	≥ 99.9 %	≥ 99.9 %	≥ 99.9 %
Relative device volume	1	~1/3	/	/
Operational characteristics	Control pressure difference/dealkalization	Quick start stop, only water vapor	Quick start stop, only water vapor	Inconvenient start stop, only water vapor
Maintainability	Strong alkaline corrosion	Non corrosive media	Non corrosive media	/
Environmentally	Harmful asbestos membrane	Pollution-free	Pollution-free	/
Technology maturity	Full industrialization	Preliminary commercialization	Laboratory stage	Initial demonstration
Single machine scale /($N \cdot m^3 \cdot h^{-1}$)	≤ 1000	≤ 200	/	/

3. Hydrogen Accumulation

The phenomenon of hydrogen accumulation pertains to the process of preserving and withholding hydrogen gas for subsequent utilization. The process at hand pertains to the capture and retention of superfluous hydrogen that is engendered in times of elevated renewable energy production. Approaches to hydrogen accumulation comprise electrolysis, power-to-gas, subterranean storage, and biological processes. The chief objective of hydrogen accumulation is to stockpile superfluous renewable energy in the form of hydrogen to surmount the sporadic nature of renewable energy sources [12]. The stored hydrogen can be utilized subsequently to balance energy supply and demand, particularly during periods of low renewable energy generation or high energy demand.

Electrolysis, a prevalent technique, is frequently employed for the accumulation of hydrogen. By passing an electric current through the water, the process splits the water molecules into hydrogen and oxygen. There exist four frequently observed variations of electrolysis. For four different types of electrolyzed water (ALK, AEM, PEM and SOE), the electrolyte membranes used are asbestos membrane, proton exchange membrane, anion exchange membrane and solid oxide [13]. The process of electrolysis has the capability to harness superfluous renewable energy, such as solar or wind power, to fabricate hydrogen, thus facilitating effective energy storage.

The utilization of power-to-gas technology enables the transformation of excessive renewable electricity into either hydrogen or methane gas. The given process entails the utilization of electrolysis method on water molecules to generate hydrogen, which is subsequently amalgamated with carbon dioxide to bring forth synthetic methane through the process of methanation. This synthetic methane can be stored in existing natural gas infrastructure. Power-to-gas offers a flexible and scalable solution, allowing surplus renewable energy to be stored and distributed through existing gas networks.

Biological processes, such as microbial electrolysis and dark fermentation, present an innovative approach to hydrogen accumulation. The process of microbial electrolysis entails employing bacteria to generate hydrogen from organic waste or wastewater, whereas dark fermentation relies on anaerobic bacteria to produce hydrogen from organic matter. These processes provide an eco-friendly and sustainable way to accumulate hydrogen while simultaneously treating waste materials.

Several chemical reactions can be utilized to accumulate hydrogen. One method is steam reforming, in which high-temperature steam reacts with hydrocarbons to produce hydrogen. Another method, known as the water-gas shift reaction, reacts carbon monoxide with steam to produce hydrogen and carbon dioxide. Chemical reactions offer the advantage of utilizing various feedstocks and can be optimized for specific applications or available resources.

The accumulation of hydrogen presents a significant opportunity as an essential element of the shift towards energy systems that are both clean and sustainable. Through the utilization of diverse techniques such as electrolysis, bio-based mechanisms and chemical reactions, superfluous renewable energy can be proficiently retained and employed to generate hydrogen. As technology advancements continue and costs decline, hydrogen accumulation has the potential to transform energy storage systems, providing a reliable and flexible solution to balance energy supply and demand. By adopting the practice of hydrogen storage, we can unleash the complete capability of sustainable energy resources and facilitate the path towards a more environmentally-friendly and robust future.

4. Hydrogen Distribution

There are three common methods for hydrogen distribution: 1) Pipeline; 2) Tube trailers; 3) Tankers. Gaseous hydrogen can be distributed by pipeline or tube trailers, and liquid hydrogen can be distributed by tankers. The pipeline is the best choice for the situation of large amounts over long distances; The tube trailers is the best choice for the situation of small amounts and short distances; The tankers is the best choice for the situation of medium amounts and long distances, as shown in Fig. 2 [14].

