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TRENDS AND PROSPECTS IN INTERNATIONAL HYDROGEN TRADE IN THE FACE OF NEW BARRIERS AND CHALLENGES TO GLOBAL COOPERATION

ТРЕНДИ І ПЕРСПЕКТИВИ В МІЖНАРОДНІЙ ТОРГІВЛІ ВОДНЕМ В УМОВАХ НОВИХ БАР'ЄРІВ ТА ВИКЛИКІВ ГЛОБАЛЬНОМУ СПІВРОБІТНИЦТВУ

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Abstract. *The article aims to identify key trends, prospects, and features of international hydrogen trade, focusing on new barriers and challenges to global cooperation. It is determined that the current growth of interest in hydrogen is associated with incentives in developed countries to reduce greenhouse gas emissions and combat global warming. It is argued that international hydrogen trade is becoming an important factor in countries' energy and economic transformation, and the hydrogen energy global market will be actively developed and supported. Still, it will have to overcome technical limitations to achieve significant success. Based on theoretical and empirical generalizations, the author concludes that hydrogen has significant explicit and latent potential for international trade and sustainable development of global energy and is a key factor in achieving global decarbonization goals. Still, the main challenges remain high production and transportation costs and the need to invest in innovative technologies. The study emphasizes that the oil refining and fertilizer industries mainly generate the demand for hydrogen. However, experts argue that in the future, sectors that are heavily dependent on fossil fuels, such as heavy industry, long-haul transportation, and air transport, may benefit most from hydrogen energy. Currently, the largest importers of hydrogen are Asian countries, driven by the region's demand for chemicals and the transportation, iron, and steel sectors in China and India. The main exporters of hydrogen in the future may be the countries of Oceania, North America, and the Middle East. The main barriers and challenges in international hydrogen trade are identified, which can be classified into economic, political, technical and infrastructural. It is emphasized that different regions of the world use unique strategies to develop the hydrogen market, and some cases are presented. The study concludes that the prospects for international hydrogen trade and the future introduction of hydrogen into the global*

economy will depend on the factors that affect a country's ability to produce and export hydrogen, which is multifaceted and interdisciplinary and covers many areas. For example, a country's hydrogen production may be limited by its oil resources, renewable energy potential, water resources, or land area, and difficulties in producing or exporting hydrogen due to its infrastructure, financial capacity, political climate, and government policies.

Keywords: *hydrogen, hydrogen economy, decarbonization, sustainable development, green transition, circular economy, green investments, innovations in hydrogen production technologies, international trade, barriers and challenges, global cooperation, emissions trading system, regulation, strategic interests, economic interests, the strategy of using hydrogen for energy, country strategies.*

Анотація. *Метою статті є визначення ключових тенденцій, перспектив та особливостей міжнародної торгівлі воднем з акцентом на нові бар'єри та виклики глобальному співробітництву. Визначено, що нинішнє зростання інтересу до водню пов'язане зі стимулами в розвинених країнах до скорочення викидів парникових газів і боротьби з глобальним потеплінням. Стверджується, що міжнародна торгівля воднем стає важливим фактором енергетичної та економічної трансформації країн, а водневий енергетичний глобальний ринок активно розвиватиметься та підтримуєтсья, проте для досягнення значного успіху йому доведеться подолати технічні обмеження. Зроблено висновок на основі теоретичних і епріричних узагальнень, що водень має значний явний і латентний потенціал для міжнародної торгівлі і сталого розвитку глобальної енергетики і є ключовим фактором для досягнення глобальних цілей декарбонізації, проте основними викликами лишаються: висока вартість виробництва, транспортування та необхідність інвестицій в інноваційні технології. В дослідженні підкреслено, що попит на водень в основному створюється нафтопереробною промисловістю та виробництвом добрив. Проте експерти стверджують, що у майбутньому галузі, які значною мірою залежать від викопного палива, такі як важка промисловість і далекомагістральні перевезення, авіаційний транспорт, можуть отримати найбільшу вигоду від водневої енергетики. Наразі, найбільшими імпортерами водню є країни Азії, що обумовлено попитом регіону на хімічні речовини, а також транспортними, залізними і сталеливарними секторами в Китаї та Індії. Головними експортерами водню у перспективі можуть стати країни Океанії, Північної Америки та Близького Сходу. Ідентифіковано основні бар'єри і виклики у міжнародній торгівлі воднем, що можуть бути класифіковані на економічні, політичні, технічні та інфраструктурні. Акцентовано увагу, що різні регіони світу використовують унікальні стратегії для розвитку водневого ринку, наведені окремі кейси. В дослідженні зроблено висновок, що перспективи міжнародної торгівлі воднем і майбутнє впровадження водню в глобальну економіку залежатимуть від факторів, які впливають на здатність країни виробляти й експортувати водень, які є багатогранними та міждисциплінарними та охоплюють багато сфер. Наприклад, виробництво водню в країні може бути обмежене її нафтовими ресурсами, потенціалом відновлюваної енергії, водними ресурсами або площею землі, труднощами у виробництві або експорті водню через свою інфраструктуру, фінансову спроможність, політичний клімат і державну політику.*

