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RESEARCH **ARTICLE**

Hydrogen Hub Potential in the Caribbean: Towards a Sustainable Future

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ABSTRACT

The Caribbean presents a wide range of opportunities with varying potential to contribute to the Gross National Incomes of the countries. However, the tourism industry remains a key source of income but is vulnerable to disasters and other upheavals. There are alternatives to sustainable growth such as the blue economy with the potential for hydrogen extraction from the Caribbean Sea, which can make a significant contribution. The Caribbean Transshipment Triangle boasts significant port infrastructure that plays a crucial role in transporting goods and has the potential to become hydrogen hubs. The aim of this research is to examine the potential for countries in the region to develop this industry. A quantitative methodology was employed to examine the correlation between renewable energy and economic growth among six major transshipment countries in the Caribbean transshipment triangle, from 2010 to 2020. The study employed the Pearson correlation coefficient to analyze the data collected from these countries. The findings indicated that the Dominican Republic and Panama had the highest correlation between renewable energy and economic growth. Specifically, Jamaica, Panama, and the Dominican Republic demonstrated a moderate to high correlation between Renewable Power Capacity (RPC) and GDP. Consequently, investing in port infrastructure to facilitate hydrogen production, storage, distribution, and export could have positive effects on these economies. These findings are of interest to governments, managers, professionals, policymakers, and investors in the power generation sector. The research supports visions of a resilient blue economy and ad-

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dresses sustainable development concerns in the Caribbean region.

Keywords: Caribbean Region; Green Hydrogen; Renewable Energy; Transshipment; Hydrogen Hub; Sustainable Growth

1. Introduction

The Caribbean is a highly diverse region with many economic growth and development opportunities. The Gross National Income (GNI) per capita varies extensively, ranging from US$800 for countries such as Haiti to over US$30,000, for countries such as the Bahamas. However, most countries rely heavily on tourism while others rely on a combination of tourism and commodity exports [1]. The Caribbean is world-renowned for its breathtaking landscapes and rich cultural experiences, making it a prime tourist destination. While the tourism product has expanded from sand, sea and sun, they remain the main areas around which activities are organized. In this age of climate change concerns and the search for renewable energy, the sustainable management and use of ocean resources, commonly referred to as the "blue economy," offers a promising avenue for economic diversification while simultaneously preserving the environment. Specifically, the blue economy holds significant potential for extracting hydrogen from the Caribbean Sea.

Researchers have successfully developed a cost-effective method for non-invasive hydrogen extraction, which is highly advantageous. This approach has led to the production of green hydrogen, a highly reactive fuel alternative that reduces emissions, offering a viable substitute for the Caribbean's dependence on fossil fuels. Due to the region's heavy reliance on the aviation and maritime industries to drive its economies, hydrogen fuel produced within the Caribbean presents a promising option for use in cruise and cargo ships. Furthermore, hydrogen can also be utilized to generate electricity, enabling the establishment of stationary power plants in the region, thereby reducing the demand for fuel imports. Leveraging the vast potential of seawater, hydrogen energy represents an excellent way for the region to promote sustainability and economic growth.

The global trade industry heavily depends on maritime shipping, which accounts for more than 80% of trade by volume and over 70% by value [2]. In the Caribbean region, maritime transport is responsible for transporting 90% of international goods by sea, making it a crucial player in the global economy [3]. This mode of transportation also generates more CO_2 emissions than the entire Latin America and Caribbean region combined, making it imperative to explore alternative fuel options. Hydrogen fuel presents a potential solution to meet the International Maritime Organization's (IMO) targets of reducing shipping carbon intensity by 40% by 2030 and halving emissions by 2050. Given the Caribbean's reliance on marine and coastal resources, increased greenhouse gas emissions could have profound environmental and economic impacts.

The utilization of hydrogen fuel presents a promising solution to the economic and environmental challenges currently faced by the region. As shown in **Figure 1**, the Caribbean Transshipment Triangle encompasses several crucial transshipment ports, such as Colon in Panama, Kingston in Jamaica, Freeport in the Bahamas, Caucedo in the Dominican Republic, Point Lisas in Trinidad and Tobago, Cartagena in Colombia, Manzanillo in Panama, Bridgetown in Barbados, and Willemstad in Curaçao These ports play a pivotal role in facilitating the transportation of goods and possess the potential to serve as hydrogen hubs in the wider Caribbean region. For example, Jamaica's strategic location renders it a prime location as a hydrogen fuel supply hub.

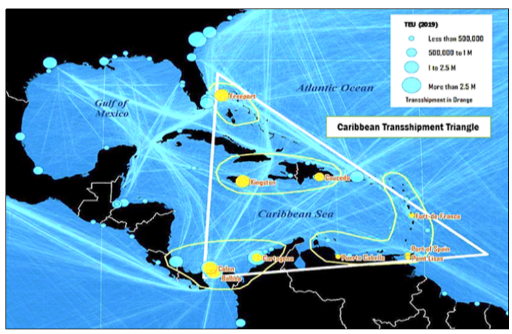

Figure 1. The Caribbean transshipment triangle.