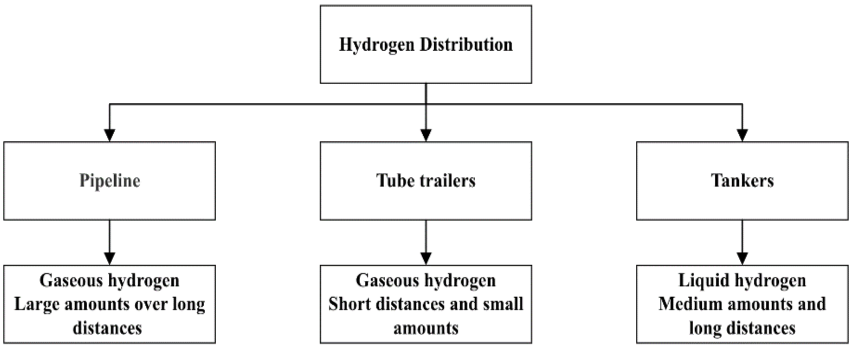

Fig. 2. Three common methods for hydrogen distribution

5. Hydrogen Storage Systems

Safe and efficient hydrogen storage is a challenging problem that involves many aspects of hydrogen as a fuel, such as distribution, delivery, safety, etc. There are multiple ways to store hydrogen, and there are two more advanced and typical methods, namely physical hydrogen storage and chemical hydrogen storage, as shown in Fig. 3 [15]. In the physical based, the common ways are compressed gaseous hydrogen (CGH2) storage, cryo-compressed hydrogen (CCH2) storage, and liquefied hydrogen (LH2) storage. In chemical based, there are sorbents, metal hydrides and chemical hydrides [16, 17].

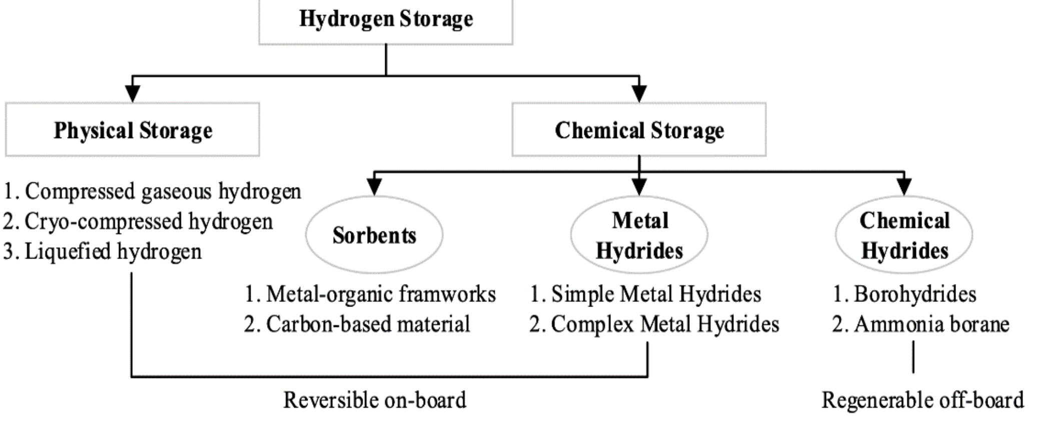

Fig. 3. Hydrogen storage technologies

Compressed gaseous hydrogen (CGH2) refers to gaseous hydrogen with a pressure higher than atmospheric pressure. [18] CGH2 storage is the simplest hydrogen storage method, which is relatively mature and the fastest growing among all hydrogen storage technologies currently under research. There are four main types of storage tanks used for CGH2 storage as presented in Fig. 4 [19]. The Comparison of four type tanks is presented in Table 3 [20–22].

- Type Ⅰ tanks: These storage tanks are generally cylindering which whole bodies are thick metal liners, and widely used in the in industrial situation. The max storage pressure of this tanks can reach 200bar.
- Type Ⅱ tanks: These storage tanks are composed of thick metal liners and wrapped in cylindrical components using fiber resin composite materials in hoop winding manner. The max storage pressure of this tanks can reach 300 bar.
- Type Ⅲ tanks: These storage tanks are composed of thick metal liners and wrapped in the entire surface using fiber resin composite materials. The max storage pressure of this tanks can reach 350 bar.
- Type Ⅳ tanks: These storage tanks are composed of polymer liners and wrapped in the entire surface using fiber resin composite materials. The max storage pressure of this tanks can reach 700 bar.