Ключові слова: *водень, воднева економіка, декарбонізація, сталий розвиток, зелений перехід, циркулярна економіка, зелені інвестиції, інновації у технологіях виробництва водню, міжнародна торгівля, бар'єри і виклики, глобальне співробітництво, система торгівлі викидами, регулювання, стратегічні інтереси, економічні інтереси, стратегія використання водню для енергетики, стратегії країн.*

Introduction. Fuel has always been a driving force behind human technological progress, from the wood fire that was first used for cooking to fossil fuels that fueled the Industrial Revolution and enabled the modernization of the global economy. (*What is hydrogen energy, 2024; Yatsenko O, Panchenko V., Ivashchenko O., 2024*). One of the problems that needs to be solved for the future of

humanity is related to energy, global warming, and the depletion of fossil fuels. Therefore, the use of fossil fuels has come under scrutiny for its role in climate change

The current growth of interest in green hydrogen is primarily due to the stimulating initiatives of developed countries to reduce greenhouse gas emissions and combat global warming. For example, the European Union actively supports the development of hydrogen energy by promoting the creation of infrastructure for producing «green» hydrogen using renewable energy sources. European countries are introducing decarbonization and clean air regulations, which indirectly increase the competitiveness of hydrogen as a fuel cell. Developed countries also help attract investment and create demand for this gas (*Low-emission hydrogen, 2024; Duginets & Panchenkoet al., 2024; Yatsenko et al., 2024; Osaulenko O., Reznikova N. et al., 2020*).

International hydrogen trade is gradually becoming a key element of global energy markets. As the world moves towards decarbonizing its economies, hydrogen is a potential solution to meet energy needs while reducing carbon dioxide emissions. However, the formation of a global hydrogen market requires the transformation of both trade and environmental policies at the international level.

A study of the potential of hydrogen for sustainable global energy development points to the need to create infrastructure for hydrogen production, storage, and transportation, which contributes to the formation of new markets, especially in Europe, Asia, and North America. The main challenges include the high cost of production and the need for significant investment in innovative technologies. Nevertheless, with the development of technologies, such as electrolysis based on renewable energy (wind and solar), the cost is expected to decrease gradually, especially after production is scaled up (*Werner Antweiler, David Schlund, 2024*).

The purpose of the article is to identify key trends, prospects, and specifics of international hydrogen trade with a focus on new barriers and challenges to global cooperation.

Literature review. Hydrogen is today enjoying unprecedented momentum. The world should not miss this unique chance to make hydrogen an important part of our clean and secure energy future. Hydrogen and energy have a long-shared history – powering the first internal combustion engines over 200 years ago to becoming an integral part of the modern refining industry. It is light, storable, energy-dense, and produces no direct emissions of pollutants or greenhouse gases. But for hydrogen to contribute significantly to clean energy transitions, it needs to be adopted in sectors where it is almost completely absent, such as transport, buildings and power generation. The Future of Hydrogen provides an extensive and independent survey of hydrogen that lays out where things stand now, how hydrogen can help achieve a clean, secure, and affordable energy future, and how we can realize its potential (*Fatih Birol, 2019).*

Some scientists see hydrogen as the next step in energy production. Hydrogen energy can be a cleaner and more efficient way to power our world. After all, hydrogen and other energy sources can potentially replace natural gas in an environmentally friendly way. The analysis of the hydrogen economy is reflected in the studies of many domestic and foreign scholars. Over the past decades, the hydrogen economy has become one of the priority areas for reducing dependence on fossil energy sources and their environmental challenges (*Enabling the European Hydrogen Economy, 2021*).

The WTO Report (*WTO report, 2022*) emphasizes the importance of standardization in hydrogen trade. One of the key aspects is the creation of common international standards for the production and transportation of hydrogen, which will simplify trade barriers between countries. It also emphasizes integrating hydrogen markets with existing energy networks and ensuring technology compatibility.

The World Bank report (2023) emphasizes that the hydrogen economy can become a driving force for the economic development of many countries, in particular those with rich resources for renewable energy (*World Bank Report, 2023*). However, at the initial stages, government subsidies to support hydrogen production and transportation remain important. The hydrogen economy can have a significant impact on the labor market, creating new jobs in the areas of hydrogen production, transportation, and storage. This is especially important for countries seeking to modernize their economies and move towards sustainable development.

The European Union is one of the leaders in shaping hydrogen policy. The Hydrogen Insights 2024 report (*Hydrogen-Insights-2024, 2024*) states that the EU plans to increase the production of green hydrogen and help reduce carbon emissions. This includes subsidies for hydrogen production from renewable sources and support for cross-border hydrogen trade. Importantly, hydrogen is seen as a strategic resource for the EU's energy security. Changes in environmental policy, in particular the adoption of the Paris Climate Agreement, are stimulating the development of the hydrogen economy. It is emphasized that in order to achieve the 2050 climate goals, it is necessary to significantly reduce the use of fossil energy sources and make hydrogen available to a wide range of industries, from industry to transportation (*Dawood Hjeij, Yusuf Bicer, Mohammed bin Saleh Al-Sada, Muammer Koç, 2023*).