Source: [3]

This study explores the feasibility of this proposal. It examines the countries in the transshipment triangle to assess their potential as hydrogen hubs. Its conclusions will be invaluable for policymakers, investors, and environmental advocates.

The remainder of this paper first discusses the production of hydrogen from the sea, including the global demand for this energy source, and how ports have been used as hydrogen hubs in other parts of the world. Next, the methodology of the paper is outlined. The findings are then discussed and conclusions drawn.

2. Production of Hydrogen from the Sea

The production of hydrogen from seawater involves the utilization of electricity to split water molecules into hydrogen and oxygen gases through electrolysis (**Figure 2**). Hydrogen is a dynamic alternative fuel source for energy production in various sectors, particularly in regions where fresh water is scarce. Research conducted by Aal, Atekwana and Atekwana [4] has indicated that seawater and solar energy sources could be employed to produce hydrogen. This is particularly useful in the renewable energy sector. Nevertheless, generating clean hydrogen energy from seawater poses several challenges, as noted by Mohammed-Ibrahim and Moussab [5], who suggest that the system's efficiency could be improved by utilizing efficient electrocatalysts and anticorrosion measures.

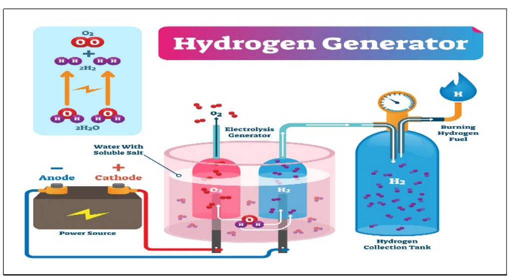

Figure 2. The principle of extracting hydrogen from seawater.

Source: Deloitte [6].

Electrolysis is an expensive and energy- and water-intensive process, and it produces toxic chlorine as a byproduct, according to a report by the University of Colorado Boulder [7]. The US Department of Energy [8] highlights the need to decrease production costs to make hydrogen competitive with conventional transportation fuels. Despite these challenges, breakthrough technology has helped overcome them. For example, an international team of scientists from the University of Adelaide has developed a cost-effective method to directly produce hydrogen from seawater [9]. This technology is continuously evolving to reduce energy costs and environmental impact and benefit vulnerable economies, such as those in the Caribbean.

2.1. Hydrogen Production Model (Decarburization)

In the realm of decarburization, two primary types of hydrogen are utilized. The first variant, known as "green" hydrogen or renewable hydrogen, is generated through the process of electrolysis, whereby water molecules are separated using electricity sourced from renewable energy sources. The second type, referred to as "blue" hydrogen or low-carbon hydrogen, is created through the utilization of methane reforming plants that incorporate CO_2 capture mechanisms and subsequently store the CO_2 [9]. As shown in **Figures 3** and **4**.

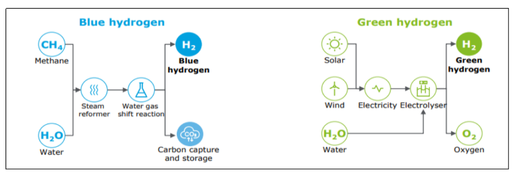

Figure 3. Green vs blue hydrogen production.

Source: Deloitte [6]

2.2. Concept of Green Hydrogen

Water electrolysis is a widely used method for producing green hydrogen. The process involves passing an electric current through water (H_2O) via electrodes to separate oxygen gas (O_2) and hydrogen gas (H_2). Renewable energy sources such as wind and solar power are used to power the electrolyzers, ensuring that the production process generates no greenhouse gas emissions. This makes it one of the most environmentally friendly methods for producing H_2. Companies that produce green hydrogen recognize the importance of their fuel in the shift towards sustainable energy. It offers a viable alternative to traditional, pollutant-emitting fossil fuels and is a key factor in achieving a cleaner, more sustainable future [9]. **Figure 4** shows the concept of sustainable green hydrogen production that would be a proposed model for ports within the Caribbean transshipment triangle.

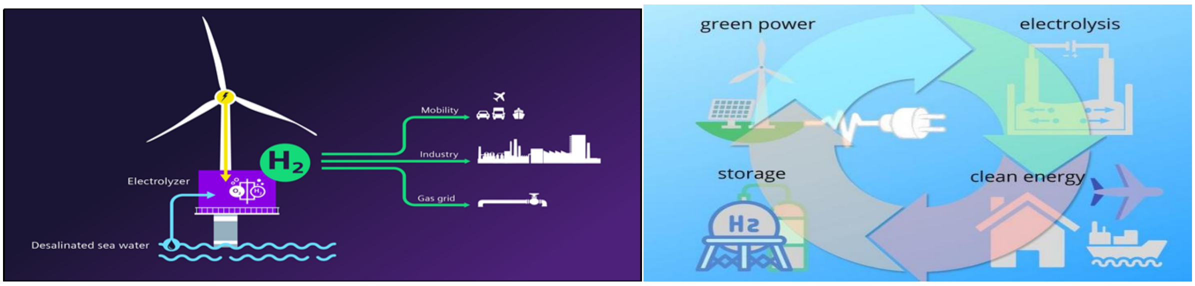

Figure 4. Generation of seawater and sustainable model for green hydrogen.

