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Hidrojen Enerjisi Depolama Teknolojisinin Uluslararası İlişkilere Etkileri

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Özet

Renksiz, son derece yanıcı bir gaz olan hidrojen, tüm elementlerin en hafifidir. Hidrojen sadece evrenin en hafif elementi olarak bulunmaz; amonyak ve metanol yapımında işe koyulur, petrol rafinasyonunu canlandırır, organik maddelere ivme kazandırır ve roketleri uçurur. Basınçlı veya kriyojenik depolama yöntemleriyle karşılaştırıldığında, hidrojenin katı hal depolaması çok daha güvenli ve verimlidir ve küresel olarak malzeme tabanlı hidrojen depolama teknolojilerine olan talebi artırma olasılığı yüksektir. Bu ayrıcalıklı özellikleriyle hidrojen enerjisi, küreselleşen dünyanın geleceğine ışık tutan en önemli unsurlardan biridir. Bilimsel ve teknolojik araştırmaların yanı sıra şirketler hidrojen enerjisini kullanarak öne çıkmaya çalışmaktadır. Ayrıca, dünyanın çeşitli bölgelerindeki devletler, özellikle ABD ve Çin, hidrojen enerjisi için rekabete girmiştir. Küresel hegemonyanın içeriğini değiştirdiği bu dönemde, hidrojen enerjisinin kullanımı uluslararası ilişkiler bağlamında belirleyici bir role sahiptir. Bu makale, hidrojen enerjisi depolama teknolojisini ve uluslararası ilişkiler üzerindeki etkilerini araştırarak literatüre katkıda bulunmayı amaçlamaktadır. Bu araştırma, hidrojen enerjisinin sürdürülebilir bir gelecek için küresel ve çok boyutlu ihtiyaçları karşılayıp karşılamadığı sorusuna cevap arayacaktır. Bu bağlamda, hidrojen enerjisi depolama teknolojisinin uluslararası ilişkileri nasıl etkilediğini analiz etmek için makalenin metodolojisi olarak nitel analiz yöntemi kullanılacaktır.

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The Impacts of Hydrogen Energy Storage Technology on International Relations

Abstract

Hydrogen, a colorless, highly flammable gas, is the lightest of all elements. Hydrogen does not just sit as the universe's lightest element; it gets down to business in making ammonia and methanol, spruces up oil refining, gives organic substances a boost, and sends rockets soaring. Compared to pressurized or cryogenic storage methods, solid-state storage of hydrogen is much safer and efficient, and is likely to increase the demand for material-based hydrogen storage technologies globally. With such privileged properties, hydrogen energy is one of the most important elements that shed light on the future of the globalizing world. In addition to scientific and technological research, companies are trying to stand out by using hydrogen energy. Furthermore, states from various parts of the world, especially the United States and China, have entered into a rivalry for hydrogen energy. In this period when global hegemony changes its content, the use of hydrogen energy has a decisive role in the context of international relations. This article aims to contribute to the literature by investigating hydrogen energy storage technology and its effects on international relations. This research will seek to answer the question of whether hydrogen energy meets global and multidimensional needs for a sustainable future. In this context, the qualitative analysis method will be used as the methodology of the article to analyze how hydrogen energy storage technology affects international relations.

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1. Introduction

Hydrogen energy storage harnesses excess renewable power (Stolten, 2019). Hydrogen energy storage systems are not only capable of storing grid electricity and returning it to the grid later, but they also provide auxiliary grid services such as fuel for fuel cell electric vehicles or material handling equipment like backup power, forklifts/airport tugs, ammonia plants, feedstock to refineries, and other industrial processes (Rahman et al., 2022). Furthermore, glass, fertilizer, metal refining, and chemical sectors face the tough job of shrinking their carbon tracks to keep up with green laws and what buyers want (Rissman, et al., 2020). Traditional fossil-fuel-fired melting systems have reached their maximum capability, making it difficult to meet stringent CO2, NOx, and SOx emission regulations (Normann et al., 2009). Even with the deployment of complex and costly add-on technologies, meeting targets within the glass industry is becoming increasingly difficult. Therefore, alternative fuels such as hydrogen heating are the most practical and feasible solution (Giddey et al., 2012). This can be achieved by combining electrical furnace boosting with a hybrid melting system or going all electric.