At the request of the government of Japan under its G20 presidency, the International Energy Agency produced a landmark report to analyze the current state of play for hydrogen and to offer guidance on its future development (*IEA, 2019*). The report finds that clean hydrogen is enjoying unprecedented political and business momentum, with the number of policies and projects worldwide expanding rapidly. It concludes that now is the time to scale up technologies and reduce costs to allow hydrogen to become widely used. The pragmatic and actionable recommendations to governments and industry that are provided will make it possible to take full advantage of this increasing momentum. In contrast to renewable energy sources such as wind, solar, and biogas, the hydrogen economy has become popular and widely used due to its positive image in the media and social communications. However, the hydrogen economy is still less studied and not fully understood on a social level (*Hydrogen isn't the fuel of the future, 2019*). This is despite the importance of the hydrogen economy. The benefits include a clean environment and the possibility of ensuring the country's energy independence.

It should be noted that this problem has an economic and political dimension, as resource extraction is often used as an instrument of political pressure and blackmail, posing a threat to international security (*Oil Embargo, 1973–1974, n.d.*). A striking example is the Arab oil embargo of 1973-74, which led to major economic turmoil.

The Hydrogen Insights 2023 study indicates that hydrogen can be a key element for decarbonizing industries such as sustainable steel production, chemicals, and power generation. These sectors are the main consumers of fossil fuels and sources of significant CO_2 emissions. Hence, using hydrogen as a clean energy source is key to achieving greenhouse gas emission reduction targets. However, this requires a significant transformation of existing production processes and the introduction of innovative technologies, such as electrolysis, which helps reduce CO2 emissions (*Hydrogen Insights 2023, 2023*).

Long-distance transportation of hydrogen remains a major trade challenge. The article by van Wijk et al. analyzes the prospects for creating an international infrastructure for thydrogen transportationby pipelines and in the form of liquefied hydrogen (Ad van Wijk, Frank Wouters, 2021). It is noted that hydrogen transportation prices are significantly higher than for natural gas, as hydrogen is a very low molecular weight gas that can penetrate the walls of conventional pipes, causing their degradation. Therefore, hydrogen transportation requires pipelines using more durable and specialized materials, which in turn limits its competitiveness in international markets.

Foreign research usually focuses on technological innovations, economic models, and successful cases of hydrogen technology implementation in different countries, which is useful for adaptation to the national conditions of other countries.

The scientific work of domestic researchers is aimed at studying the potential of hydrogen energy in Ukrainian conditions, including environmental and economic aspects. In their works, domestic scientists highlight two key elements of developing the hydrogen economy in Ukraine *(Reznikova N., Grod M., 2024; Shkvarylyuk, S., 2024; Repkin A., 2020; Onysiuk, S., 2024; Zelenko O. O., Gutsan T. G., Osmirko I. V., 2022; Dmitriieva, O., 2024; Khalatur, S., 2024).* On the one hand, they note favorable climatic conditions that make hydrogen production using “green” technologies possible and profitable. On the other hand, they emphasize that the potential for cooperation with European initiatives, such as integration into the ENTSO-E energy system, is highlighted, which

opens up new opportunities for developing hydrogen energy. However, Ukrainian researchers also highlight some challenges facing the country's energy system. They emphasize the unpreparedness of the energy infrastructure for the large-scale introduction of hydrogen technologies and the overall complexity of the transition to renewable energy.

Ukraine's task is to create effective mechanisms to facilitate the integration of hydrogen technologies into the national energy system, which involves research and development and a national strategy that considers the economic interests of large energy companies and the state. It is also necessary to minimize social tensions related to the transition to new technologies in the country. It is important to create the conditions for integrating the hydrogen economy in Ukraine to be gradual, gentle, and without adversely affecting employment and economic stability.

Main results of the research. Hydrogen (H_2) is considered a promising future energy carrier due to its versatility, similar to fossil fuels. It can be transported in gaseous and liquefied form, similar to natural gas, and as ammonia (NH_3), which requires less cooling (-33 °C compared to -252 °C for liquefied water). Hydrogen can be mixed with natural gas, burned in gas turbines to generate electricity, and used in fuel cells to produce electricity (*Hydrogen chemical element, n.d.*). In addition, as an alternative to conventional batteries, hydrogen can store energy for long periods of time at minimal cost. These advantages have prompted many countries to actively pursue hydrogen production, use, storage, and transportation strategies.