Source: Deloitte [6].

2.3. Growth of Hydrogen Demand

2.3.1. Global Demand

The demand for hydrogen as an environmentally friendly and versatile energy source has experienced a significant upsurge across various sectors, owing to its potential in transportation, industrial processes, and exportation. This trend is driven by several factors, including efforts towards decarburization. According to the 2023 Grand View report, the global hydrogen generation market was valued at USD 155.35 billion in 2022 and is expected to experience an annual growth rate of 9.3% from 2023 to 2030. This growth can primarily be attributed to the increasing regulations by governments for the desulfurization of petroleum products and the need for cleaner fuel. This demand is motivated by the increased emphasis on decarburization. A recent study by Vijayakumar et al. [10] looked at hydrogen adoption in global economies, focusing on Japan, Germany, South Korea, and the United States. Japan, Germany, and South Korea, prioritize sustainable hydrogen supply chains, while California focuses on increasing demand, particularly for transportation. Japan, South Korea, and Germany will import hydrogen, while California can produce it at lower costs but needs to invest in infrastructure. Similarly, the demand for hydrogen for industrial users is unprecedented.

According to IEA [11], the demand for hydrogen has experienced a more than threefold increase since 1975 and there are no indications of this decelerating. This implies that 6% of the world's natural gas and 2% of the world's coal are utilized in the generation of hydrogen. The increasing demand for hydrogen is accompanied by a significant environmental impact stemming from its production. As stated by IEA [11], the yearly production of hydrogen results in the emission of approximately 830 million tons of carbon dioxide. This volume of CO_2 emissions is equivalent to the combined emissions of the United Kingdom and Indonesia.

According to the World Energy Council [12], the number of hydrogen partnerships worldwide is increasing and expected to grow; global trade in hydrogen is likely to follow current traditional fossil fuel trades. Regions and countries such as the Middle East, Africa, the United States, South America, and Australia have tremendous potential to become the largest exporters, primarily due to access to ample renewable energy or large oil and natural gas reserves. Hydrogen needs to be decarbonized, which will require the total capacity of our worldwide renewable energy production. Developing countries could respond to this need by exporting green hydrogen produced by the wind and solar energy they possess in abundance.

2.3.2. Demand for Hydrogen within Latin America and the Caribbean (LAC)

The adoption of low-carbon hydrogen is gaining traction in Latin America, with many nations currently developing long-term hydrogen strategies and boasting a pipeline of more than 25 projects. Notably, several of these ventures are gigawatt-scale in size, indicating a strong drive to export hydrogen beyond the region. Although the prospect of the venture is in line with several policies geared towards reducing carbon emissions, which inevitably makes Latin America play a major role in the low-carbon hydrogen energy transition [13]. The demand for hydrogen is fueling the demand for its production.

IEA [13] reported that in 2019, the region's industrial and oil refining sectors required more than 4 MT of hydrogen, representing approximately 5% of the global demand. Trinidad and Tobago account for more than 40% of total hydrogen demand. Currently, there exist 12 countries within the region that have either adopted or are in the process of developing green hydrogen strategies. Notably, Chile, Colombia, Uruguay, Costa Rica, Trinidad and Tobago, and Panama have published their strategies within the past three years. While Chile and Colombia have recently released their strategies, they have already initiated the process of updating them. Paraguay and Argentina have established hydrogen roadmaps, while Bolivia, Brazil, Ecuador, and Peru are presently developing their strategies [13]. Panama and Costa Rica intend to be the distribution hub for the region as shown in **Figure 5**.

Figure 5. Framework of GH2 for LAC.

Source: IEA [11].

2.4. The Port as a Hub for Hydrogen Supply Chain

The significance of ports as pivotal centers for developing and supporting hydrogen supply chains is on the rise. They offer a multitude of advantages for incorporating hydrogen production, storage and distribution [11]. Major ports located within the Caribbean transshipment triangle (see **Figure 1**), such as Colon, Panama; Freeport, Bahamas; Limon, Costa Rica; Kingston, Jamaica; Caucedo, Dominican Republic; Lisas, Trinidad and Tobago, and Bridgeport, Barbados, hold the potential to contribute to the establishment of a sustainable hydrogen supply chain. However, several factors must be carefully considered, including infrastructure, proximity to demand centers, transportation, integration with renewable energy sources, industrial synergies, export possibilities, economic growth, energy storage, and environmental benefits. The readiness of a port to take on the investments and policies can be a major challenge for both regional and international ports.

Chen et al. [14] reviewed the readiness of ports to facilitate international hydrogen trade. The findings revealed that the capacity of ports to facilitate global hydrogen trade is subject to a multitude of factors, including the availability of hydrogen infrastructure, the regulatory framework, and stakeholder involvement. Further findings also identified several ports, such as Rotterdam, Antwerp and Hamburg, as optimal locations for the early implementation of hydrogen import and export. Seaports have the potential to serve as crucial hubs for the exportation of green hydrogen to other nations, thereby playing a significant role in propelling the global transition towards clean energy. To establish a strong foothold in the green hydrogen industry, ports must actively engage in every aspect of the hydrogen value chain [15].