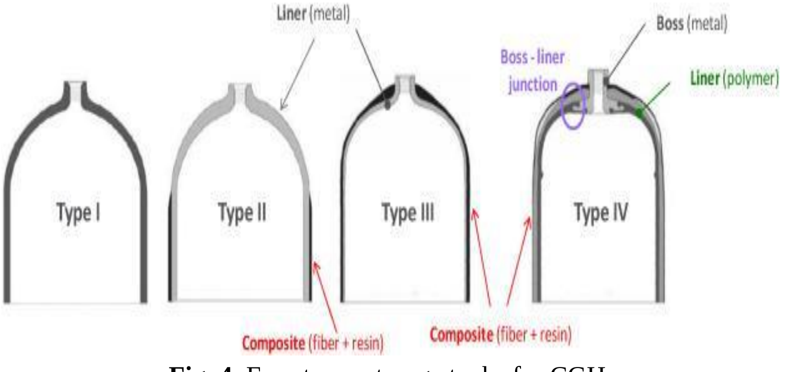

Fig. 4. Four types storage tanks for CGH_2

Table 3. The comparison of four types storage tanks

Types	Construction	Max Pressure (bar)	Gravimetric Capacity (wt %)	Volumetric Energy Density (MJ/L)	Application Scenarios	Cost (USD/Kg)
Type I	Metal body	200	1.1	1.4	Transportation	83
Type Ⅱ	Metal liner with composite hoop winding	300	2.1	2.9	Transportation	86
Type Ⅲ	Metal liner with composite overwrap	350	4.21	2.9	Fuel cell vehicle	700
Type Ⅳ	polymer liners with composite overwrap	700	5.7	4.9	Fuel cell vehicle	633

Liquefied hydrogen (LH2) refers to hydrogen gas in liquid form, which is a colorless, transparent low-temperature liquid. The normal boiling point is 20.38 K, and the density at boiling point is 70.77 kg/m3 [18]. The volumetric energy density of liquid hydrogen is up to 8.5 MJ/L. To take advantage of the advantages of liquid hydrogen, liquefaction cycles can be used to liquefy hydrogen at 253°C (20 K). Linde Hampson (L-H) liquefaction cycle is the simplest way, and there are some other hydrogen liquefaction cycles, such as Linde Hampson Cycle, Claude Cycle, Collins Helium Cycle, Helium Brayton Cycle, Magnetic Liquefaction, and Catalyzed Ortho- to Para-Hydrogen Conversion, as shown in Fig. 5 [23, 24].

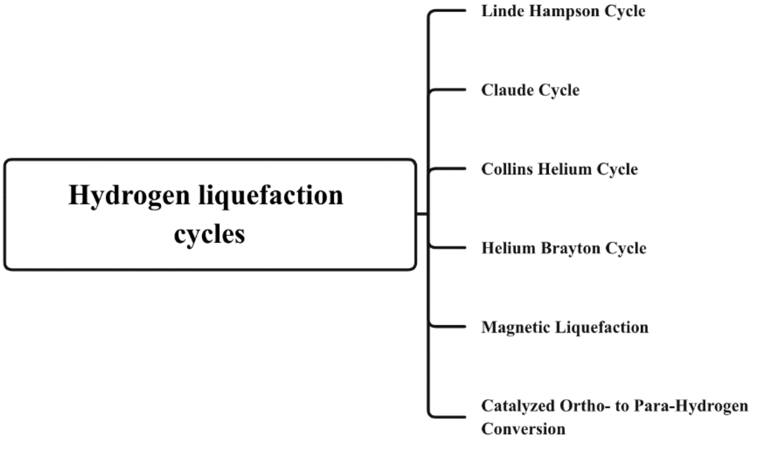

Fig. 5. Various Hydrogen Liquefaction Cycles

CcH2 combines the characteristics of CGH2 and LH2. Compared with compressed CGH2 and LH2 methods, CcH2 storage shows superior performance in terms of storage density and dormancy time [25]. The main advantages associated with cryogenic storage are the density of the liquid and the storage efficiency (See Fig. 6) [16]. The comparison of CGH2, CCH2 and LH2 are shown in table 4 [25].

