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The Green Hydrogen Economy and the Global Net Zero Agenda: A Green Powershoring & Green Watershoring Perspective

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Abstract

The global Green Hydrogen economy offers the opportunity to unleash a new global energy paradigm, and a new virtuous cycle of global sustainable economic growth and development. The Green Hydrogen economy addresses the urgent need for global decarbonization, addressing a number of the Sustainable Development Goals (SDGs) established in the 2030 agenda. This paper addresses the promises and challenges permeating the establishment of a global Green Hydrogen economy. This paper introduces two new approaches and concepts, Green Powershoring and Green Watershoring, to assess and analyze how the global Green Hydrogen will evolve, and which countries will take the leadership in the global Green Hydrogen economy. Given the renewable energy-intensive and fresh water-intensive nature of green hydrogen production, countries which are more endowed with these natural resources will develop a clear lead and a competitive advantage over countries that do not possess these natural resource endowments. Thus, the creation of a global Green Hydrogen Divide is inevitable, leading to a number of global geoeconomics and geopolitical consequences.

Keywords

Green Hydrogen Economy, Green Powershoring, Green Watershoring, Blue Economy, Brazil

1. Introduction

The global Green Hydrogen economy offers the opportunity for the unleashing of a new economic and business paradigm, and a new virtuous cycle of global sustainable economic growth and development. The Green Hydrogen economy and the Blue Economy are interconnected, both addressing the urgent need for global decarbonization efforts and companies' net zero emissions goals and objectives (NZE). Thus, addressing a number of the Sustainable Development Goals established in the 2030 agenda. The 2023 United Nations Climate Change Conference COP 28 stressed the importance of Green Hydrogen in the global decarbonization effort (IISD, 2023; ING, 2023; UNEP, 2023a; U.S. Department of Energy, 2023; Wiatros-Motyka, 2023).

Green hydrogen and green-hydrogen fuels have the potential to decarbonize up to one-quarter of the global energy-related CO_2 emissions, constituting one of the pillars of global decarbonization efforts, assisting several heavy CO_2 emitters economic sectors, such as electricity generation, heavy industry, and transportation to assist in the global decarbonization efforts. Moreover, green hydrogen also addresses the increasing need for renewable energy that can be traded across countries, in the form of liquefaction or ammonia, addressing a growing need for the use of renewables in order to meet the 2030 agenda (UNCTAD, 2023; Siemens Energy, 2023; Deloitte, 2023; Hydrogen Council, 2023; IEA, 2023a, 2023b).

It is expected that green hydrogen will account for close to 20% of the global energy needs in the next three decades, generating US$2.5 trillion in revenues. It is expected that by 2050 green hydrogen will displace close to 10.4 billion barrels of oil equivalent, when producing close to 530 million tons of green hydrogen. It is expected that the global green hydrogen industry will be valued at US$300 billion annually, creating 42 million jobs worldwide by 2050. It is also important to address that the global electricity generation sector is the world's largest CO_2 emitter, thus it is imperative that the sector be one of the vital economic sectors that must be decarbonized. Moreover, green hydrogen offers decarbonization opportunities for a number of industries as well, such as agriculture, mining, manufacturing, to knowledge-intensive industries (Anouti, Elborai, Kombargi, & Hage, 2023; Heid, Sator, Waardenburg, & Wilthaner, 2022; IRENA, 2022a, 2022b; U.S. Department of Energy, 2023; Squadrito, Maggio, & Nicita, 2023).

This paper addresses the interconnection and synergies between the global Blue Economy and the global Hydrogen Economy. We use a Green Powershoring and a Green Watershoring approach to investigate the main factors propelling the production of green hydrogen around the globe. Competitive advantages established by a country's factor endowments, in a Heckscher-Ohlin international trade framework of analysis, such as countries' abundance of freshwater reserves and abundance of renewable energy, are some of the key elements in assigning promising sites for green hydrogen production. Moreover, countries better positioned from a cost perspective of green hydrogen advantage will develop additional competitive advantages for their agricultural products, manufacturing products, knowledge-intensive products, and their services industries in global markets. Furthermore, these countries will be able to establish a leadership and oligopolistic position in global markets (Arbache, 2022; Arbache & Esteves, 2023;

Leamer, 1995; IRENA, 2022a, 2022b; World Economic Forum, 2023).

2. The Green Hydrogen Economy

The green hydrogen economy holds the promise to create another cycle of a virtuous global sustainable development and growth. It is projected that by 2050, the global green hydrogen economy will be generating US$2.5 trillion in revenues, accounting for 20% of the global energy supply. Green hydrogen also holds the promise to address the "energy trilemma", i.e., the global need to establish a balance between reliability, affordability, and sustainability making the Net Zero Emissions (NZE) goals and objectives a reality. Green hydrogen can address one the major issues with solar and wind, their intermittency, while at the same time addressing the issue of decarbonization of production processes and transportation, amongst other uses. Thus, green hydrogen holds the promise to address one of the major issues surrounding a high level of dependency on solar or wind energy, their lack of steadiness and reliability, what deeply impacts a country's energy security (Heid, Sator, Waardenburg, & Wilthaner, 2022; Hydrogen Council, 2023; IEA, 2023a, 2023b; Offutt, 2023).

However, transitioning to a global hydrogen economy will require substantial amounts of investments to develop green innovations and technologies, infrastructure, manufacturing capabilities, develop human capital, and establish global demand for a green hydrogen economy (Maersk Mc-Kinney Moller Center, 2022; Oil & Gas, 2022; Siemens Energy, 2023).

The transition from a Brown Economy to a Green/Blue Economy encompasses several steps, such as: 1) the increase in the supply of renewable energy, 2) expansion of global demand for renewable energy, 3) investments in green/blue innovation and R&D, 4) expansion of the green/blue infrastructure, and 5) increasing coordination of efforts between the private sector and governments, the research & academic environment, and the civil society as a whole. This quadruple-helix approach is a fundamental step towards the expansion of the Green/Blue and Hydrogen economies worldwide (Gouvea & Gutierrez, 2023; Siemens Energy, 2023; World Population Review, 2023).

Still, green hydrogen or low-emission hydrogen only accounts for close to 1% of all the global hydrogen production. If the hydrogen economy is to have an impact on NZE global effort, production of low-emission hydrogen will have to grow substantially in the next few years. The global market size for green hydrogen is close to US$112 billion, what will have a substantial impact on countries' economies that engage in fostering their low-emission hydrogen capacity. However, in order for the global low-emission hydrogen industry to expand, countries must develop common regulations and certifications in order to avoid the creation of international trade barriers for the trade of low-emission hydrogen (IEA, 2023a, 2023b; Talman, 2023; Squadrito, Maggio, & Nicita, 2023).

The main dimensions of the green hydrogen economy are 1) production, 2) utilization, 3) storage and 4) transportation. Therefore, ports play a major role in the green hydrogen economy, as they play a vital role in the global green hydrogen supply valued-added chain. The matter of port readiness to handle green hydrogen trade is a new phenomenon. Ports have well established infrastructure to handle fossil fuel exports, including natural gas and LNG. The easiest ways of export green hydrogen are in the form of ammonia, methanol, or liquid organic hydrogen carriers (Chen, Fan, Enshaei, Zhang, Shi, Abdussamie, Miwa, Qu, & Yang, 2023; National Secretariat of Ports and Waterway Transportation, 2023).

Green hydrogen can be transported to ports via railway tankers, pipelines, road tankers, and other ways of transportation. Ammonia is presenting the most friendly and easiest operational strategy for the export of green hydrogen giving that many ports around the globe have been trading in ammonia. It is estimated that given these countries infrastructure and overall green hydrogen industry strategy, countries such as Australia and Chile, and Norway could become net exporters of green hydrogen (Chen, Fan, Enshaei, Zhang, Shi, Abdussamie, Miwa, Qu, & Yang, 2023).

Green hydrogen production, however, is a renewable energy-intensive and water-intensive process, and has a high production cost, in addition to current infrastructure constraints such as on the transport and storage sides. The splitting water molecules process using energy from a renewable energy source, such as hydropower or off-shore wind, is an expensive process. The cost of renewable energy has been dropping steadily for the last decade, however, there is an increasing shortage of fresh water globally. The whole green hydrogen production process is very water-intensive. For instance, each MWh uses five thousand liters of water, when compared to only 20 liters of MWh from solar generation. Thus, only water-intensive and renewable energy-intensive countries will be able to cost effectively manufacture and become competitive producers and exporters of green hydrogen. Again, our assumption that Green Powershoring and Green Watershoring will became increasingly more important to domestic and foreign companies' foreign direct investment (FDI) decisions and strategies, seems to hold for companies seeking to use green hydrogen to address their overall net zero sustainability targets and strategies (Beswick, Oliveira, & Yan, 2021; DiFelice & Vargas, 2022; Braga, Gouvea, & Gutierrez, 2023; Talman, 2023; UNCTAD, 2023).