Ports play a critical role in the hydrogen supply chain and present numerous growth opportunities for the hydrogen industry. They are integral to the logistics of hydrogen transportation, facilitating both import and export, and providing essential handling and services to ships that utilize hydrogen fuel. Moreover, the implementation of hydrogen technologies such as fuel cells to power marine service vessels and other port assets like vehicles and heavy machinery can significantly lower CO_2 emissions or even achieve zero emissions. Therefore, ports can play a crucial role in promoting sustainable practices and reducing the carbon footprint of the transportation industry [16]. Deloitte's report [9] revealed that the industries and shipping sector will continue to be the main users of hydrogen in European port areas, accounting for 42% and 31% of the total demand by 2050. This emphasizes the significant role these sectors play in determining the future of hydrogen use and highlights the necessity for strategic planning and investment in this field.

2.5. Maritime Industry

2.5.1. Hydrogen Hubs

The maritime industry is accountable for a mere 2.9% of worldwide greenhouse gas emissions and boasts some of the lowest carbon emissions per ton-kilometer (t.km) of any transportation sector [17]. Nevertheless, maritime emissions are projected to increase as international trade continues to expand [9]. Furthermore, maritime shipping is vital in facilitating low-carbon transitions in other industries.

The maritime industry plays a pivotal role in facilitating international hydrogen trading. However, for hydrogen to become a practical and effective alternative fuel that drives the transition towards clean energy, it is crucial to establish a comprehensive supply chain, logistics, supportive infrastructure, and new ports. The emergence of hydrogen import and export hubs worldwide is anticipated, aimed at facilitating countries' decarbonization efforts and leveraging existing trade connections with port terminals [18].

Hydrogen hubs serve as a platform for diverse hydrogen users, including those from the industrial, transport, and energy sectors. These hubs alleviate infrastructure expenses and foster economies of scale in the production and delivery of hydrogen to consumers. Additionally, they promote collaboration and innovation across various sectors [18]. Small Island Developing States (SIDS) such as those in the Caribbean can capitalize on using renewable energy to generate exports to major markets such as Japan, Singapore, South Korea, and Germany (see **Figure 6**). Hydrogen can act as a new energy vector, and the maritime sector has a major role to play.

Figure 6. Potential hydrogen import-export market.Source: IEA [11].

Potential applications of hydrogen through hydrogen hubs:

1. Import and export of hydrogen and derivatives such as ammonia.
2. Storage and distribution through multimodal transport for delivery to customers (road, rail, pipeline, inland waterways, etc.)
3. Hydrogen/ammonia fueling for ships.
4. Use green hydrogen to power a power plant and produce green electricity.
5. Hydrogen fuel cells for port vehicles and equipment.
6. Hydrogen refueling stations for local transport, such as cars, trucks and buses.
7. Application to support various industries by generating heat, electricity or chemical feedstock.

2.5.2. Hydrogen Powered Ships

Hydrogen-powered ships, also known as hydrogen fuel cell ships, are vessels that use hydrogen gas as a fuel to generate electricity through fuel cells. This electricity is then used to power the ship's propulsion and onboard systems [17]. The use of hydrogen as a fuel for ships is gaining attention due to its potential to reduce greenhouse gas emissions and air pollutants compared to conventional fossil fuels. Although it is forecast that zero-emission hydrogen demand is expected to increase by 500% by mid-century. Infrastructural development is the key factor that will foster economic growth from sustainable hydrogen production. Hence, investing in renewable energy is of utmost importance in the pursuit of cost-effective green hydrogen for shipping purposes. According to Matthé et al. [18], the production of green hydrogen must be competitive with the current marine gas oil or liquid natural gas (LNG) in order to succeed. This necessitates significant production on a large scale within nations to ensure a sustainable return on investment (ROI).

The Latin American region holds promise as a significant producer and distributor of green hydrogen. While the cost of petroleum-based hydrogen production is dominant, the negative impact of carbon emissions is counterproductive. To address this, experts suggest employing sustainable energy to extract hydrogen from the sea. This approach is crucial for creating a sustainable hydrogen market, generating important by-products, and obtaining fresh water from the sea. The

Caribbean's transshipment ports can serve as a strategic source of hydrogen production and distribution to significant markets such as Germany, Japan, South Korea, and Singapore. The aim of this research is to examine the potential for countries in the region to develop this industry to serve as a strategic hub for hydrogen production and distribution via the maritime supply chain network. Pearson correlation will be utilized to determine which renewable energy capabilities and maritime factors contribute to economic growth. The findings of this research will aid policymakers and investors in decision-making and contribute to academic studies.