Glass-making leaders are pushing hard to hit that "zero-emission" target, exploring a bunch of clean alternatives in the process (Shah, 2021). In this regard, different countries are actively working to reduce their carbon footprints and achieve clean energy generation (Saidi and Omri, 2020). For example, the Federal Association of the German Glass Industry (BV Glass) is leading the way by studying how green hydrogen can be used as fuel in glass manufacturing through its Hyglass project in Essen (Atzori et al., 2023). Working closely with the Gas and Heating Institute, BV Glass is laying down a strong base for hydrogen to take center stage in fueling our factories (Singh et al., 2015). Within this context, glass is an essential raw material and replacing natural gas with hydrogen in the melting process will reduce CO 2emissions by approximately 3.3 million tonnes per year (Atzori et al., 2023).

Hydrogen is a big deal, not only for powering up clean energy sources but also as a key ingredient in making stuff like ammonia and methanol-these are the unsung heroes behind all sorts of industry magic (Zang et al., 2021). Hence hydrogen is not just vital for creating key chemicals; it also pairs up with lighter substances like ammonia and methanol to form eco-friendly fuels that, when used in fuel cells or turbines, release zero carbon dioxide (Stathopoulou, 2021). Similarly, methanol really holds its own in the industry game, fueling not just our cars and power stations but also playing a big part in making stuff like formaldehyde and all kinds of fuel boosters (Khare and Sharma 2003). Furthermore, methanol is also used as an antifreeze in pipelines and as a windshield washer fluid. The world's largest methanol exporter, Trinidad and Tobago, exports mainly to the US (Houghton-Alico, 2019). Thus, as industries clamor for more ammonia and methanol, the need for hydrogen energy storage is set to skyrocket. Hydrogen's role is critical in the refining game-it's not just about transforming oil or whipping up ammonia. Although some hydrogen is created as a by-product of the refining process in refineries, it is usually insufficient to supply the entire refinery's hydrogen needs. Hence, on-site hydrogen production utilizing natural gas or naphtha reforming is frequently required (Gheorghe and Ion, 2011). Natural gas reforming units are often built on-site to supply the refinery's overall hydrogen needs.

Stationary power systems are fuel cells' applications that are associated with an electric grid to provide supplementary power or backup power for critical areas (Yun et al., 2023). Tapping into hydrogen's potential, fuel cells are versatile enough to juice up small gadgets like smartphones or meet the hefty power requirements of big industry players. A range of sectors, including telecoms and data hubs to healthcare facilities and stores, are turning to fuel cells for their main and backup energy needs (Zakaria et al., 2021). As industries like telecom and healthcare hunt for stable power, fuel cells are snagging the limelight as a cleaner, more reliable power source shake-up (Helberg, 2021). Moreover, portable power systems are associated with highly mobile electricity generation units used to recharge batteries and power electronic gadgets. Hence, portable fuel cells are very convenient in areas where grid power is absent, unavailable, or unreliable. In this respect, compressed hydrogen's versatility shines, powering cars on the road, fueling stations where we top up, and keeping stationary power generators humming (Koohi-Kamali et al., 2013).

The US Department of Energy (DOE) has taken action to overcome this challenge by developing a public-private partnership called H2USA. H2USA is teaming up the big players-government agencies, energy giants, automakers, hydrogen providers, and top-notch research institutions-to give America's hydrogen fuel scene a serious boost. As of mid-2021, there were 48 open retail hydrogen stations in the

US, with an additional 60 stations in various stages of planning or construction. Most of these stations are in California, with one in Hawaii and 14 in the Northeast (Reddi et al., 2016). Hydrogen fueling facilities will be coordinated with vehicle deployment as the market grows, and customers should have the same experiences at hydrogen fueling stations as they do at gasoline stations (Greene et al., 2020). Most hydrogen dispensers will be installed at existing gas stations. In the Asia Pacific region, various incentive programs, such as China's Fuel Cell Electric Vehicle pilot program, reward clusters of cities that deploy more than 1,000 Fuel Cell Electric Vehicles that meet specified technological standards, reach a maximum delivered hydrogen price of CNY 35/kg (USD 5/kg), and build at least 15 operational hydrogen refueling stations for setting up cost-efficient hydrogen storage stations. These incentives also favor fuel cell electric vehicles over completely electric vehicles. China had over 2,000 primarily commercial fuel cell vehicles (13% of the global fleet) at the end of 2020, including more than 400 buses and trucks, with 15 refueling stations providing hydrogen to these vehicles (Zhang and Cooke, 2010).