With the development of hydrogen energy as an important energy carrier, international hydrogen trade is expected to increase significantly, and countries will begin to exploit their comparative advantages in hydrogen production. Since this new market will develop with multiple firms entering the market simultaneously in each period (with considerable heterogeneity and stochasticity), the resulting complexity defies closed-form analytical solutions. Long-term contracts are expected to dominate the first few decades of the hydrogen market (*Werner Antweiler, David Schlund, 2024; Dawood Hjeij, Yusuf Bicer, Mohammed bin Saleh Al-Sada, Muammer Koç, 2023; Krzysztof Urbaniec, Anton Friedl, Donald Huisingh, Pieternel Claassen, 2010*).

International trade makes hydrogen more available and cheaper than without trade, creating opportunities to capitalize on comparative advantage. Since hydrogen is a pathway to decarbonize emissions-intensive industries, international trade has a potentially positive environmental impact.

The current growth of interest in green hydrogen is primarily due to the stimulating initiatives of developed countries to reduce greenhouse gas emissions and combat global warming. For example, the European Union actively supports the development of hydrogen energy by promoting the creation of infrastructure for producing “green” hydrogen using renewable energy sources. European countries are introducing decarbonization and clean air regulations, which indirectly increase the competitiveness of hydrogen as a fuel cell. Developed countries also help attract investment and create demand for this gas (*Hydrogen, iea50, n.d.*). The Circular Economy Action Plan is one example. The circular economy involves a radical change in the organization of production and consumption – from a linear growth model (extract, produce, dispose) to one where waste becomes a sustainable alternative to resources (recover, reuse, recycle, share).

Hydrogen is the most abundant element in the universe, but it is practically not found on Earth in its pure form. Under normal conditions, hydrogen is a colorless, odorless, and tasteless gas with a density of 0.08987 g/l (c.v.), a boiling point of -252.76 °C, and a calorific value of 142.9 kJ/kg. In its liquefied state, hydrogen exists in a very narrow temperature range from -252.76 to -259.2 °C. At 253 °C, its density is about 70.8 g/l. In other words, this element has a high energy density per unit mass, which makes it an extremely efficient fuel. However, it is very inefficient in terms of storage and transportation. For example, natural gas has a calorific value of up to 16-34 kJ/kg and a density of 0.7 g/l (dry gaseous) or 400 g/l³ at 160 °C (liquid) (*Hydrogen chemical element, n.d.*). That is, according to a rough calculation, one imaginary 10-liter cylinder can hold (0.0708*10*142.9 = 101.17) 101.17 kJ of energy if hydrogen in a liquefied state is collected there, and (0.4*10*25 = 100) 100 kJ if it contains natural gas of average quality.

Therefore, the energy indicators are equal for the same volume. However, the costs associated with creating the conditions for international trade are different due to the possibility of long-distance

hydrogen transportation. And herein lies the main disadvantage of hydrogen: its boiling point, or liquefaction, which reaches -253 °C. This is a very low temperature, one of the lowest boiling points among all chemical elements, only 20 °C warmer than absolute zero. This makes transporting hydrogen by pipeline or ship difficult over land or sea. When transported, it must either be liquid or converted to ammonia. Both processes are costly and require the creation of appropriate infrastructure, such as high-powered refrigeration units that would be capable of liquefying industrial volumes of hydrogen. For comparison, natural gas is liquefied at a temperature of 160°C. While a hydrogen refrigeration unit has to reduce the temperature to a much lower level. Of course, the difference should be offset by the price of hydrogen. The only question is whether, after transportation, it will become uncompetitive against other environmentally friendly fuel substitutes, such as biogas or biofuels.

This is why hydrogen's share in the global energy balance is currently quite modest. However, experts estimate its potential as enormous: hydrogen can become the basis for achieving carbon neutrality by 2050. Instead, the transportation problem is planned to be solved by building hydrogen pipelines. In his research, Michael A. Semeraro found that for distances of 1000 miles with 2030 technology, a hydrogen pipeline could be an economically competitive method of transmitting renewable energy (*Michael A. Semeraro III., 2021*). However, the same article emphasizes that the methods need further research.

The international hydrogen energy market will be actively developed and supported, but it must overcome technical limitations to achieve significant success.

Hydrogen demand is mainly generated by the oil refining and fertilizer industries. However, experts argue that in the future, industries that are heavily dependent on fossil fuels, such as heavy industry long-haul transportation and air transport, may benefit most from hydrogen energy (*What is hydrogen energy, 2024*). Hydrogen, as a clean fuel, can significantly reduce carbon emissions in these sectors, which is a key factor in achieving global decarbonization goals.

Supplying hydrogen to industrial users is now a major business around the world. Demand for hydrogen (figure 1), which has grown more than threefold since 1975, continues to rise – almost entirely supplied by fossil fuels, with 6% of global natural gas and 2% of global coal going to hydrogen production. As a consequence, the production of hydrogen is responsible for CO2 emissions of around 830 million tons of carbon dioxide per year, equivalent to the CO2 emissions of the United Kingdom and Indonesia combined.