3. Methodology

The production of green energy relies on renewable sources, in contrast to non-renewable sources such as fossil fuels. Across the globe, individuals, organizations, and governments are shifting away from fossil fuel energy to green energy in order to mitigate the effects of climate change and pollution. The relationship between renewable energy and GDP growth is intricate and influenced by various factors, including governmental policies, technological advancements, market dynamics, and environmental considerations. Nevertheless, renewable energy has a positive impact on economic development [19]. This study assesses the feasibility of establishing a hydrogen hub in the Caribbean Transshipment Triangle, which encompasses six regional transshipment ports (Jamaica, Panama, Bahamas, Barbados, Dominican Republic (DR), and Trinidad & Tobago). By employing a multiple regression model and Pearson correlation, we will examine the connection between specific variables and economic growth. These variables consist of Gross Domestic Product (GDP), Port Infrastructure Index, Port Liner Shipping Connectivity Index, renewable power capacity, renewable power generation, alternative and nuclear energy, and carbon dioxide emission. Could other countries be added? There are more countries in the Triangle, how do you account for using these alone and why? For the conference to expand and change it a bit to something "new" if other countries can be added, it would be good.

3.1. Model

3.1.1. Model of Pearson Correlation

The Pearson correlation coefficient, often denoted as r, is a statistical measure that quantifies the linear relationship between two continuous variables. It assesses the strength and direction of the linear association between these variables. The correlation coefficient ranges from −1 to +1, where −1 indicates a perfect negative linear relationship, +1 indicates a perfect positive linear relationship, and 0 indicates no linear relationship.

3.1.2. Mathematical Formula

The Pearson correlation coefficient between two variables X and Y is computed using the following formula:

$$r = \frac{\Sigma(Xi - \bar{X})^2 (Yi - \bar{Y})}{\sqrt{\Sigma(Xi - \bar{X})^2 (Yi - \bar{Y})^2}} \tag{1}$$

Where:

N is the number of data points.

X_i and Y_i are individual data points of variables X and Y respectively.

$\bar{X}$ and $\bar{Y}$ are the means of variable X and Y respectively.

3.2. Data

The data was retrieved from the World Bank and The Global Economy for the six (6) port countries for the period 2010 to 2020. The following data were retrieved:

3.2.1. Gross Domestic Product (GDP)

The Gross Domestic Product (GDP) denotes the comprehensive value of all the finished goods and services that a nation produces within its territorial boundaries during a specified time frame. This parameter serves as a comprehensive measure of a country's economic prosperity [20]. **Figure 7** illustrates the GDP of the six countries in the study.

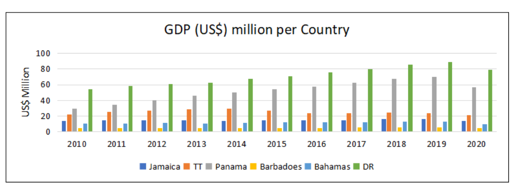

Figure 7. GDP per country.

Source: Own elaboration.

3.2.2. Renewable Power Capacity (Million Kilowatts)

Renewable power generation capacity is measured as the maximum net generating capacity of power plants and other installations that use renewable energy sources to produce electricity. **Figure 8** illustrates the renewable power capacity per country.

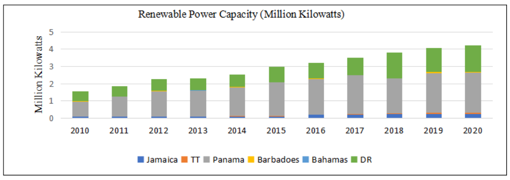

Figure 8. Renewable Power Capacity per country.

Source: Own elaboration.

3.2.3. Renewable Power Generation (Billion Kilowatt Hours)

Renewable power generation refers to the process of generating electricity from renewable energy sources that are replenished naturally and sustainably, such as solar, wind, hydro, geothermal, and biomass. **Figure 9** illustrates the renewable power capacity per country.

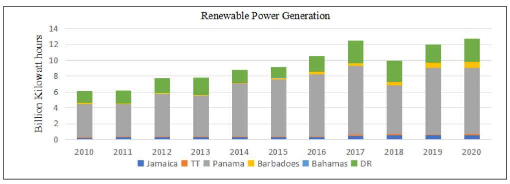

Figure 9. Renewable Power Generation.

Source: Own elaboration.

3.2.4. Alternative and Nuclear Energy, Percentage of Total Energy

Alternative energy refers to energy sources that are replenished naturally and can be used without depleting their finite resources. These sources are considered more environmentally friendly compared to fossil fuels. **Figure 10** illustrates the alternative and nuclear energy as a percentage of total energy per country.

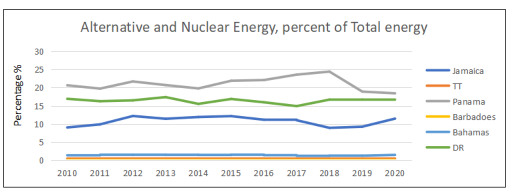

Figure 10. Alternative and nuclear energy, percent of total energy.

Source: Own elaboration.

3.2.5. Carbon Emission per Capita

The concept of "carbon dioxide emissions per capita" pertains to the level of CO_2 generated by an individual within a specific region or country. Typically, this is quantified as metric tons per person per annum. This metric provides insight into the degree of CO_2 each person generates towards overall emissions. It is crucial to consider when addressing accountability for greenhouse gas emissions and assessing the ecological impacts of various populations [20]. **Figure 11** illustrates the carbon emissions per country.