Electricity can be stored in the form of hydrogen by using the electrolysis process. The stored hydrogen can then be used again as electricity, but the round-trip efficiency is currently lower than other storage technologies (Posdziech et al., 2019). Hydrogen energy storage is more expensive than fossil fuels. Specifically, liquid hydrogen as an energy transporter has a higher density than gaseous hydrogen, but it involves liquefaction, which requires a complex mechanical plant with added cost. Most hydrogen storage systems are either in the initial or developmental phase, and the cost and time for charging and discharging hydrogen in these systems are high, along with the process costs. As a result, hydrogen's got huge promise as a green energy source, but we've got to slash the storage costs, or it'll continue to be a roadblock (Züttel et al., 2010). What is more, power-to-gas steps up our green energy game, deftly catching the ups and downs of renewables. Power-to-gas tech gives our energy setups the agility they need, letting us weave unpredictable green power sources smoothly into the market. Interestingly, the use of hydrogen in fuel-cell-based transport and space heating purposes is already widespread in the commercial sector (Fox-Penner, 2020).

The International Energy Agency (IEA) predicts that up to 4 million tonnes of hydrogen, sourced from renewable resources, will be available for heating purposes by 2030, reducing carbon dioxide emissions. Power-to-gas tech opens a whole new world of chances for green hydrogen-it's not just for keeping our rides running clean with fuel-cell vehicles, but also for cranking up the heat in our spaces when it gets chilly. Hydrogen stands out as a clean energy champ, emitting nothing nasty when used to power up our rides and rigs. Hydrogen shines as a fuel, not only because it's clean but also due to fossil fuels getting pricier and scarcer by the day. Hydrogens got the spotlight right now, especially for powering fuel cell electric vehicles and for rocketing stuff into space in the aerospace sector. Fuel cell-operated vehicles reduce reliance on fossil fuels because they can be refilled quickly and provide long-distance travel options for electric vehicles (Gielen et al., 2019).

With dropping costs in fuel cell tech and hydrogen storage, hotspots like California, Europe, Japan, and Korea are gearing up for a surge in the market. In terms of international relations, governments of various countries are expected to launch hydrogen programs during the forecast period (Rath et al., 2019). Accordingly, developing the optimum net-zero CO2 emissions strategy, including the most effective green hydrogen strategy, is a challenging task (van der Spek et al., 2022). However, for most applications and end uses, there are decarbonization alternatives, and the relative costs and benefits of each solution are likely to change over time, depending on the rate of innovation and development of each given technology. Governments of different countries are, therefore, exploring which technologies are most suited to their countries and avoiding potential hazards such as locking in less efficient carbon reduction pathways. While these net-zero commitments must yet be translated into action, they will need to reduce emissions in "hard-to-abate" sectors where green hydrogen can play a pivotal role. Acknowledging these obstacles, the drive for hydrogen energy as a go-to power source is intensifying, especially in sectors were cutting back on emissions proves to be exceptionally challenging (Bataille et al., 2018).

Battery storage prices are going down due to technological advancements and the surging demand for electric vehicles. Big players from regions like Asia, Europe, and North America are seriously upping their game in making lithium-ion batteries. They're not just chasing the electric car wave but also other energy-hungry applications that are popping up left and right (Tollefson, 2008). The Energy Information

Administration (EIA) forecasted in 2019 that solar, wind, and other non-hydroelectric renewables would be the fastest-growing areas of the energy portfolio for the next two years. On the other hand, battery prices are dropping, and even the big power players like natural gas plants are sitting up and taking notice because they need a ton of electricity to keep things running smoothly. As a consequence, batteries are increasingly being called on to nimbly balance power supplies in a range of settings. Lithium-ion batteries are expected to become the leading energy storage technology in the coming years, with continuous improvements in battery technology giving them the edge of storing energy for an additional 4-8 hours. As battery tech gets better, more folks might lean towards lithium-ion for their energy needs. This could make it tough for hydrogen to keep up in the storage game. Hydrogen pipelines are expensive and energy-inefficient beyond short distances.