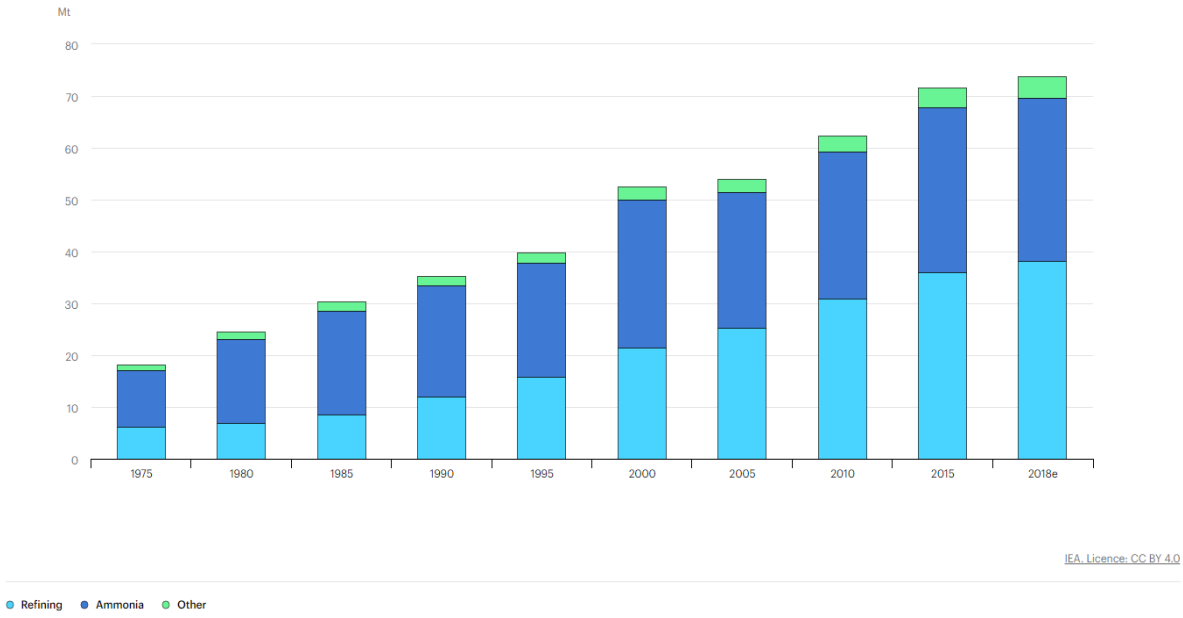

Figure 1. Global demand for pure hydrogen, 1975-2018 (*IEA, 2019*)

Today, the largest importers of hydrogen are Asian countries (Figure 2). This is primarily due to the region's demand for chemicals and the transportation, iron, and steel sectors in China and India (What is Hydrogen Energy, 2024). This trend is expected to continue until 2050. However, in Japan and South Korea, a significant share of hydrogen demand is expected to come from electricity generation, as these countries are actively investing in hydrogen infrastructure to support their national energy strategies.

The main exporters of hydrogen in the future may be the countries of Oceania, North America, and the Middle East (What is hydrogen energy, 2024). Currently, Saudi Arabia and the United Arab Emirates are already developing plans to use solar energy to produce hydrogen for export. Australia also looks promising, as it could become a leader in the production of green hydrogen due to its vast renewable resources.