The establishment of the global green hydrogen industry faces a number of opportunities and challenges. First, green hydrogen offers the potential to replace current brown hydrogen or carbon-intensive hydrogen in economic sectors such as agriculture, manufacturing, and services. In the next years, as the production costs of green hydrogen falls, as a result of additional investments resulting in economies of scale, and as a result of green innovations and green R&D efforts, we can expected the increasing utilization of green hydrogen worldwide. Moreover, the creation of Public-Private Green Hydrogen Partnerships (PPGHP) will accelerate investments in needed hydrogen infrastructure that will be mostly funded by the private sector as a result of incentives put in place by governments. This will allow for the further adoption of green hydrogen by more industries by reducing the delivery costs and final price of green hydrogen.

Moreover, the combination of low cost and abundant renewable energy, abundant fresh water resources, low cost equipment and manufacturing, low cost and reliable hydrogen storage, an effective and efficient infrastructure, including pipelines, that allows for the shipment of hydrogen from low-cost regions to demand hubs and clusters, and a strong demand from several economic sectors, will largely determine the future of the global hydrogen economy. In addition, the creation of green-hydrogen supplies value chains are also another key dimension of the global hydrogen economy. Thus, the expansion in the availability of parts and components for electrolysers, in addition to the raw materials required, will largely determine the vitality of the green hydrogen economy. It is expected that in three decades, the cost of producing green hydrogen from solar energy and on-shore wind is expected to be in the US$1 per kilogram of hydrogen, with CIF prices in the range of US$1.5 - 2 (Klein, 2023; IRENA, 2022a, 2022b; U.S. Department of Energy, 2023; Mason, 2023).

Currently production of green hydrogen is way more expensive than producing gray hydrogen, close to two to three times as expensive. However, declining cost of renewable energy costs such as solar, wind, and hydropower, as well as innovation in the electrolysis process and technology such as PEM have added more efficiency to these systems. In addition, lower costs of materials will have a positive impact in lowering the cost of PEM equipment, and increasing economies of scale could lower the final cost and price of green hydrogen (World-Energy, 2020; Anouti, Elborai, Kimbargi, & Hage, 2023).

Moreover, the reduction of operation costs to produce green hydrogen and the challenges involved in scaling the industry are major hurdles, as well as opportunities. For instance, fossil fuel produced hydrogen is substantially less expensive to produce than green hydrogen, close to two to three times less expensive. Liquid water Electrolyzers demand large quantities of renewable energy to electrolyze water, close to 50 kWh/Kg of green hydrogen produced, Still, liquid water electrolyzers (Alkaline and Polymer Electrolyte Membrane (PEM)) are gaining more market share than gaseous steam electrolyzers are way more expensive and require more frequent maintenance (Mason, 2023).

Green hydrogen also presents high energy losses. For instance, at every junction in the green hydrogen supply chain there are losses. Close to 30% - 35% of the energy used to produce green hydrogen is lost if ammonia is the preferred conversion that will be another 13% - 25% energy loss, and the transportation of hydrogen will add additional losses, that is close to 10% - 12% of the green hydrogen's inner energy. Moreover, the use green hydrogen in fuel cells will subtract an additional 40% - 50% energy loss. Thus, more innovation and R&D must be developed in order to address these excessive losses in energy (Ouziel & Avelar, 2021).

Thus, Energy consumption, plant performance, production rates, and purity of the green hydrogen are important dimensions to be controlled and monitored. If relying on solar or wind, even weather forecasting it is an important variable that must be monitored. If hydro power is the main source of electricity, climate change impacts on hydro power plants must also be monitored.

Ports are another major dimension of the hydrogen economy. Ports are an integral dimension of the global green hydrogen economy as they are important links between global green hydrogen supply chains. Countries exploring the production of green hydrogen must also pay attention to the green hydrogen infrastructure and logistics needed. Some countries are looking at their green hydrogen as a way to green or blue their economies and business landscape and environment, while others are looking at the green hydrogen economy as another potential exporting opportunity. In any case, eventually countries involved in the global green hydrogen industry will need to upgrade and prepare their infrastructure and logistics industries to fully address the needs of the green hydrogen industry (Chen, Fan, Enshaei, Zhang, Shi, Abdussamie, Miwa, Qu, & Yang, 2023).

3. Green Hydrogen Producing Countries (GHPC)

Global production of green hydrogen is expected to grow substantially by 2030. The global annual production of low-emission hydrogen is expected to reach 38 Mt by 2030. The low-emission electricity and electrolysis account for 27 Mt of the expected global production of 38 Mt by 2023, and the remaining from fossil fuels. Nowadays, only 3% of all the global production of hydrogen can be classified as green hydrogen (Deloitte, 2023; Offutt, 2023; Fekete & Imogen Outlaw, 2023).

Developing not only the green hydrogen supply valued chain side, but also developing the demand side are major challenges facing the establishment of a global green hydrogen economy. The next paragraphs will elaborate on some of the global front runners in the global green hydrogen economy.

China is one of the world's leaders in the production and domestic consumption of hydrogen, producing around 24 million tons annually. However, most of China's hydrogen production is of the grey nature, mostly based on coal. But China is increasingly interested in developing and establishing a green hydrogen economy. China is actively developing its fuel cell electric vehicles (FCEVs), in addition to trucks and buses. In 2022, China had an installed capacity of more than 200 MW in electrolyser capacity. It is expected that 2030, China will account for close to 50% of global installed capacity. It is expected that by 2030, there will be 155 GW/year of installed manufacturing capacity (IEA, 2023b; Wood, 2022).

The U.S. is the world's second largest producer and consumer of hydrogen, with a 13% global share. In 2021 the Biden Administration passed the Infrastructure Investment and Jobs Act allocating close to US$9.5 billion to foster the development of a green hydrogen industry in the U.S. The Biden Administration's Hydrogen Earthshot Programme was another initiative towards solidifying the government's support for the development of a dynamic green hydrogen industry. For instance, the U.S. is proposing the "U.S Hydrogen Production Tax Credit" and the United Kingdom's "Low Carbon Hydrogen Business Model" are some examples. It is also expected that close to 20% of all the hydrogen produced by 2030 will be exported. Thus, building the global infrastructure of ports and terminals is fundamental for the expected increasing trade of hydrogen (IEA, 2023b; Wood, 2022).

Moreover, the U.S. government is funding the so-called "Hydrogen Hub Funding", by offering tax credits, the hydrogen production tax credit (PTC), DOE's Hydrogen Shot, and by engaging in private-public hydrogen partnerships (PPHP) in order to expand the demand for green hydrogen use in the U.S. The U.S. goal is to expand production of green hydrogen from 1 million metric ton per annum (MMTA) to about 10 million metric tons of hydrogen (MMTA) by 2030. If the U.S. decides to follow a water electrolysis approach to green hydrogen production, the U.S. will need an additional 200 GW of additional renewable energy sources (U.S. Department of Energy, 2023).

The European Union is planning to install close to 40 GW of green hydrogen electrolysers capacity by 2030. The EU has also listed green hydrogen as one of the technologies it is promoting and supporting. The EU has allocated close to US$5 billion to establish its green hydrogen economy. The European Clean Hydrogen Alliance is just one of the initiatives being unleashed in the EU to support its own green hydrogen economy. Countries such as Spain are developing a number of green hydrogen projects aiming at production and exporting. The HyDeal Spain project is planning to produce 330 thousand tons of green hydrogen yearly and Valle Andaluz del Hidrogeno Verde is expected to produce close to 300,000 tons of green hydrogen per year. Germany is planning to produce 1 million tons of green hydrogen by 2035, and the Netherlands are planning to produce close to 800 thousand tons of green hydrogen from off-shore wind farms. Australia is investing close to 100 billion AUD to develop wind and solar farms aiming at producing green hydrogen as well. The Western Green Energy Hub will produce 50 GW of green energy leading to the production of 3.5 million tons of green hydrogen per year (Wood, 2022; Good New Energy, 2023).