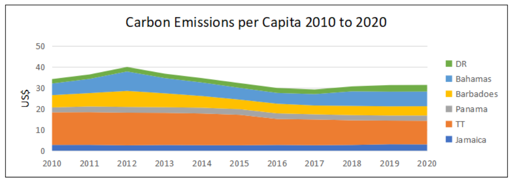

Figure 11. Carbon emissions per capita.

Source: Own elaboration.

3.2.6. Port Infrastructure Index

Carbon dioxide emissions per capita represent the quantity of CO_2 discharged by an individual in a specific region or country. This metric is typically gauged in metric tons per person annually and offers valuable insights into the average contribution of each person to the overall CO_2 emissions. It is a critical factor when deliberating on liability for greenhouse gas emissions and evaluating the environmental impact of different populations [20]. **Figure 12** illustrates the port infrastructure index per country.

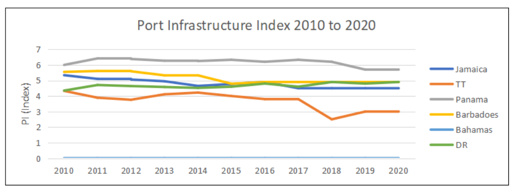

Figure 12. Port infrastructural index 2010 to 2020.

Source: Own elaboration.

3.2.7. Port Traffic

The quantification of port container traffic necessitates meticulously monitoring container movements between land and sea transport modes, both domestic and international, utilizing twenty-foot equivalent units (TEUs) as a standard metric. This process also encompasses transshipment traffic, accounting for two lifts at the intermediate port (once for off-loading and again for outbound lifting) and includes empty units[20]. **Figure 13** illustrates the port traffic per country.

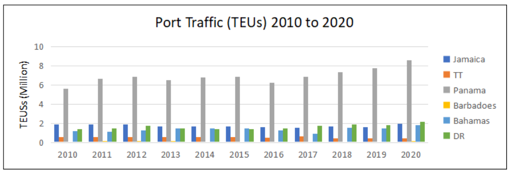

Figure 13. Port traffic (TEUs).

Source: Own elaboration.

3.2.8. Port Liner Connectivity Index (PCI)

The Port Liner Connectivity Index is a metric that measures the level of connectivity of ports to liner shipping services. These services involve regular and scheduled cargo transportation provided by shipping companies between specific ports. The degree of connectivity is critical for a port's integration into regional and global shipping networks, as well as its desirability to liner shipping firms and cargo shippers. This index assesses the extent of connectivity and reflects a port's degree of integration. **Figure 14** illustrates the port liner connectivity per country.

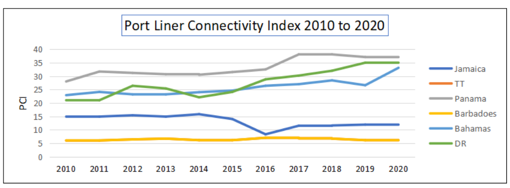

Figure 14. Port Liner Connectivity Index (PLCI).

Source: Own elaboration.

4. Results

The Pearson correlation for the six (6) countries relates to the correlation between economic (GDP) for Renewable Power Capacity (RPC), Renewable Power Generation (RPG), Alternative and Nuclear Energy (ANE), Carbon Emission per Capita (CE), Port Infrastructure Index (PI), Port Traffic, and Port Liner Connectivity Index (PCI) (see **Table 1**).

4.1. Jamaica

The data analysis reveals a robust positive correlation (0.550) between Jamaica's Gross Domestic Product (GDP) and its Renewable Power Capacity. Similarly, there is a significant positive correlation (0.618) between the country's GDP and Renewable Power Generation. In contrast, the maritime factors of Port Infrastructure (−0.543) and Port Traffic (−0.419) exhibit a negative medium correlation with the GDP. Moreover, the Port Connectivity (−0.274) demonstrates only a slight correlation with the GDP. These results suggest that investment in renewable power capacity and generation may have a positive impact on Jamaica's economic growth, while maritime factors such as port infrastructure and traffic may have a negative effect.

4.2. Trinidad & Tobago

The results of the study indicate that there exists a moderate negative correlation of −0.489 between the renewable power capacity and the GDP of Trinidad &Tobago. However, no correlation was found between the generation of renewable power, alternative energy, nuclear energy, and GDP. Conversely, a high correlation of 0.618 was observed between the GDP and carbon emissions per capita. Additionally, port infrastructure and port traffic were found to have a moderate correlation with maritime factors, showing correlations of 0.395 and 0.447, respectively.

4.3. Panama

The results of the study indicate that the majority of the analyzed factors demonstrated a significantly positive correlation with Panama's Gross Domestic Product (GDP). Specifically, Renewable Power Capacity, Renewable Power Generation, Port Traffic, and Port Liner Connectivity demonstrated correlations of 0.936, 0.842, 0.628, and 0.842, respectively. However, Carbon Emission per Capita and Port Infrastructure exhibited little to no correlation, with respective correlations of −0.267 and −0.358. These findings suggest that Panama's GDP is heavily influenced by certain factors such as renewable power sources and port connectivity, while others

Table 1. Correlation results for the six (6) port countries within the Caribbean transshipment.