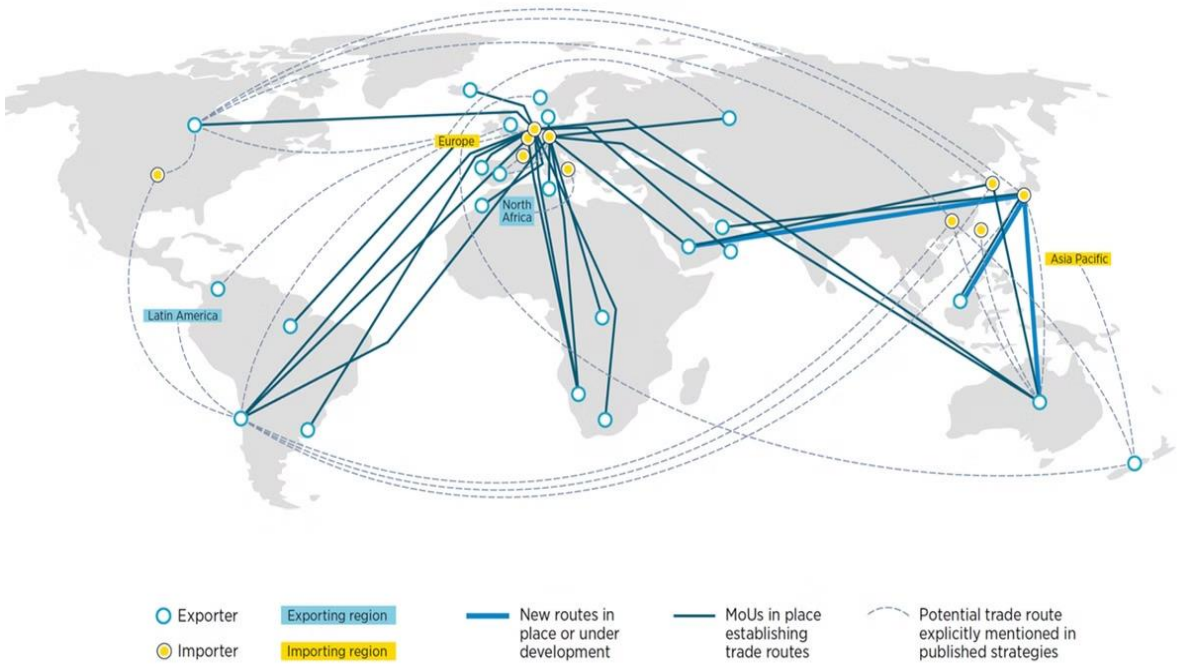

Figure 2. Key regions of global hydrogen trade (*Here's how global trade will be key, 2023*)

The number of countries with policies that directly support investment in hydrogen technologies is increasing, along with the number of sectors they target (figure 3). Around 50 targets, mandates, and policy incentives are in place today that directly support hydrogen, with the majority focused on transport. Over the past few years, global spending on hydrogen energy research, development, and demonstration by national governments has risen, although it remains lower than the peak in 2008.

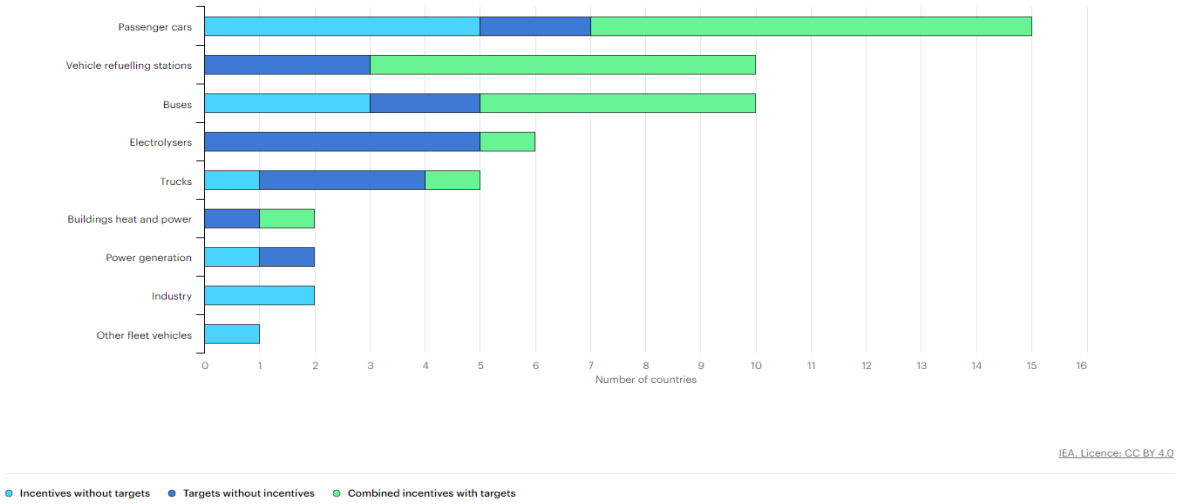

Figure 3. Current policy support for hydrogen deployment, 2018 (*IEA, 2019*)

Current trends in international hydrogen trade demonstrate significant progress in the development of both infrastructure and policy support aimed at boosting the hydrogen economy. Hydrogen is turning into a commodity of strategic importance, and global energy chains are adapting to the new reality. One of the key trends is the development of partnerships between exporting countries rich in renewable energy sources and importing countries with a high level of demand for clean energy. For example, in 2021, Australia announced several international hydrogen export agreements with Japan and South Korea, which include both joint infrastructure investments and long-term supply agreements.

Another important trend is the emergence of new technologies in hydrogen production, storage, and transportation. A key factor is the reduction in the cost of water electrolysis, which allows for the production of green hydrogen from renewable energy sources at lower prices. According to a BloombergNEF report (*Kamala Schelling, 2023*), the cost of producing green hydrogen is expected to fall by 85% by 2030, making it competitive with hydrogen produced from natural gas. In addition, new storage technologies, such as using ammonia as a transportation carrier for hydrogen, can reduce transportation costs and increase the economic efficiency of international hydrogen trade.

Governments of different countries also actively support hydrogen infrastructure development at the international level. The European Union, for example, has launched a strategy for developing the hydrogen economy, which envisages the creation of a trans-European network for the transportation of hydrogen and its integration into the general energy market. In addition, the International Energy Agency (*IEA, 2019*) has set up special groups to develop recommendations to stimulate international hydrogen trade.

Another important trend is the growing role of the private sector in developing international hydrogen trade. Global corporations such as Shell, Siemens, and Toyota actively invest in hydrogen projects and create partnerships with governments to develop international supply chains. This shows that the hydrogen economy is becoming not only a political but also an economic priority.