The geopolitics of hydrogen energy provides multidimensional and innovative contributions to the literature on international relations, bringing new perspectives to key theoretical areas such as energy security, alliance relations, technological balance of power, and normative transformations. Hydrogen reshapes the classical understanding of energy geopolitics in international relations. Hydrogen energy can break this hierarchy. This leads to a redefinition of the concept of energy dependency and a revision of classical energy security theories. Hydrogen geopolitics opens up the energy issue not only in terms of resource ownership but also in terms of technological superiority and production capacity. Thus, it adds a new dimension to the energy diplomacy literature. Therefore, it opens up new theoretical areas of discussion by transforming classical energy security understandings.

The ever-expanding use of hydrogen energy affects countries in many areas such as technology, science, trade, military, etc. and becomes an important tool to stand out in international relations rivalry. From this point on, the political affairs of states are also affected by their positions in international relations; because while production in our age mostly refers to technological production, alternative energy uses are an important move that can lead the rest of the world. When we approach the subject from the perspective of international relations theories, the basic argument of constructivism, "always being open to reconstruction", shows that hydrogen energy expands its areas of use over time in parallel with the rapid technological developments in the globalization process and affects international relations as it does in every field. In terms of identity and norms, which are the main constructivist arguments, the concepts of “environmentally friendly country identity” and “compliance with international norms for a sustainable future” are important roles for the international relations of states. The tendency of states, companies and societies towards hydrogen energy is related to how these actors see themselves and how they want to be seen. Political leaders around the world should support hydrogen as a "clean energy", it is also noteworthy in terms of pursuing their own state interests. In addition, the multidimensional use of hydrogen energy also fits into the multi-actor structure of constructivism. The future use of hydrogen energy has a political meaning in terms of the connection between technology and power. The relationship between hydrogen energy storage technologies and international relations is quite complex and multi-layered in the context of energy security, technological competition, geopolitical power balances and international cooperation. The fact that hydrogen can be stored and transported provides a strategic advantage for countries in terms of energy security. It has important advantages such as reducing external dependency on fossil fuels and storing excess renewable energy. This situation may enable some countries to switch from being energy importers to producers and exporters. This also affects the balance of power. In addition, the country that sets the standards in hydrogen technologies becomes an effective actor in the global energy order in the long term.

In terms of technological and strategic competition, the international diplomacy and trade relations of these countries can be shaped according to their strategies for spreading and marketing hydrogen technologies. In addition, multilateral projects such as energy diplomacy based on hydrogen energy pave the way for new regional and global collaborations. In this context, fossil fuel-rich countries may lose geopolitical importance with the increasing role of hydrogen. This article discusses in a multidimensional way the hydrogen energy that people and countries will use in many aspects of life in the future. While it aims to contribute to the literature in terms of technological developments in hydrogen energy and storing this energy, it also aims to inform those who do not have knowledge on this subject. In this context, throughout the article, the questions of what hydrogen energy is and how storage technology is applied will be also answered. Then, the role of states in terms of international relations in this technological competition and the practices of governments and companies in various countries will be explained. Finally, materials for hydrogen energy storage will be examined. In our article, which is an interdisciplinary study, quantitative data will be used as well as qualitative analysis.

2. Hydrogen Energy Storage Technology

The hydrogen energy storage market can be divided into three categories: gas, liquid, and solid based on the method of hydrogen storage. Hydrogen, a colorless, highly flammable gas, is the lightest of all elements. Hydrogen does not just sit as the universe's lightest element; it gets down to business in making ammonia and methanol, spruces up oil refining, gives organic substances a boost, and sends rockets soaring. Despite having the highest energy per mass of any fuel, its low ambient temperature density leads to a low energy per unit volume, necessitating the development of advanced storage methods with high potential for energy density. Hydrogen gas storage usually involves high-pressure tanks (350-700 bar tank pressure). Storing hydrogen gas via compression is the easiest and most cost-effective method, which is why it is in high demand in the hydrogen energy storage market globally (Abe et al., 2019).

Liquid hydrogen requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere of pressure is -252.8 °C. Although liquid hydrogen has a higher energy density than gaseous hydrogen, it requires liquefaction at -253°C, which involves a complex technical plant and an additional economic cost. Liquid hydrogen quietly powers through in the electronics and metals sectors, fueling processes with its robust energy profile while staying under the radar. Liquid hydrogen isn't just for shooting rockets into the sky; it's a low-key powerhouse in the electronics and metal crafting game, too. Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption). In adsorption, hydrogen is attached to the surface of a material either as hydrogen molecules or as hydrogen atoms. In absorption, hydrogen is dissociated into hydrogen atoms, and then the hydrogen atoms are incorporated into the solid lattice framework. Storing hydrogen in solid form involves the use of metal hydrides, sorption materials, and chemical hydrides. For example, hydrogen can be reacted to form ammonia, which can then be stored as a solid. It is possible to store large quantities of hydrogen in smaller volumes at low pressure and temperature close to room temperature if stored in the solid-state. Therefore, this is likely to be the primary reason for its higher demand in the hydrogen energy storage market. The hydrogen energy storage market has been further divided into compression, liquefaction, and material-based technologies (Lim et al., 2010) (Roszak et al., 2016) (Aziz, 2021).