Germany is positioning itself to be a meaningful player in the global green hydrogen economy. In 2023, Germany had 120 hydrogen projects under study or under construction, generating close to 5 GW of electrolysis capacity. The expectation is that by 2030, this installed capacity is increased to 30 GW. A 5100 kilometers of pipelines will be used to supply green hydrogen parts of the German economy. However, the southern part of Germany, who is the second largest demand for green hydrogen is located, will not be served by the initial green hydrogen network. Germany will utilize green hydrogen in six key industries: steel industry, semiconductor industry, petroleum sector, chemical industry, glass and ceramics industry (Strategy&, 2023).

Australia is also a major green hydrogen investor. There are several projects being developed in Australia such as: a) the Asian Renewable Energy Hub, a 14 GW project, with a cost of US$36 billion, b) the Murchison Renewable Hydrogen Project, a 5GW project with an estimated cost of US$12 billion, c) the Pacific Solar Hydrogen project, a 3.6 GW project, d) the H2-Hub Gladstone, a 3 GW project with an estimated cost of US$1.6 billion, and e) the Geraldton green hydrogen project with an estimated production of 1.5GW (World-Energy, 2020).

India is also pursuing the development of a vibrant domestic hydrogen economy. India is heavily dependent on imports of fossil fuels; domestic production of green hydrogen could alleviate this dependency. Most of India's refineries and fertilizer producers, in addition to its transportation industry could benefit from using green hydrogen, as well the extreme urban pollution that plagues major India's cities (Wood, 2022).

In Brazil, green hydrogen production is being developed in triple-helix arrangement, where the Brazilian government and some of Brazil's state-run companies, such as Petrobras, work in conjunction with Brazilian domestic companies and foreign companies. In 2023, close to US$27 billion of investments have been announced to be invested in Brazil's green energy economy. The expectation is that by 2025, Brazil will be producing 16 million tons of green hydrogen and 2.8 million tons of green ammonia, mostly allocated towards exports. In 2023, the European Union announced a major green hydrogen project in Brazil, establishing a 10 GW production facility for green hydrogen. This is an export-driven project with the aim of shipping the product to the port of KRK in Croatia. By 2030, Brazil is expected to invest US$50 billion in green hydrogen projects. Companies such as Unigel are investing close to US$1.2 billion million to produce green hydrogen producing 100,000 tons yearly. The French Company Qair Group is planning to also invest close to US$7 billion, 290,000 tons of green hydrogen. Fortescue is also investing close to US$6 billion, aiming to produce most of these investments are taking in Brazil's Northeast region, where most of Brazil's solar and wind farms. Additional green hydrogen investments are also planned the Brazilian state run oil and gas company Petrobras, US$1.5 billion by Unigel a fertilizer company, Casa dos Ventos e Comerc companies are planning a US$4 billion investment to produce 2.2 million tons of green ammonia and 365 thousand tons of green hydrogen (Castro, Braga, Pradelle, Chaves, & Chantre, 2023; Chiappini, 2023; European Commission, 2023; Deloitte, 2023; IEA, 2023a, 2023b; Hydrogen Council, 2023; Siemens Energy, 2023).

Several African countries have pledge investments to foster their green hydrogen industries. For instance, Namibia pledged close to US$9.4 billion in order to generate 2 GW of renewable green hydrogen for its local domestic and global markets. In 2022, South Africa also pledged US$17.8 billion to develop a number of green hydrogen related projects. Other countries in Africa, such as Morocco, Kenya, and Nigeria are also developing programs to add green hydrogen to their electricity matrixes (Yohannes & Diedou, 2022).

Several GCC countries, such as Saudi Arabia, Oman, are also pursuing the diversification of their energy matrix and looking at the next decades. They have access to funding, suitable land for renewables such as solar and wind, and the ability to retrofit some of the fossil fuel infrastructure to adapt to green hydrogen exports. Since 2000, the addition of renewable energy power is severely impacting the demand for global fossil fuels, deeply affecting oil exporting countries, such as the GCC oil and gas exporting countries. Saudi Arabia for instance, is developing the Helios Green Fuels Project, a 4 GW green hydrogen production project, aiming at exporting green hydrogen and ammonia to global markets. The UAE is also investing in the production of green hydrogen using solar power, aiming at 75% of Dubai's total demand for renewable energy. For instance, Asia has saved close to US$199 billion, Europe saved close to US$176 billion, South America close to US$71 billion, North America close to US$23 billion, Africa US$19 billion, and Eurasia US$15 billion (IRENA, 2023; World-Energy, 2020; Oil & Gas, 2022; Dewa, 2021).

The global major green hydrogen companies are mostly found in the U.S., Western Europe, and Asia. Companies such as Air Liquid and Engie (France), Air Products and Chemicals, Inc, (U.S.A), Green Hydrogen Systems (Denmark), Siemens Energy Global GmbH (Germany), Toshiba (Japan), and Tianjin Mainland Hydrogen equipment Co. Ltd (China). The increasing global demand for renewable energy in a more flexible and dispatchable or transportable fashion is increasing the appealing of green hydrogen. Emerging green hydrogen producers such as Brazil, will have to develop strong and globally competitive green hydrogen domestic producers in order to be more competitive globally. In Brazil, the state-run company Petrobras is making sizable investments in the production of green hydrogen. Thus, the creation of a green hydrogen global oligopoly is to be expected as well as the creation of a Green Hydrogen Organization of Exporting Countries (GHOECs), similar to an OPEC. Thus, one is to expect a substantial change in the geopolitics of energy, with countries like Brazil, Australia, China, the U.S., India, Canada, Norway, and GCC countries having a leading role in the global green hydrogen trade and production. In the longer-term, a number of African countries and additional Latin American countries will join the global effort to increase the role of renewable energy and green hydrogen in the quest to decarbonize the global energy matrix (Blackridge Research & Consulting, 2023; Leal, Couto, & Rosas, 2023; UNCTAD, 2023).

A hydrogen economy as a renewable energy carrier, and as a replacement for fossil fuels, may be able to open the door for hydrogen to be used in transportation, heat for manufacturing, on indoor heating applications, and other uses. For instance, hydrogen could be used to replace fossil-fuel internal combustion engines with hydrogen-based fuel cell trucks, ships, and automobiles. Hydrogen could also be used to substitute natural gas in heating applications, in a blended format with natural gas. Hydrogen has the advantage when comes to emissions, since it does with zero emissions of harmful air pollutants (Offutt, 2023; Pacheco, 2023; Onorati et al., 2022).

Green hydrogen is an important component of the global effort to achieve net zero emissions (NZEs) by 2050. Green hydrogen has a number of applications. For instance, green hydrogen can be used in the transportation industry, aviation, maritime transportation, chemical and petrochemical industry, iron and steel industry, aluminum, cement industry, and decarbonization of the natural gas industry. Moreover, the green hydrogen economy will also have a great impact on electric vehicles (EVs), since these electric engines instead of relying on batteries could rely on fuel cells powered by green hydrogen. And it has been noted that fuel cell EVs are more efficient that battery powered EVs (Anouti, Elborai, KImbargi, & Hage, 2023; Castro, Braga, Pradelle, Chaves, & Chantre, 2023).

The global shipping industry accounts for close to 80% of global trade by volume. Carbon dioxide is the global shipping industry main GHG, accounting for close to 2% of global emissions. The global shipping industry is committed to a net zero emissions by the end of the century, and by 40% by 2030. In the U.S. the transportation sector is the largest sector when comes to GHG emissions. The shipping industry is heavily dependent on diesel engines. Thus, switching to green hydrogen will greatly address the global shipping industry GHG emissions issues (Castellanos et al., 2021; Holland & Knight, 2021).

4. Green Hydrogen & Green Powershoring and Green Watershoring

Green hydrogen production is a renewable energy-intensive and a fresh water-intensive production process. Green hydrogen production and exports will gravitate towards countries that are endowed with abundant freshwater resources and the ability to produce abundant renewable energy in a cost effective manner. The cost of renewable energy accounts on average for close to 70% of the cost of manufacturing green hydrogen. Thus, countries that have developed the ability to develop additional competitive advantages based on these two key natural resources are expected to dominate the global transition from a Brown-led economy towards a Green-led economy (Arbache, 2022; Arbache & Esteves, 2023; Braga, Gouvea, & Gutierrez, 2023; Gouvea & Kassicieh, 2010; Gouvea, Kassicieh, & Montoya, 2013; Gouvea & Gutierrez, 2023).

Figure 1 highlights the total renewable capacity of generation of major economic regions from around the globe. The global renewable energy generation was close to 3,068,297 CAP MW. Asia produces close to half of the world's renewable energy, 1,455,861 CAP MW, or close to 47% of the world's renewable energy. Europe and North America are second and third in the production of renewable energy, with South America and Africa in fourth and fifth place respectively. As illustrated by **Figure 2**, when comes to hydropower electricity, Asia is the world' largest producer, followed by Europe, North America and South America (IRENA, 2020, 2022a, 2022b, 2023).