It is important to note the issue of barriers and challenges to international hydrogen trade. Although international hydrogen trade has great potential, it faces several significant barriers and challenges that could delay its development. These challenges can be categorized into economic, political, technical, and infrastructural. Economic and political barriers are of primary importance. One of the main economic barriers is the high cost of hydrogen production, storage, and transportation. For example, the cost of producing green hydrogen remains high due to the cost of electrolyzers and renewable energy sources. Despite the decline in prices, they are projected to become competitive with traditional hydrogen production methods only by 2030. This may reduce investor interest in financing hydrogen projects (*IEA, 2021*).

Political barriers can also significantly impact the development of international hydrogen trade. The absence of harmonized international standards and regulations governing the production and

transportation of hydrogen creates obstacles to trade relations between countries. Countries may have different approaches to safety, environmental standards, and licensing, making it difficult to do business internationally. As a result, companies may avoid investing in projects due to concerns about legal risks. In addition, political changes can lead to instability in the financing of hydrogen projects. For example, changes in governments or political regimes may lead to canceling government programs to support the hydrogen economy's development. These risks make investments unprofitable.

Technical and infrastructure challenges are also very significant. Technical challenges related to hydrogen production, storage, and transportation also play an important role in the development of international trade. One of the main problems is the reliability and efficiency of existing technologies. Hydrogen storage systems that operate at high pressure or in liquid form require significant investment in development and testing. Many of these technologies are not yet ready for mass deployment, making it difficult to access hydrogen on the market (*IEA, 2021*). In addition, the infrastructure needed to transport hydrogen is still underdeveloped. Many countries lack appropriate pipelines or terminals for hydrogen storage and transportation, which can be a serious obstacle to international trade. For example, negotiations are underway in Europe and North America to create hydrogen corridors, but their implementation will take time and significant investment. Additionally, safety technologies for hydrogen transportation have not yet reached the required level, which is a concern among investors and government agencies. Genuine leaks or accidents could significantly damage the image of the hydrogen economy, reducing confidence in the industry.

Taken together, all these barriers and challenges can slow down the development of international hydrogen trade. However, given the global trend toward renewable energy sources and reduced greenhouse gas emissions, it is important that governments and companies work together to overcome these challenges. Cooperation between countries and investors can help create a stable legal and economic environment for the development of the hydrogen economy, which in turn will strengthen international hydrogen trade.

Different regions of the world have unique strategies for the development of the hydrogen market (*IEA, 2019*) For example, Australia is actively developing the production of “green” hydrogen, using its abundant renewable energy resources, in particular solar and wind energy. The country's main strategy is to export hydrogen to countries needing alternative energy sources, such as Japan and South Korea. These countries are limited in domestic renewable energy production due to geography and high population density, so they are looking to import hydrogen as part of their energy strategies to reduce emissions and improve energy security. Australia is already in talks with these countries and actively invests in infrastructure for hydrogen production, liquefaction, and transportation. While Saudi Arabia, in particular through its large-scale NEOM project, is also making great strides in developing the hydrogen economy. The country is focusing on using its natural resources to create giant solar and wind farms that will be used to produce green hydrogen. Saudi Arabia's strategy is to reduce its dependence on oil and develop clean energy, which will help diversify its economy. This project has already attracted significant foreign investment, and Saudi Arabia plans to become a key supplier of hydrogen to Europe and Asia.

France plans to become a global leader in the production of clean hydrogen by 2030, investing €7 billion. The government's strategy includes three main areas: development of hydrogen production through electrolysis, decarbonization of heavy transport (including hydrogen trucks and zero-emission aircraft by 2035), and support for innovation and research in the field of hydrogen energy. Total and Engie are jointly building France's largest green hydrogen plant, which will produce 5 tons of hydrogen daily using solar energy (*Green hydrogen: a new step in the energy, 2024*).

An interesting strategy for using hydrogen for energy is the strategy of mixing hydrogen with natural gas. This approach, for example, is planned to be used by New Zealand (*Hydrogen blending: A step, 2022*). The decision is based on the fact that the gradual introduction of hydrogen to the private sector and industry would reduce the number of harmful emissions from domestic and industrial consumption. Hydrogen blending starts small. The first step is to inject small amounts of hydrogen into the existing natural gas network. Subsequently, the amount of hydrogen can be increased to about

20% by using the existing gas infrastructure to supply homes and businesses. Natural gas currently provides over 20% of New Zealand's primary energy supply.

To summarize, we can conclude that the trends in international hydrogen trade are well-established:

1. Unique strategies of countries for the development of the hydrogen market.
2. Innovations in hydrogen production technologies. It is worth noting that one of the most promising areas is the use of artificial intelligence.
3. The hydrogen economy will become a driving force for the economic development of countries. The hydrogen economy can have a significant impact on the labor market, creating new jobs in the areas of hydrogen production, transportation, and storage.