Compressed hydrogen storage is one popular method of storing hydrogen in containers [34]. In this method, hydrogen is compressed and stored in steel or carbon composite cylinders to increase storage density. Compressing hydrogen gas is the simplest storage solution, requiring only compressor and pressure vessel equipment, which is why it is in high demand in the global hydrogen energy storage market. Another technique used for storing maximum hydrogen in a restricted volume is to convert hydrogen gas to liquid hydrogen by cooling it to an extremely low temperature Cryogenic containers are designed to minimize conductive, convective, and radiant heat transfer from the outer container wall to the liquid. Hydrogen is liquefied and stored at -253°C in cryogenic tanks. Therefore, the demand for liquefaction storage technology is increasing in the hydrogen energy storage market. The stationary power segment is expected to dominate the global hydrogen energy storage market due to the increasing demand for fuel cell-based applications (Yartys, 2005).

According to the International Energy Agency (IEA), between 2021 and 2026, the global renewable power capacity is estimated to increase by an average of 305 GW per year. With the increasing renewable energy sources, hydrogen energy storage has proven its benefits (Olanrewaju, 2023). Leading the charge in Europe's hydrogen energy storage growth, key sectors like chemical manufacturing, waste treatment, agriculture for nutrient production, and glass industry are powering up. In the realm of glassmaking, they rely on stashed hydrogen to craft a shielded environment that wards off any muck from sullying the smooth surface of flat glass. In the commercial segment, hydrogen is used for fuel cell-based mobility and for commercial space heating purposes (Sikiru et al., 2024). According to the IEA, by 2030, up to 4 Mt of potential hydrogen will be used for heating purposes, and it could come from renewable energy resources that could help to reduce CO2 emissions. Hydrogen-fueled vehicles aren't just quick to refuel; they're also about three times as energy-efficient compared to traditional cars, which means less fuel for more miles. Tapping into hydrogen for both fuel cell transport and heating in businesses is set to rev up the hydrogen energy storage scene (Taibi et al., 2018) (Capurso et al., 2022) (Pathak et al., 2023).

3. International Relations on Hydrogen Energy Storage Technology

During the process of globalization, the rivalry in the international relations of states has changed dimensions. Just as when we look at the history of diplomacy, the hegemony country changes location, the concept of hegemony has changed in the period of globalization. The globalization we are currently experiencing is the reality that has most comprehensively changed human life around the world. In this context, it is no longer possible to say that the United States has unconditional hegemony as in the past. Instead, we can now say that there is a hegemonic competition between states. Although there are various countries that stand out in different fields and take part in this competition, the strongest competitors today are the United States, China and Russia. On the other hand, when it comes to production, technological production has become more important than agricultural production. In this context, hydrogen energy is of great importance to states in terms of its use in many areas. Nowadays, governments are trying to stand out as technologically as possible by determining the most suitable route for their state interests and are researching appropriate technologies for their own needs. Hydrogen is one of the most vital investments a state can make for the future, and the state that stands out in this competition can also gain a great trump card in the hegemonic competition. In this context, the United States and China have an undeniable competition in the field of hydrogen energy. Since hydrogen can be used extensively, it can be predicted that the state that wins this competition will have a say in the future of the world.