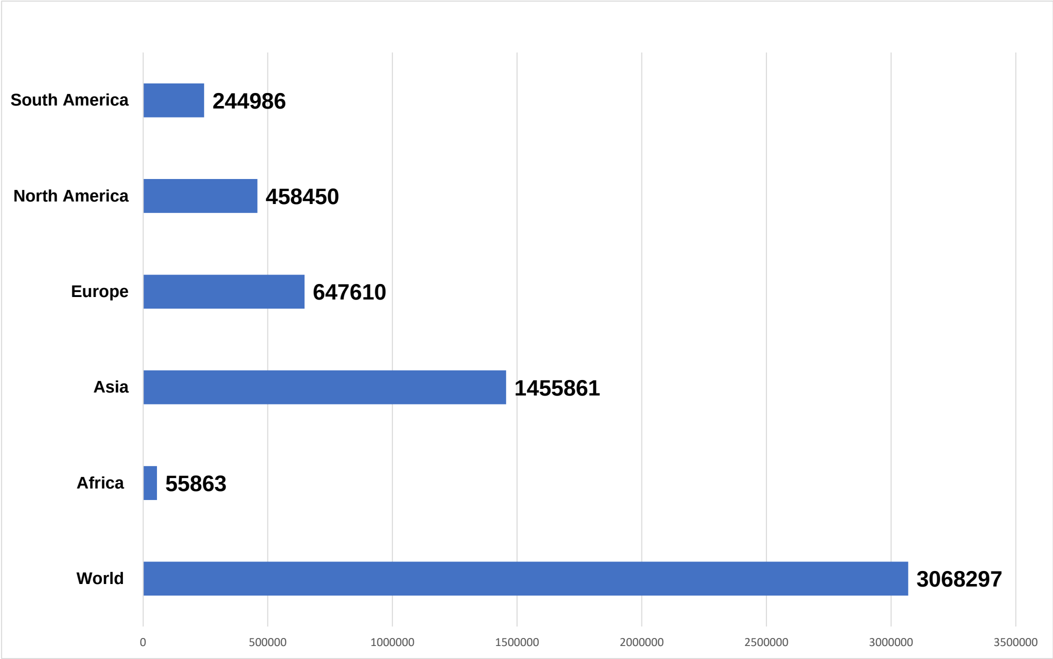

Figure 1. Total Renewable Capacity Generation by Major Economic Region, 2022. CAP MW. Source: Elaborated by the authors from data obtained from IRENA (2022a).

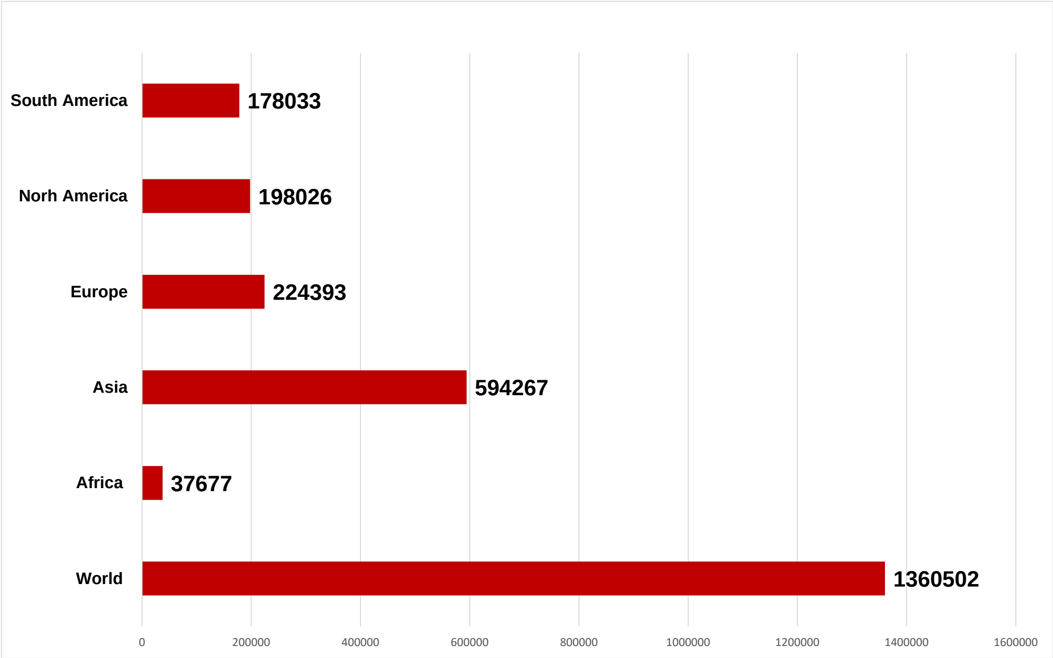

Figure 2. Hydropower Electricity Generation by Major Economic Region, 2022. CAP MW. Source: Elaborated by the authors from data obtained from IRENA (2022a).

As illustrated by **Figure 3**, Asia is also the world's largest producer of on-shore wind electricity, followed by Europe, North America, South America, and Africa. When comes to off-shore wind electricity generation, as illustrated by **Figure 4**, Asia and Europe are the world's largest producers. When come to solar energy electricity generation, as illustrated by **Figure 5**, Asia is the world's largest, accounting for close to **56.8%** of the world's solar electricity generation, followed by Europe, North America, South America, and Africa (IRENA, 2022a).

It is important to highlight that China produces close to 70% of all Asia's renewable energy. In North America, the U.S. also accounts for close to 70% of all the North American renewable electricity generation. In Europe, countries such

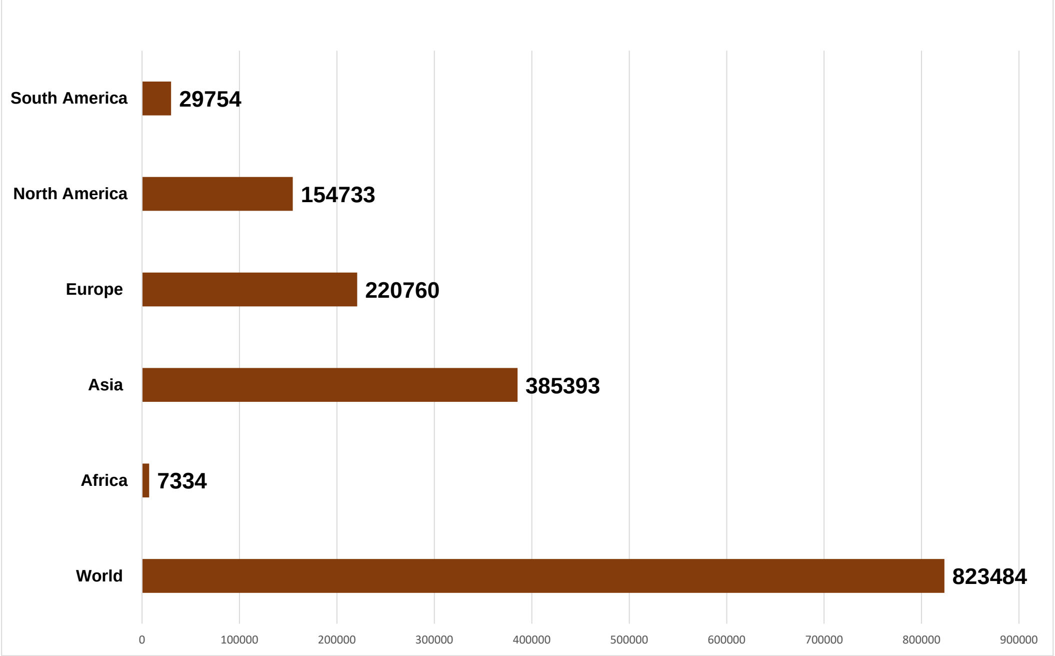

Figure 3. Wind Energy On-Shore Electricity Generation by Major Economic Region, 2022. CAP MW. Source: Elaborated by the authors from data obtained from IRENA (2022a).