Table 4. Comparison of CGH_2, CCH_2 and LH_2

Storage method	Volumetric density (g/L)	H2 loss rate (maximum) (g/h/kg)	Volumetric energy (MJ/dm3)
CGH_2	40 (700 bar/288 K)	/	4.2
CcH2	80 (300 bar/38 K)	0.2-1.6	9.6
LH_2	69 (1.5–3 bar/26 K)	8	10

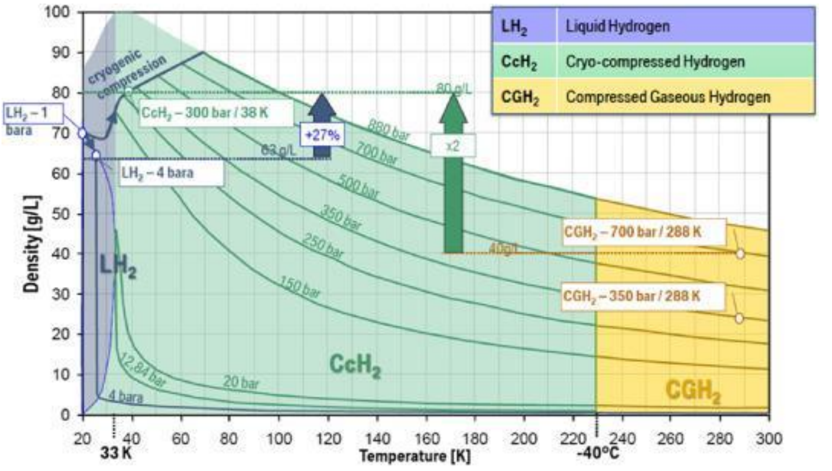

Fig. 6. Hydrogen density versus pressure and temperature

Compared with compressed hydrogen storage methods, storage of hydrogen in solids has certain advantages in volumetric density. Under certain temperature and pressure conditions, hydrogen can be reversibly absorbed by solid compounds. The creation of hydrides is a consequence of dissociative chemisorption. The atoms of the hydrogen molecule initially dissociate on the solid's surface, then diffuse into the host metal. Depending on the bonding mechanism between hydrogen and the host material, different hydride families exist: ionic hydrides, covalent hydrides, and interstitial metal hydrides. Ionic and covalent hydrides are also called complex metal hydrides [16].

6. Conclusion

In essence, the production of hydrogen is centered on the creation or extraction of hydrogen from primary energy sources. The accumulation of hydrogen involves the preservation of surplus hydrogen for subsequent utilization. The distribution of hydrogen encompasses the conveyance and delivery of hydrogen. The storage systems for hydrogen pertain to the technologies and infrastructure employed to retain hydrogen for future deployment. Collectively, these constituents establish a comprehensive hydrogen value chain that facilitates the generation, preservation, and distribution of hydrogen as a sustainable and environmentally friendly energy solution.

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ПОРІВНЯЛЬНИЙ АНАЛІЗ СИСТЕМ ВИРОБНИЦТВА, АКУМУЛЮВАННЯ, РОЗПОДІЛУ ТА ЗБЕРІГАННЯ ВОДНЮ

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Анотація. *Глобальний попит на енергію у світі продовжує зростати, а забруднення навколишнього середовища, спричинене спалюванням викопного палива, стає дедалі серйознішим. Важливим напрямом розвитку науки та техніки стало розроблення та використання нових джерел енергії. Розроблення та використання нових джерел енергії є однією з актуальних тем міжнародної дискусії, що формує варіанти можливих рішень для забезпечення чистої відновлюваної енергії та, відповідно, зменшує вплив на навколишнє середовище. Водень, як чисте, продуктивне, безвуглецеве вторинне джерело енергії, має потенціал для використання як палива та основної речовини для різних галузей, таких як опалення, транспорт, промисловість та виробництво електроенергії. Оскільки міжнародне співтовариство прагне досягти переходу до більш екологічно свідомого та сталого майбутнього, водень отримав широке дослідження та увагу завдяки своїм багатим ресурсам та екологічним властивостям. Основною метою цього дослідження було описати та порівняти ефективне виробництво, накопичення, розподіл і зберігання водню. Сьогодні його виробництво зосереджено на створенні або видобутку з первинних джерел енергії. Накопичення водню передбачає збереження його надлишків для подальшої утилізації. Розподіл водню охоплює його транспортування та доставку. Системи зберігання водню належать до технологій та інфраструктури, що використовуються для його збереження для майбутнього розгортання. У комплексі ці компоненти створюють інтегрований ланцюжок вартості водню, що сприяє його продукуванню, збереженню та розподілу як сталого та екологічно чистого енергетичного рішення.*

Ключові слова: порівняльний аналіз, технології виробництва водню, акумулювання, дистрибуції та систем зберігання водню.

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