North American countries like the US and Canada are currently working towards transforming their utilities and have the biggest capacities for ammonia production. As North America gears up to green its utilities, there's a soaring demand for hydrogen to fuel cells and drive metal production (Azarpour et al., 2022). With its economic muscle flexing the strongest in Europe, Germany also tops the charts as the EU's most voracious energy user. In February 2021, German gas company EWE began constructing a hydrogen storage cavern in Rüdersdorf, near Berlin. The 500-cubic-meter cavern will be constructed at a depth of roughly 1000 meters and will be utilized to store only five to six tons of hydrogen. An increase in the acceptance and commercialization of fuel cell electric vehicles is expected to provide growth opportunities to the fuel cell market in this country. German utilities are also looking at hydrogen energy storage technology as it provides them with the option of long-term energy storage and an interconnection between the electricity, gas, and transport sectors (Takach et al., 2022). The fuel cells and hydrogen joint undertaking initiative is the primary body that supports R&D in fuel cells and hydrogen technologies in Europe. The increasing demand for electric vehicles is also expected to boost the fuel cells market in this region, thereby driving the hydrogen energy storage market as well. Europe has a binding EU target of at least a 40% reduction in greenhouse gas emissions by 2030 compared with 1990, and countries in Europe are at different stages of developing their new energy policies (Meyer-Ohlendorf et al., 2018).

As Europe's hydrogen energy storage scene thrives, the UK alongside France and Italy are taking lead roles in this fast-evolving arena. The UK has a significant natural gas storage and transmission infrastructure, but it is highly dependent on imported natural gas. Carbon280's Hydrilyte refueller, a non-toxic, non-reactive metal dust suspended in mineral oil with hydrogen bonding as a hydride, was tested in the UK for the first time in February 2022. In France, tapping into hydrogen energy storage is a smart move for those in the power game-it lets them turn extra electricity into hydrogen gas that can sit tight until it's needed. The HyPSTER project in Etrez, France, aims to develop underground storage of green hydrogen in a saline cavity in the Ain region of France. Italy's spot at the crossroads of African and Middle Eastern supply routes, coupled with its robust renewable energy sector, positions it as a key player in pioneering green hydrogen through advanced "power to gas" tech-transforming excess clean power into storable and transportable methane or hydrogen. Italy's strategic location, bridging major hydrogen producers in Africa and the Middle East with the markets of Northern Europe, positions it well to become a key player in the hydrogen trade. The Ministry of Economic Development in Italy has released the first "Guidelines for the National Hydrogen Strategy," which identifies the sectors where green hydrogen is expected to become highly competitive soon (Garcia et al., 2016) (Edwards et al., 2021) (Neumann et al., 2023).

Hydrogens on the rise as a clean energy contender, with Europe and Asia Pacific racing ahead in the market. The Netherlands is at the forefront of hydrogen infrastructure development, accounting for a 10.2% share of the European market in 2021. With Rotterdam being Europe's largest container seaport, an international natural gas pipeline network, and depleted natural gas fields and national salt caverns that can be used for hydrogen storage, the Netherlands has become the first European country to build a national hydrogen infrastructure (Nunez-Jimenez and De Blasio, 2022) (Sijm et al., 2022) (Lüth et al., 2023). Spain's pouring a hefty $19.3 billion into clean energy, banking big on renewables and hydrogen storage, while Denmark's all in to set up one of the planet's largest eco-friendly hydrogen factories (Scita et al., 2020) (Coppenolle, 2023).

China dominates the Asia Pacific region, holding the highest market share of the hydrogen energy storage market in 2021. Amidst a surge in energy demand, China is stepping up with hydrogen storage solutions to power its growth more cleanly and shrink its carbon footprint. Over in Asia Pacific, hydrogen storage is on the rise, powering through in areas that crank out stuff like ammonia and methanol. But with big goals for hydrogen use and heaps of cash pouring in from governments and companies alike, the global market for storing this clean energy is quickly becoming a powerhouse in our shift away from fossil fuels (Aditiya, 2021) (Gong et al., 2023).

India, with an 8.2% share of the hydrogen energy storage market in Asia Pacific in 2021, is exploring options to utilize green hydrogen technologies with the India Energy Storage Alliance's (IESA) MIGHT initiative. In addition, India's first green hydrogen-based energy storage system will soon be operational, with NTPC Simhadri awarded the project 'Standalone Fuel-Cell based Micro-grid with hydrogen production utilizing electrolyser' in December 2021. India's push for cutting-edge tech is clear as day, with trials of the Tata Hydrogen Fuel Cell Bus and Toyota's Mirai showing a strong drive to embrace cleaner energy solutions (Kar et al., 2022) (Li, 2023).

Australia, with a significant 12.7% share of the hydrogen energy storage market in Asia Pacific in 2021, is well-suited to become a key exporter of hydrogen with its vast availability of land and high-quality renewable energy resources. Australia's gearing up to flip the script on its energy strategy, zeroing in on hydrogen-a power player that's not just clean and budget-friendly but also steady and green (Longden, 2020) (Li et al., 2023) (Makepeace et al., 2024).