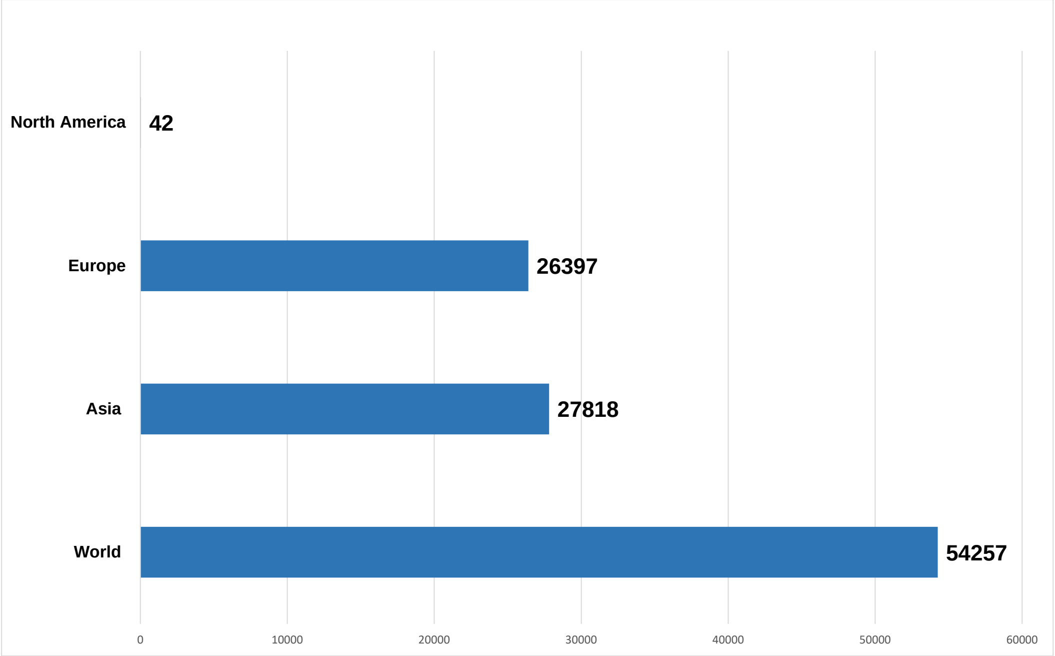

Figure 4. Off-Shore Wind Electricity Generation by Major Economic Region, 2022. CAP MW. Source: Elaborated by the authors from data obtained from IRENA (2022a).

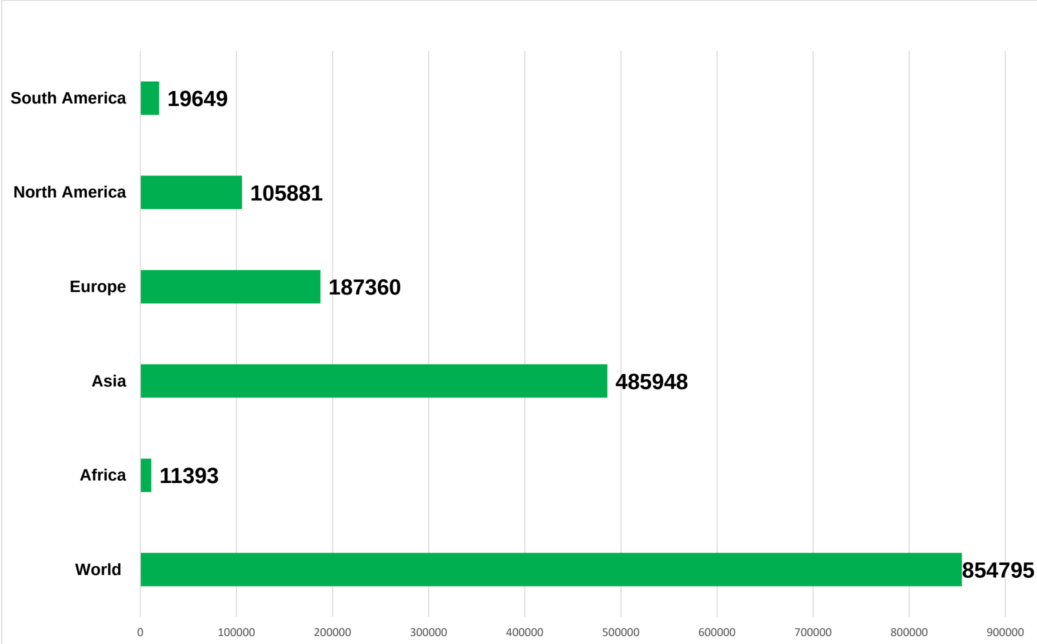

Figure 5. Solar Energy Electricity Generation by Major Economic Region, 2022. CAP MW. Source: Elaborated by the authors from data obtained from IRENA (2022a).

as Germany accounts for close to 21% of the European renewable electricity generation, followed by France, Italy, Spain, and the U.K. In South America, Brazil accounts for close to 65% of South America's renewable electricity generation (IRENA, 2022a).

In terms of hydro power, China accounts for 65% of the hydro power electricity in Asia, followed by India with 8.5%. In Europe, Norway, Italy, and Spain, are the largest producers of hydro power electricity. In North America, the U.S. and Canada are the largest producers, with the U.S. generating close to 51% of all hydropower electricity and Canada accounting for 41%. In South America, Brazil accounts for 61% of all South America's hydropower electricity generation. In terms of on-shore wind energy, China accounts for 85% of Asia's on-shore electricity generation, followed by India with 10%. In Europe, Germany with a 28% share, is followed by Spain, France, and the U.K. In North America, the U.S. has 85% market share, followed by Canada. In South America, Brazil accounts for 72% of the on-shore wind electricity generation, followed by Chile with a 10% share. In terms of off-shore wind energy, China is Asia's largest producer of off-shore wind electricity with a 96% production share. In Europe, the U.K accounts for 42% of all off-shore electricity generation, followed by Germany with 26%. North America, South America, and Africa are minor players in the global off-shore electricity generation, However, there has been a number of new projects in these regions aiming at increasing their global participation (IRENA, 2022a).

Asia also plays a large role in the solar generated electricity. China, accounts for 63% of all Asia's solar electricity generation, followed by India with 10%. In Europe, Germany accounts for 31% of all solar electricity generation, followed by Italy with 11%, followed by France, and Spain. In North America, the U.S.

accounts for 90% of all the solar electricity generation in North America. In South America, Brazil accounts for 68% of all South America's solar electricity generation (IRENA, 2022a).

In sum, renewable energy has gained substantial momentum and market share in the global electricity generation. Asia, especially China, has made substantial gains in adding renewables to their energy matrix. The European and North American countries come second and third in the global renewables race, with a heavier reliance on solar and wind energy. South America is also speeding the deployment of solar and wind capabilities. South America, however, contrary to North American countries and European countries has a substantial untapped hydropower potential. With Africa and Oceania also showing tremendous potential for the development of renewable energy from hydropower, to solar and wind, it is clear that solar and wind energy are the fastest growing segments of the global energy renewal effort. Wind and solar energy reached a 12% share of the global electricity generation in 2022. This global renewable trend is fostering and facilitating the establishment and transition to a global-driven green hydrogen revolution, a true inflection point in the world electricity generation paradigm (Wiatros-Motyka, 2023; Maguire, 2023).

Figure 6 illustrates a sample of countries that are leading the global green hydrogen transition. These countries showcase the increasing specialization that is taking place in the global green hydrogen industry. We can categorize these countries into three major groups: 1) some countries will become export platforms for the export of green hydrogen to global markets, 2) some countries will be producing green hydrogen mostly for their own domestic consumption, and 3) some of these countries, giving their abundance of natural resources be able to become major exporter of green hydrogen as well as major domestic consumers of green hydrogen.

In the first group of groups expected to become major green hydrogen export platforms we may list countries such as Australia, Brazil, and Norway. In the second group of countries mostly producing green hydrogen for their own domestic consumption we may list countries such as China, Spain, Germany, Italy, France, India, and the U.S.A. In the third group of countries, we may list countries such as Brazil, Canada, and Norway. Countries like Brazil are showing the potential to become of the world's largest producers of green hydrogen for its own domestic consumption and for exports. The same applies to countries such as Canada and Norway.

Figures 6-9, illustrates a sample of 11 countries covering Asia, Oceania, North America, South America, and Europe. It is clear that Norway, Brazil, and Canada show the largest share of renewables in the generation of electricity, followed by China, Germany, Spain, Australia and Italy. France, India, and the U.S. show a smaller share of renewables in the generation of domestic electricity. Brazil and Norway show the largest percentage of renewable electricity generated by hydropower, 68% and 88% respectively. When comes to solar power, countries like Germany, France, Australia, and India, are showing the highest share. Wind power is also another major renewable source of electricity generation for this group of countries. Germany, Spain, and Brazil showcase the largest share in the total generation of domestic electricity, followed by the U.S., Australia, and Norway.