Variables \ Country	Jamaica	Trinidad &Tobago	Panama	Barbados	Bahamas	Dominican Republic
GDP	1	1	1	1	1	1
RPC	0.550268152	−0.48942986	0.936530177	0.380490926	7.60818E−16	0.896929971
RPG	0.618460469	1.28031E−16	0.842798666	0.452620874	7.60818E−16	0.692717151
ALTE	−0.347800408	1.28031E−16	0.259941466	1.81341E−15	−0.72862547	−0.198345927
CDE	0.203015561	0.617556988	−0.26798821	−0.561554739	−0.20040774	0.682295074
PI	−0.542916892	0.447107026	−0.35801149	−0.569411501	7.60818E−16	0.716229001
PT	−0.419614721	0.395406392	0.628014219	0.650952568	−0.068548983	0.613127664
PCI	−0.27403849	0.012450925	0.842114247	0.333563107	0.111774819	0.880685196

Note: 0.0 < 0.1 – no correlation, 0.1 < 0.3 – little correlation, 0.3 < 0.5 – medium correlation, 0.5 < 0.7 – high correlation and 0.7 < 1 – very high correlation.
Source: Own elaboration.

such as carbon emissions and port infrastructure may not play as significant a role.

4.4. Barbados

The results of the analysis indicate that there exists a moderate correlation between Renewable Power Capacity and Renewable Power Generation and the Gross Domestic Product (GDP) of Barbados, with correlation coefficients of 0.380 and 0.452, respectively. Conversely, Port Traffic exhibits a strong correlation, while Port Liner connectivity shows a moderate correlation of 0.650 and 0.333, respectively. In contrast, both Carbon Emission per Capita and Port Infrastructure display a negative and strong correlation with GDP. These findings highlight the importance of renewable power sources and sustainable transport infrastructure in driving economic growth, while also emphasizing the need to address carbon emissions and improve port infrastructure to support economic development.

4.5. Bahamas

The results revealed that all variables showed little to no correlation to Bahamas GDP due to the limited data.

4.6. Dominican Republic

The findings of a recent study indicate that the Gross Domestic Product (GDP) of the Dominican Republic displays a strong correlation with several key factors, while others seem to have little to no impact. Specifically, the study found that alternative and nuclear energy sources did not have a significant correlation with the country's GDP. However, several other factors exhibited a strong correlation with the GDP, including renewable power capacity, renewable power generation, carbon emissions per capita, port infrastructure, port traffic, and port liner connectivity. The respective correlation coefficients for each of these factors were 0.896, 0.692, 0.682, 0.716, 0.613, and 0.881.

5. Discussion

The findings of the study revealed that the relationship between the variables of RPC, RPG, ALTE, CDE, PI, PT, and PCI, and economic growth (GDP) is subject to variation in different countries (**Table 1**). Moreover, the synchronization of renewable energy variables with green hydrogen production also varies depending on the country, in terms of sustainable renewable energy supply. Furthermore, the capacity of a port to handle maritime activities is a critical factor in the supply chain for sustainable hydrogen fuel. This is evidenced by the port performance indicators (PPI) such as PI, PT, and PCI, which indicate the ability of the port to play an integral role in the supply chain of sustainable hydrogen fuel (**Figures 12–14**).

The Dominican Republic presents an appealing prospect for investing in hydrogen, thanks to its reliance on sustainable energy sources and its significant involvement in maritime activities, including port infrastructure, port traffic, and port liner connectivity. Meanwhile, Panama boasts the most pronounced association between Renewable Power Capacity, Renewable Power Generation, and economic growth, outperforming the other countries under review. This can be predominantly attributed to its major ports and the Panama Canal, which significantly augment port liner connectivity and port traffic. Consequently, Panama's strategic location makes it an ideal candidate for emerging as a regional center for hydrogen, as demonstrated in **Table 1**. Among the six countries, Jamaica's Renewable Power Capacity and Renewable Power Generation showed a strong correlation to economic growth; however, the maritime aspect in terms of port infrastructure and traffic showed a negative correlation to economic growth, suggesting improvements are needed for port infrastructure, port traffic and port liner connectivity to make Jamaica a strong contender for a hydrogen generation and distribution hub. It is important to note that Trinidad & Tobago is the primary distributor of hydrogen gas in the region. As anticipated, there exists a minimal correlation between Renewable Power Generation and Alternative Energy with regard to economic growth. Nevertheless, Renewable Power Generation exhibits a moderately negative correlation with economic growth. The high correlation between carbon emissions per capita and economic growth suggests that the byproduct of fossil fuels contributes significantly to economic growth in the area. Despite being a significant exporter of hydrogen gas, Trinidad and Tobago's environmental impact continues to be a concern therefore, hydrogen production needs to be decarbonized [12].