Japan dominates the hydrogen energy storage market in Asia Pacific, holding a massive 24.6% share in 2021. With bold plans to utilize hydrogen for large-scale electricity generation and mobility, Japan has set an impressive target of 200,000 fuel cell vehicles and 320 hydrogen-refueling stations by 2025. Two demonstration projects are already under development to supply hydrogen to Japan, including the Hydrogen Energy Supply Chain pilot project, exporting Liquefied Hydrogen from Victoria, Austria to Kobe in Japan, and the Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) project in Brunei, exporting hydrogen as Methylcyclohexane (Zou, 2020) (Aditiya, 2021) (Gallardo et al., 2021). South Korea's strategy slashes reliance on coal and nukes, while boosting renewables big time-putting hydrogen fuel cells front and center as the new power players (Hart et al., 2020) (Rajalakshmi et al., 2021).

North America comprises the US, Canada, and Mexico, and in 2021, it accounted for a 16.1% share of the total hydrogen energy storage market. The region's seeing more action in the hydrogen market, mainly because fuel cells are taking off, there's a real push for clean energy, and the rules on emissions are tighter than ever. With the heat on to address environmental woes, governments are really zeroing in on hydrogen as a key player, ramping up investment in its research big time. The US, which accounts for the highest hydrogen energy storage market share in North America, held a 72.9% share in 2021. The primary drivers of the hydrogen energy storage market in the US are the rise in motor vehicle emissions, the need for cleaner transportation fuels, the increase in merchant hydrogen gas due to insufficient captive capacities, and the availability of heavy crude oil for processing. Canada held a 20.5% share of the North American hydrogen energy storage market in 2021. Hydrogen fuel cells are becoming super popular, and that's really boosting the market big time. Canada is the second-largest producer of ammonia and methanol in North America after the US. In 2018, Enbridge Gas Distribution and Hydrogenics opened the 2.5 MW Markham Energy Storage Facility in Ontario, Canada, as North America's first multi-megawatt power-to-gas facility that uses renewable hydrogen. Under contract with the Independent Electricity System Operator of Ontario, the facility now provides grid regulation services. The Canadian government stepped up, investing over half a million dollars into the CHFCA to back local firms, regions, and schools jumping on board with hydrogen and fuel cell tech. With oil sands, coal gasification, and cutting-edge gas conversion on the rise, Canada's hydrogen storage market is set to surge. Mexico accounted for a 6.7% share of the North American hydrogen energy storage market in

2021, driven by an increase in the use of alternative energy sources such as solar and hydrogen. It is estimated that about 46.5 million tons of hydrogen would be required every year until 2021 to cater to transportation and general industrial end-use applications in the country. Total investments in proposed green hydrogen projects in Mexico amount to USD 1.35 billion, with some projects virtually ready to build. In Mexico, the push for hydrogen energy storage is mainly driven by its role in refining oil to produce ammonia (Lemieux et al., 2019) (Lemieux et al., 2020) (Giarola et al., 2021) (Dinçer, 2021).

The Middle East and Africa accounted for a 5.9% share of the global hydrogen energy storage market in 2021, with Saudi Arabia leading the charge due to the rising demand for low-sulfur fuel for transportation applications. A green hydrogen project of approximately USD 42 billion is being planned across the region, and due to a decline in the overall crude oil quality, oil refining companies are looking for merchant hydrogen suppliers as captive production is no longer sufficient for self-consumption. South Africa is the largest market in the Middle East and Africa, accounting for a 21.2% share of the market in 2021 and projected to grow at a CAGR of 41.4% during the forecast period. South Africa is pushing hard to shrink its carbon footprint, turning to renewable energy for hydrogen production and exploring cutting-edge storage tech that could give platinum-fueled cells-a clean power source-the edge they need. To fulfill the increased demand for electricity, the government of South Africa plans to commission plants of 17.8 GW of renewable energy capacity by 2030. At the forefront of green tech, Saudi Arabia's on a fast track to spice up its bus system with new hydrogen-fueled rides. The rising demand for low-sulfur fuel for transportation applications is further expected to boost the need for hydrogen because it is used in desulfurization of fuels in domestic, as well as export, markets. Saudi Arabia is ramping up its refinery game, big time-turns out they really need hydrogen energy storage tech to make it all happen, and that's likely going to kick the market into high gear over there (Alsaba et al., 2023) (Boudellal, 2023) (Wijk, 2023) (Hasan et al., 2024).