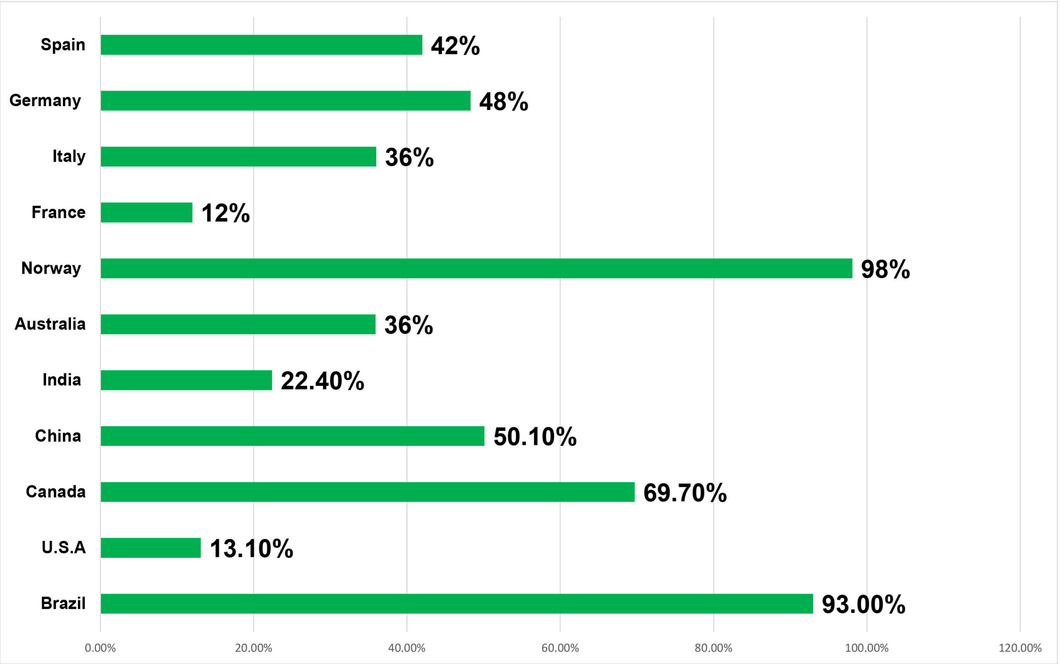

Figure 6. Percentage of Electricity Generation from Renewable Sources, 2021-2023. Source: Elaborated by the authors from data obtained from Yale Environment 360, 2023; Statista, 2023b; IRENA, 2022a, 2022b; Reuters, 2023; IEA, 2022; Renewables Now, 2023; Dennett, 2023; Ministry of New and Renewable Energy, 2023.

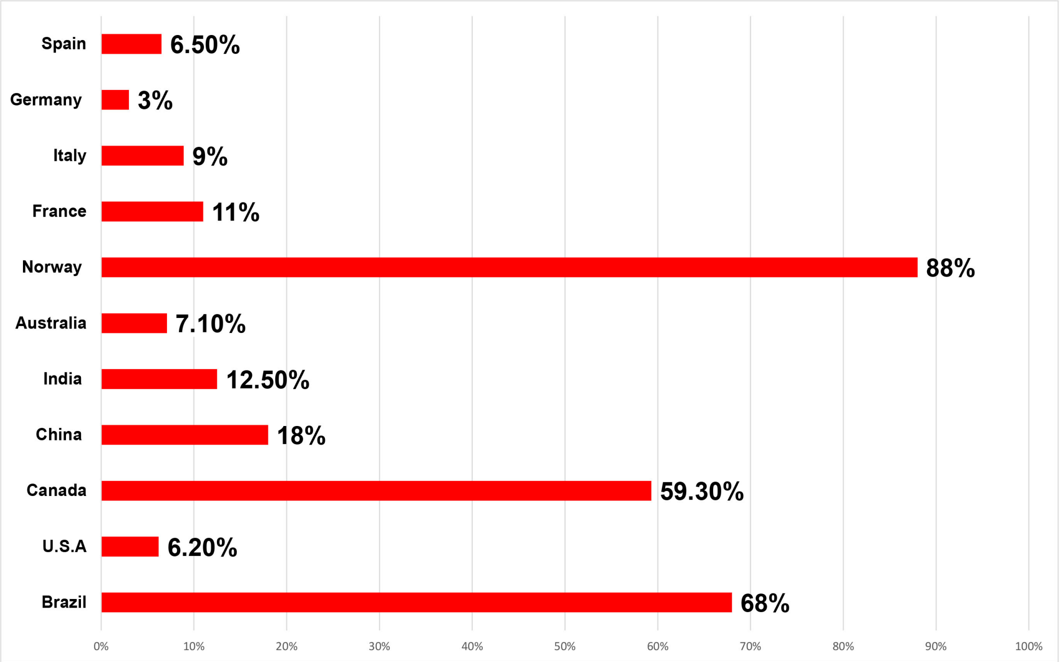

Figure 7. Share of Hydro Power Electricity Generation by Selected Countries, 2021-2022. Source: Elaborated by the authors from data obtained from Our World in Data, 2023a; IRENA, 2022a, 2022b.

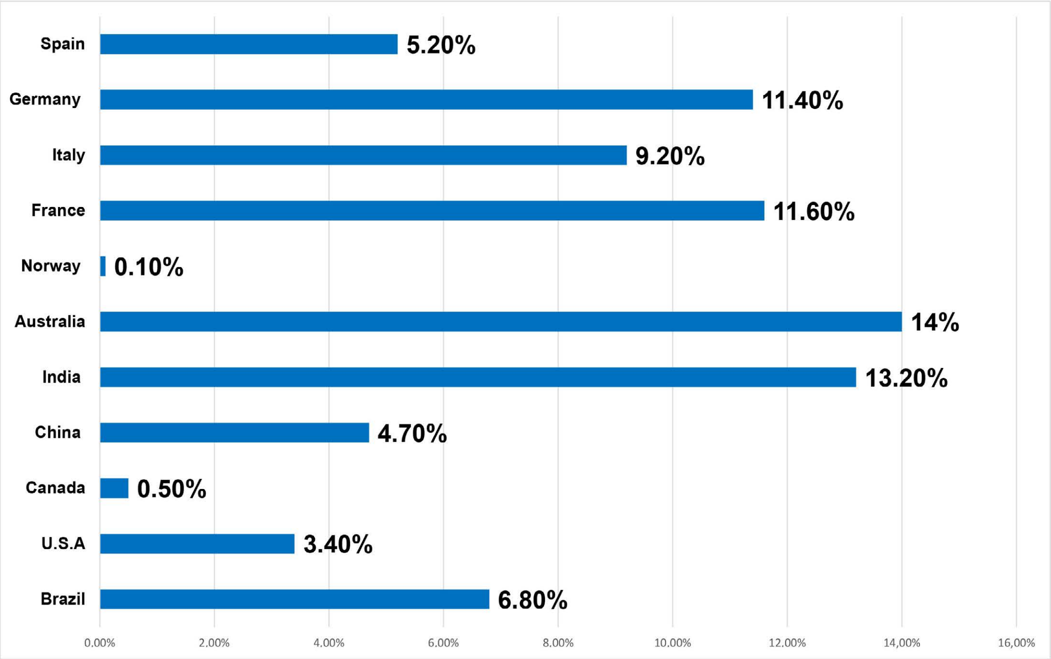

Figure 8. Share of Solar Electricity Generation, 2022. Source: Elaborated by the authors from data obtained from Statista, 2023a.