The data analysis reveals a robust positive correlation (0.550) between Jamaica's Gross Domestic Product (GDP) and its Renewable Power Capacity. Similarly, there is a significant positive correlation (0.618) between the country's GDP and Renewable Power Generation. In contrast, the maritime factors of Port Infrastructure (−0.543) and Port Traffic (−0.419) exhibit a negative medium correlation to GDP growth, which is expected because of the moderate increase in port traffic, as shown in **Figure 11**. Barbados exhibits a medium correlation between Renewable Power Capacity and Renewable Power Generation, suggesting that the government has taken measures to promote renewable energy sources. However, the tourism industry, particularly the cruise sector, is a significant contributor to carbon emissions, which could have adverse effects on economic growth. Therefore, it is imperative to improve PI and PCI to enhance the economic outlook, as evidenced in **Table 1** and **Figures 12** and **13**. Finally, for the Bahamas, the limited data have produced skewed results, which have resulted in the non-correlation of the variables to economic growth.

Based on **Figure 5**, among the six countries analyzed, only Panama has publicly disclosed a strategy and roadmap, as well as a law/regulation, to establish itself as a green hydrogen hub. The remaining Caribbean countries have yet to release their own strategies related to GH2. It is worth noting that all South American nations, with the exception of Venezuela, Guyana, and Suriname, have either published their strategies or are currently in the process of developing them, along with laws and regulations pertaining to green hydrogen. The opportunities lie within the fact that maritime trade accounts for over 80 percent of global trade. The hydrogen hubs will be a profitable venture for Jamaica based on the IMO forecast and strategies for reducing CO_2 emissions from ships; although, the designs, applications and production are constantly evolving [17]. Although the infrastructure of the port and intermodal connectivity are essential components of the production and distribution of the green hydrogen hub [18]. It is of utmost importance that policy be implemented to support the green hydrogen concept for the port of Kingston. The incorporation of hydrogen production, storage, distribution and export can be implemented because of the Jamaica's hinterland size and strategic location within the heart of maritime activities.

A recent study has revealed that renewable energy has a direct impact on a country's GDP, making it an area of interest for investors, economists, and policymakers. The success of a green hydrogen hub is influenced by several factors, including renewable energy and port performance indicators. Consequently, investing in port infrastructure to facilitate hydrogen production, storage, distribution, and export could have positive effects on Jamaica's economy. A feasibility study is recommended to determine the proximity of ports to key markets such as Japan, Germany, and Korea. Furthermore, exploring the use of hydrogen as a substitute for power generation in Jamaica could prove advantageous.

5.1. Limitation

The research has some limitations regarding the availability of data in certain Caribbean transshipment hubs for some countries. Countries such as Cuba, Costa Rica, Curacao, and other small Caribbean states were not included because of insufficient data. The extraction of hydrogen from the sea is still an emerging field, which means that there is limited data available. Moreover, the research had to limit the study to only 7 strategic factors that determine the potential applications of hydrogen hubs due to the lack of data. The study did not cover the application of hydrogen in different industries such as manufacturing and power generation sectors that could potentially create an internal supply chain.

6. Conclusions

This study explored whether countries within the "Caribbean transshipment triangle" could be used as a hub for distributing and exporting green hydrogen to local and international markets. Several factors were analyzed, including Renewable Power Capacity (RPC), Renewable Power Generation (RPG), Alternative and Nuclear Energy (ALTE), Carbon Emission per Capita (CDE), Port Infrastructure (PI), Port Traffic (PT), and Port Liner Connectivity (PCI), to identify which variable had the strongest correlation to economic growth (GDP). The results showed that the Dominican Republic and Panama had the highest correlation to economic growth. Specifically, Jamaica, Panama, and the Dominican Republic had a moderate to high correlation between RPC and GDP. At the same time, Jamaica, Panama, Barbados, and the Dominican Republic showed a similar correlation between RPG and GDP. On the other hand, ALTE had the lowest correlation with economic growth for all six countries. Further analysis revealed that Trinidad & Tobago had the highest correlation of CDE to GDP, while PT had the highest correlation to GDP for Panama, T&T, and the Dominican Republic. The Dominican Republic had the strongest correlation with GDP regarding PI, while Panama, the Dominican Republic, and PCI had the strongest correlation with GDP.

Based on these findings, the study concludes that the Dominican Republic and Panama are the most promising candidates for a green hydrogen hub, given their strong correlation with economic growth and other factors. These results could be helpful for businesses and policymakers interested in investing in green hydrogen infrastructure in the Caribbean Triangle transshipment region. Jamaica, with one of the largest exclusive economic zones (EEZ), has the potential to become a leader in green hydrogen production. Renewable energy is closely linked to economic growth, and the demand for alternative fuels is increasing. Seawater is a promising resource for hydrogen production, and Jamaica could become a strategic hub for countries like Japan, Germany, Singapore, and South Korea, which are seeking alternative fuel sources. The maritime industry's goal of zero carbon emissions from ships could also create opportunities for Jamaica to play a role in the supply chain and support the IMO's CO_2 targets. Investments will be crucial for green hydrogen production, but developing a framework for green energy could improve the country's economic outlook.

This research has important implications for stakeholders in the maritime industry, policymakers, and energy generation planners. To become a green hydrogen hub, Jamaica will need to develop port infrastructure to support production, storage, distribution, and export. These findings will be of interest to governments, managers, professionals, policymakers, and investors in the power generation sector.

Author Contributions

Conceptualization, K.M. and C.G.; methodology, K.M.; formal analysis, K.M.; writing—original draft preparation, K.M.; writing—review and editing, C.G.; All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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