4. Materials for Hydrogen Energy Storage Technology

Compared to pressurized or cryogenic storage methods, solid-state storage of hydrogen is much safer and efficient, and is likely to increase the demand for material-based hydrogen storage technologies globally. To release the hydrogen from the metal hydride, heat must be applied to break the bonds between the hydrogen and the metal. Hydrides are unique because they can adsorb hydrogen at or below atmospheric pressure and release the hydrogen at significantly higher pressures when heated. The operating range of temperatures and pressures for hydrides is wide and depends on the alloy chosen (Schneemann et al., 2018) (Dahari, 2016). Carbon nanotubes serve as a triple threat in the fuel cell arena, packing hydrogen for energy, smoothing out electron traffic, and ramping up reaction speeds on catalysts. They have been introduced to the platinum/carbon catalyst mixture at the anode of a fuel cell to increase the efficiency of catalyst reactions (Cheng et al., 2001) (Darkrim et al., 2002) (Becher, 2003) (Gundiah, 2003) (Mohan et al., 2019). Europe leads the pack, tapping into tech like chemical hydride systems and carbon absorption techniques to stash away hydrogen energy.

5. Conclusion

This article has made a difference by blending an interdisciplinary study with quantitative and qualitative tools. Energy is one of the most important concepts of our age. Issues such as energy, energy security and energy independence are constantly on the agenda in many areas, from the daily life of ordinary people to the production of companies and to the policies of states. When it comes to energy, which is a part of our lives, what energy will be used, how much, how and where it will be used pose important questions. On the other hand, as a result of the effects of globalization on our world, energy is expected to be environmentally friendly, sustainable and affordable. It has been determined that one of the most advantageous energies today is hydrogen energy, and technological research in this field can revolutionize the future with hydrogen energy.

Hydrogen, a colorless, highly flammable gas, is the lightest of all elements. Hydrogen does not just sit as the universe's lightest element; it gets down to business in making ammonia and methanol, spruces up oil refining, gives organic substances a boost, and sends rockets soaring. Hydrogen energy, whose use is increasing day by day, has begun to be used in various sectors. Technological research continues to carry out future-oriented and creative studies. In this context, the widespread use of new energy types, especially hydrogen energy, within the current production capacity creates a revolutionary difference from our past and signals that the future will be unique. States are trying to be in a leading position with technological breakthroughs in this field with their futuristic studies. Technology and energy are two fundamental pillars in the context of regional leadership and global leadership. Since the mathematics of international relations is created by power and power relations, hydrogen energy is a candidate to be a sign of power in the future.

The positive and negative global consequences of hydrogen energy use, which has environmental, economic and geopolitical dimensions, are also multidimensional. The positive consequences include its use in many areas, reduction of carbon emissions, provision of renewable energy, the possibility of providing energy independence and energy security, and new international collaborations. The negative consequences are its high cost, lack of infrastructure, and environmental discussions. In the future, the demand for cleanly produced hydrogen energy will increase. Many countries have begun to develop their own strategies and roadmaps to produce hydrogen energy. Hydrogen fuel offers a clean alternative for electric vehicles, but its large-scale use requires lower production costs and improved infrastructure. Green hydrogen stands out as a promising solution for a sustainable future. Turkey is among the countries with high potential to produce hydrogen energy and provides incentives and support for the transition to hydrogen energy technology.

This article has tried to show the content, use and importance of hydrogen energy in the context of cause-effect relationships. The technological elements of storing hydrogen energy, which are given a general definition in the introduction, are discussed. Examples of the use of hydrogen energy in different ways and in various areas are given. Numerical data on the use of hydrogen energy from Europe, America, Asia and even Australia are reflected. Then, materials in hydrogen energy storage technology were examined. As a result, it can be predicted that hydrogen will have one of the leading roles in the future, rather than an insignificant function. In addition, with the ongoing scientific studies in this field, the impact and global consequences of hydrogen energy are expected to continue to increase. The storability of hydrogen energy is not just an engineering issue, but also an international relations issue that directly affects countries' foreign policy, alliances, and energy strategies. Therefore, hydrogen storage technologies are likely to play a central role in the energy diplomacy of the future.

Yazar beyanları/ Author statements

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