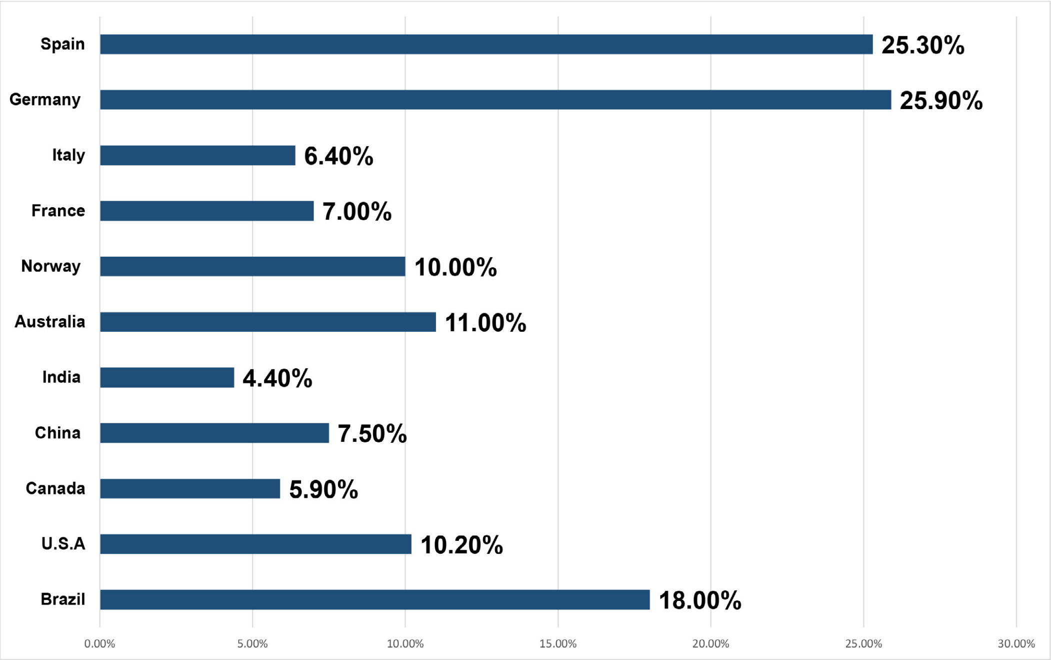

Figure 9. Wind Power Electricity Generation, 2022. Source: Elaborated by the authors from data obtained from Our World in Data, 2023b; Statista, 2023c.

Figure 10 illustrates the freshwater potential of these 11 countries. Clearly, Brazil has the world's largest fresh potential in the world, followed by the U.S., Canada, China, and India. The remaining European nations have a much smaller freshwater potential that the other countries do. Fresh water is a major component in green hydrogen production (Jagranjosh, 2022; Gouvea & Gutierrez, 2023).

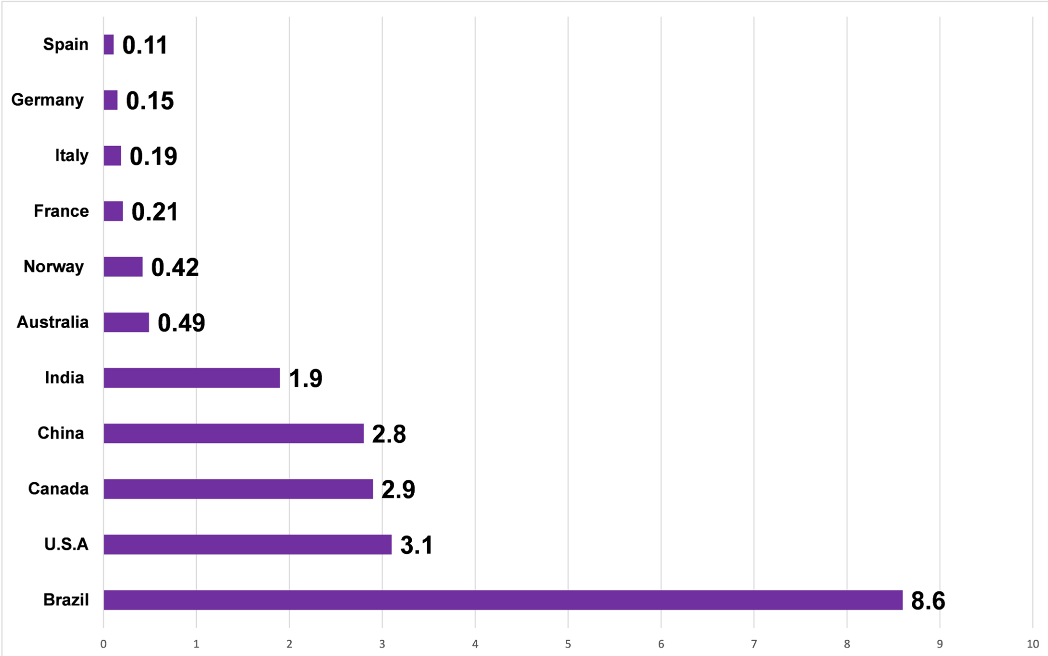

Figure 10. Selected Countries, Fresh Water Resources, in Cubic Kilometers, 2022. Source: Elaborated by the authors from data obtained from Jagranjosh, 2022.

The combination of these key natural resources for the generation of green hydrogen, renewable energy and availability of freshwater resources determine a country's ability to produce green hydrogen. Tables 1 and 10 illustrates this mix of capabilities, and also showcases how some countries have so far developed a more resilient renewable electricity mix than others, by showing a greater diversification on the renewable energy supply side. For instance, Brazil has a very diversified renewable electricity matrix, with a heavy reliance on hydropower what gives Brazil an energy security and resiliency status that many other countries do not have, by showcasing a heavier reliance on wind power and on sun power. At the same time, hydropower electricity generation is very cost effective, although the cost of solar and wind have been falling substantially in the last decade. So, clearly countries that have access to low cost hydropower electricity may be able to develop a competitive edge over countries that are more exposed to solar and wind power intermittency (ABEEolica, 2023; Agencia Brasil, 2023; Cai & Breon, 2021; Poddar, Kay, Prasad, Evans, & Bremmer, 2023).

Thus, Green Powershoring can be defined as related to a country's availability of renewable energy, such as hydropower, on and off-shore wind energy (OSW), on and off-shore solar energy, wave energy, tidal energy, kinetic energy, amongst other types of green energy. Countries that are capable of producing large amounts of renewable energy are categorized as being renewable energy-intensive economies. Thus, it is able to develop Green Powershoring competitive advantages. Countries that can be classified as having a strong Green Powershoring competitive edge are able to not only address the needs of their own domestic consumption of green hydrogen, but also capable of becoming a net exporter of green hydrogen (Arbache, 2022; Arbache & Esteves, 2023; Braga, Gouvea, & Gutierrez, 2023; Gouvea & Gutierrez, 2023).

Green Watershoring can be defined as related to a country's availability of freshwater resources. These countries can be categorized as fresh water-intensive economies. Economic activities from agriculture, manufacturing, knowledge-intensive manufacturing, to green hydrogen production, are fresh-water intensive manufacturing activities. For instance, it is estimated that by 2050, the global green hydrogen industry will demand close to 5.6 trillion liters of deionized water. Thus, only a handful of countries around the globe have the water resources to address the needs of a growing global demand for food security and renewable energy security simultaneously. Countries, like Brazil, Canada, U.S., China, and India have the Green Watershoring competitive advantage that other countries do not have (Jagranjosh, 2022; Gouvea, Kassicieh, & Montoya, 2013; Gouvea & Gutierrez, 2023).

Thus, countries with a strong Green Powershoring and a Green Watershoring competitive advantage will be able to strengthen and diversify their economies in relation to other countries from around the globe. Green-hydrogen will create a new cycle of virtuous sustainable growth and development for countries endowed with Green Powershoring and Green Watershoring competitive advantages. Green hydrogen-intensive economies will start to dominate a number of economic sectors, from agriculture to knowledge-intensive industries, creating a new environmental standard for global trade, heavily penalizing brown-driven economies. Thus, countries that are able to develop green Powershoring and green Watershoring competitive advantages will generate the creation of a green hydrogen global divide, separating countries that can cost effectively produce green hydrogen and countries that cannot produce green hydrogen. Green hydrogen producers will be price setters for green hydrogen, while importing countries will be price takers. This new geopolitical energy scenario will likely have substantial global economic consequences as well in the reallocation of energy producing centers of gravity.

For instance, global foreign direct investments are increasingly being directed towards countries that offer companies' the right environment for them to exercise their ESG's strategies. Companies seeking to design and acquire additional competitive advantages in an ESG environment, with a Net-Zero strategy, will increasingly gravitate towards countries that will allow them to fully exploit these advantages, i.e., they will increasingly relocate and be attracted to countries that are renewable-energy intensive and fresh water-intensive.

Thus, countries endowed with large amounts of fresh water and large amounts of renewable energy will be able to develop additional competitive advantages in a global economy, not only from an exporting perspective but also from and foreign direct investment perspective. For instance, companies wishing to decarbonize their production processes by also using green hydrogen, will increasingly relocate to countries capable of developing a green hydrogen supply chain, in addition to supplying green hydrogen in addition to other renewable forms of energy. Countries that are able to "green" their economies and business environments will have additional competitive advantages vis-à-vis countries that are powered by fossil fuels, the so-called brown economies.

Moreover, countries showcasing a heavier reliance on renewable sources of energy will be able to avoid the penalties being proposed by supporters of carbon taxes, giving them an additional competitive advantage over countries still relying on fossil fuels. Thus, carbon taxes will further benefit countries endowed with a strong Green Powershoring competitive advantage and further penalize countries still relying heavily on fossil fuels. It is expected that developed countries and countries endowed with a strong green Powershoring and Green Watershoring will tend to benefit the most from the imposition of a global carbon tax.