Innovations in hydrogen production technologies are a key factor in developing the global hydrogen economy and its trade. According to an article by ACS Publications (2021), one of the most promising areas is the use of artificial intelligence (AI) to optimize electrolysis processes, a technology that allows the production of green hydrogen from water using electricity generated from renewable energy sources such as solar or wind power. AI is able to analyze huge amounts of data in real-time, optimizing the operation of electrolyzers to maximize efficiency and reduce energy losses (*Pedro J. Megía Arturo J. Vizcaíno José A. Calles Alicia Carrero, 2021*). This is achieved by precisely controlling various process parameters such as temperature, pressure, reagent concentration, and electric current intensity. This reduces energy consumption for hydrogen production, which significantly reduces its cost. The article also notes that machine learning methods are used to predict the optimal operating conditions of electrolyzers based on historical data and their subsequent correction in real-time. This makes it possible to dynamically adapt hydrogen production processes to changing conditions, such as changes in the power of renewable energy sources (for example, when solar insolation or wind fluctuates). This flexibility ensures stable and cost-effective hydrogen production.

In the context of environmental policy, it is important to integrate hydrogen into sustainable development strategies. Hydrogen can contribute to the achievement of several Sustainable Development Goals, including providing access to clean energy (Goal 7), promoting economic growth (Goal 8), and reducing greenhouse gas emissions (Goal 13). It is emphasized that hydrogen can significantly reduce the impact of climate change, but this requires support from governments and international organizations such as the UN to harmonize the regulatory framework. Governments should provide funding for research and innovation in hydrogen technology. Investments are needed to build infrastructure that supports the production and use of hydrogen, such as electrolyzers, pipelines, and refueling stations (*Flavio Pinheiro Martins, Sofía De-León Almaraz, Amilton Barbosa Botelho Junior, Catherine Azzaro-Pantel, Priti Parikh, 2024*). Governments of different countries should cooperate to share experiences and technologies. International agreements and partnerships can facilitate the development of joint projects in the hydrogen economy.

It is considered that hydrogen is a key element for decarbonization. In order to dynamize international trade, it is necessary, first of all, to ensure the transportation of hydrogen over long distances:

- Pipelines. Existing gas pipelines can be repurposed or new ones built to transport hydrogen.
- Delivery. Hydrogen can be transported in liquid form by sea, enabling global trade.
- Road transportation. Hydrogen can be transported by road in specialized trucks, particularly for regional distribution.

Changes in environmental policy also set a number of trends:

- Carbon pricing. Carbon taxes and emissions trading schemes encourage the adoption of cleaner technologies such as hydrogen.
- Renewable energy mandates. Renewable energy policies create a favorable environment for hydrogen production from renewable electricity.
- Support for hydrogen infrastructure. Government subsidies and incentives promote the development of hydrogen production, storage, and distribution networks.

The importance of standardization in hydrogen trading should also be noted:

- Quality control. Standardization ensures consistent hydrogen quality, which is crucial for compatibility with different programs and infrastructures in different countries.

- Interoperability. Common standards allow for seamless integration of hydrogen infrastructure across regions and countries.

- Market development. Standardization builds market confidence and facilitates investment by providing clear guidelines and considering specific conditions.

The prospects for international hydrogen trade and the future introduction of hydrogen into the global economy will depend on factors that affect a country's ability to produce and export hydrogen, which is multifaceted and interdisciplinary, covering many areas. A country's hydrogen production may be limited by its oil resources, renewable energy potential, water resources, or land area. These factors are physical constraints that can be assessed for each country. On the other hand, a country may face challenges in producing or exporting hydrogen due to its infrastructure, financial capacity, political climate, and government policies.

Conclusions. Thus, the international hydrogen energy market will be actively developed and supported, but it must overcome technical limitations to achieve significant success. Theoretical and empirical studies show that hydrogen has significant potential for sustainable development of global energy, but the main challenges remain high production costs and the need to invest in innovative technologies.

International hydrogen trade is becoming an important factor in energy and economic transformation. The development of the hydrogen economy requires comprehensive changes in trade and environmental policies, including standardization, infrastructure projects, and support for innovation. In addition, environmental policy should be focused on reducing greenhouse gas emissions through the use of green hydrogen.

Hydrogen energy has significant potential for development, and international hydrogen trade will grow with it. Demand for hydrogen is growing as it plays a key role in reducing greenhouse gas emissions, especially in heavy industry, transportation, and energy systems. However, this market's development faces several technical challenges, including the high cost of producing green hydrogen, technical difficulties with the infrastructure for its transportation and storage due to its low density, and the need to create large-scale infrastructure.

Despite these obstacles, the initiatives of developed countries such as France, New Zealand, the UAE, Japan, and South Korea, and the growing number of investments in innovative technologies, indicate ambitious plans for developing this sector. Therefore, the hydrogen market will face a difficult path involving technical and economic issues. However, thanks to the support of governments and private investors, the sector has a great chance to become a key player in the future energy landscape, playing an important role in the decarbonization of the global economy.

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