Thus, it is imperative that the imposition of a carbon tax must use some of its revenues in order to assist poorer countries in their transition from a brown to a green economy. Otherwise, the carbon tax will further widen the gap between developed and poorer countries, further violating the inclusive and equitable nature of a proposed global green economy and distancing poorer nations' ability to address the United Nations' SDGs goals and objectives.

5. The Global Blue Economy

There is a strong nexus between the Green Hydrogen Economy and the Blue Economy. The Blue Economy is composed of rivers, lakes, aquifer, and oceans. The Blue Economy is a vital source of global food, renewable energy, minerals, and a vital source of non-market services, such as environmental services. Blue Economy's ecosystems play a key role in addressing the United Nations' 2030 Agenda Sustainable Development Goals (SDGs). The global Blue has the potential to assist the global economy transition from a brown economy towards a Green Economy and a Blue Economy (Pauli, 2010, 2015, 2017; Coelho and Menezes, 2023; UNEP, 2023a, 2023b; Li, 2023; Regazzi and Procopio, 2023).

The global Blue Economy is valued at close to US$2.4 trillion, leading to the creation of 350 million jobs worldwide. The Blue Economy also holds 80% of all global transportation. It is expected that in the coming decades, the global Blue Economy will expand faster than the mainstream global economy. However, the future growth and development of a sustainable, equitable, and inclusive Blue Economy like the Green Hydrogen Economy is related to its ability to address its intergenerational impact, i.e., the Blue Economy stakeholders must pay attention to the sustainable harnessing, preservation, and regeneration dimensions of these natural capital assets (Alam, 2023; ASEAN, 2023; Attri, 2023; Blue Resources, 2022; Sailer, Wilfing, and Strauss, 2022; Yashiro, 2022).

There are several definitions for the Blue Economy. They all point it out the inclusive, equitable, and sustainable nature of economic activities linked to the sustainable exploration of rivers, lakes, aquifers, and ocean resources, paying attention to the regenerative preservation of these natural resources, and more importantly, paying attention to the intergenerational impacts of these Blue

Economy economic activities. For instance, one of the Blue Economy definitions, mostly addressing oceans, illustrates these concerns: "A sustainable ocean economy emerges when economic activity is in balance with the long-term capacity of ocean ecosystems to support this activity and remain resilient and healthy." (The Economist Intelligence Unit, 2015: p. 7).

The United Nations Sustainable Development Goal 14 mentions the regeneration, conservation and sustainable use and development of the Blue Economy's natural capital, such as its rivers, lakes, aquifers, and oceans. The SDG 14 "Life Below Water" addresses the main challenges and opportunities permeating the global Blue Economy such as the growing need to maintain the health of rivers, lakes, aquifers, and oceans, the pillars of the global Blue Economy. Thus, the Blue Economy is an important element in the larger approach to a global sustainable, inclusive, equitable, development and growth strategy (UNDP, 2023a, 2023b; World Bank, 2016; Biber, Knodt, & Visbeck, 2022; Morgan, Huang, Voyer, Benzaken, & Watanabe, 2022; Paysant & Mivielle, 2023).

More recently, the United Nation's COP 26, the United Nation's COP 27, and the United Nation's COP 28, further reinforced the role of the Blue Economy in addressing global food security, global renewable energy efforts, and role in global climate regulation. It is important to stress that the Blue Economy plays a key role in Carbon sequestration goals and strategies, in food security, and in the economic prosperity of billions of people around the planet (Ebarvia, 2016, 2022; Drew, Barsky, Gifford, Yang, Erdman, Stettler, Ludwig, & Ribet, 2020; Economic Advisory Council to the Prime Minister Government of India, 2020; UNDP, 2023b; UNCTAD, 2023).

The Blue Economy contact points with the Green Hydrogen Economy may be segmented in four major economic sectors, such as:

1) Blue Economy non-living resources (rivers, lakes, aquifers, and oceans): oil and gas, seabed mining for products such as copper, zinc, and metals and rare earths.

2) Blue Economy Renewable Energy (rivers and ocean): hydropower energy, tide energy, wave energy, and offshore wind energy.

3) Port activities: cargo and warehousing, infrastructure such as ports.

4) Shipbuilding and maritime transport, river transportation, and lake transportation.

The Green Hydrogen Economy and the Blue Economy have a symbiotic interaction where the sustainability of fresh water resources have a great impact on the Green Hydrogen Economy as well as the Green Hydrogen economy also have a great sustainability impact on areas of the Blue Economy such as renewable energy generation, transportation, and infrastructure.

6. Final Remarks

The global economy is going through an energy inflection point. This inflection point is reflecting the dawn of a new energy paradigm, one in which renewable energy will be replacing fossil fuels. This replacement will be gradual; however, it is an inexorable change in the global energy paradigm away from fossil fuels.

Renewable energy resources and freshwater resources are fostering the introduction of green hydrogen in global markets. Increasingly, countries are introducing a number of incentives to expand their capacity to expand the production of green hydrogen. More than ever, Public-Private Green Hydrogen Partnerships (PPGHP) will have to be fostered in order to expedite the production and expansion of the green hydrogen in a number of carbon-intensive industries, such as electricity generation, transportation, agriculture, manufacturing, and services industries, targeted for decarbonization. Companies seeking to meet their net-zero emissions will be gravitating towards countries that can offer the capability of addressing their ESG strategies.

Countries able to develop a Green Powershoring and a Green Watershoring competitive advantage will have a definite edge over countries still relying heavily on fossil fuel sources to power their agriculture, manufacturing, and services industries. Moreover, this green hydrogen divide, separating green hydrogen producers from non-green hydrogen producers will create additional frictions in global markets, where trade barriers may be created in order to create incentives for countries to engage in decarbonization strategies.

Moreover, the global energy axis of power and influence will also be affected by this new energy paradigm, where traditional fossil fuel producers will be increasingly replaced by green hydrogen producers. Moreover, it is to be expected that major green hydrogen producers will organize themselves in creating a standard certification for green hydrogen. Thus, we may expect to see the creation of an organization of green hydrogen producers and exporting countries, in order to better influence the global prices of green hydrogen. Thus, we may see the creation of an organization such as the Green Hydrogen Exporting Countries (GHECs), along the lines of the current OPEC.

Countries like Brazil, Canada, the U.S., China, and Australia, will be at the center of the global green hydrogen revolution. Countries like Brazil have a diversified, resilient, and reliable renewable electricity matrix, in which hydropower, solar, and on-shore and offshore-wind power are the leading renewable sources of electricity. In addition, Brazil also has the world's largest freshwater reserves. In Brazil, green hydrogen will be introduced to power its agribusiness industry, manufacturing, and services industry, offering Brazil a new cycle of a virtuous sustainable development and growth. Products such as green steel and hydrogen intensive intermediate products could signal Brazil's re-industrialization as a result of embedded green hydrogen in several sectors of Brazil's economy. Moreover, Brazil's green-hydrogen production possibility frontier is able to expand given Brazil's Green Powershoring and Green Watershoring competitive advantages. Thus, being able to accommodate Brazil's growing domestic demand for green hydrogen, as well as allowing Brazil to become a major global exporter of green hydrogen.

Moreover, efforts must be made to establish common rules and guidelines regarding hydrogen certification in order to avoid the creation of trade barriers and non-tariff trade barriers in the global green hydrogen global trade.

Demand-side challenges are one of the barriers when establishing a global green hydrogen-based economy. For instance, lowering the delivery transportation cost of green-hydrogen from co-located production and offtake is a major barrier in a number of countries. For instance, Brazil could take advantage of its hundreds of hydropower plants located all over the country in order to lower the transportation and energy losses derived from long distance shipment of green hydrogen. For instance, Brazil could produce green hydrogen near its largest hydropower power plant, Itaipu a 14,000 MW power plant, thus supplying green hydrogen to its most developed economic regions—the South and Southeast regions. Thus, some countries more than others, will be able to producer and deliver green hydrogen to its final customers more competitively than others.

Thus, cutting cost recommendations would include the development of green hydrogen distribution and storage infrastructure, scaling the production of electrolyzers, create mechanisms to attract private investment such as developing regulations, standardize regulations across countries, standardize processes and systems, invest on green hydrogen innovation and R&D, invest in green hydrogen human capital, expand green hydrogen financing. Policy-makers and the private sector also must engage in partnerships in order to expand and solidify a growing demand for green hydrogen in a number of global economic sectors.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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