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Hydrogen economy horizons: assessing investment risks and opportunities

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ABSTRACT

The global transition to a low-carbon economy positions hydrogen as fundamental for climate change mitigation and sustainable finance. However, the financial viability of hydrogen-related investments remains largely underexplored. This study addresses this gap by analyzing the risks and rewards of 123 publicly traded hydrogen-related companies globally from 2019 to 2022. Using a mean-variance approach, we characterize the evolution of hydrogen-related stock markets during their early phase. We provide the first comprehensive evaluation of investment opportunities across the entire hydrogen value chain and with a global sample of firms, expanding beyond previous limited geographical or stage-specific analyses. Our findings indicate that value chain positioning and geographical location significantly influence financial performance, unlike diversification. We offer a novel comparative analysis of the distinct financial impacts of both the COVID-19 pandemic and the 2022 energy crisis on hydrogen investments, revealing the latter's greater negative effect. Our constructed optimal hydrogen portfolios consistently outperform global and sustainability benchmarks, particularly during turbulent periods, providing robust evidence for strategic investment. This research highlights the critical role of public and private investment, offering actionable insights for investors in portfolio construction and risk management and guiding policymakers in designing stable regulations to accelerate the hydrogen economy.

IMPACT STATEMENT

This study offers the first comprehensive financial evaluation of investment opportunities across the entire global hydrogen value chain. It shows that a company's position in the value chain and its geographical location are key drivers of financial performance, and that optimal hydrogen portfolios consistently outperform global and sustainability benchmarks, especially during turbulent periods. This research provides actionable insights for both investors and policymakers: it guides investors in portfolio construction and risk management in this emerging sector, and it highlights the need for stable, targeted policies to accelerate the public-private funded transition to a hydrogen economy.

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Environmental Economics; Finance; Sustainable Development

1. Introduction

Climate change is recognized as a major risk to global economies, societies, and businesses, with increasing relevance in financial and policy discussions (O'Brien & Leichenko, 2000). Decarbonizing the economy and fostering sustainable financing are critical for addressing climate change and advancing environmental sustainability (United Nations Framework Convention on Climate Change, 2015). However, the transition to a low-carbon economy in a world with 37.4 Gt of energy-related CO2 emissions (International Energy Agency, 2022) requires the commitment of all social, political, and economic actors (Fankhauser et al., 2022). In this context, sustainable finance plays a pivotal role in directing investments toward eco-friendly projects and integrating environmental, social, and governance (ESG) factors into financial decisions (Organization for Economic Cooperation and Development, 2021).

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Within this framework, hydrogen has been identified as a relevant factor in reducing global carbon emissions and facilitating the transition to a climate-friendly economy. It enables the storage and transport of renewable energy, presents the possibility of heating through existing natural gas infrastructure, and can serve as an alternative feedstock for energy-intensive manufacturing industries (Acar & Dincer, 2014; Alanne & Cao, 2017; Beheshti et al., 2016; Kalinci et al., 2017; Mehrpooya et al., 2017; van Renssen, 2020). Hydrogen could reduce annual global emissions by more than 20% by 2050 (Hydrogen Council, 2022).

However, almost all hydrogen is currently produced from fossil fuels (IEA, 2022). To mitigate climate change effectively, this hydrogen should be produced via electrolysis using zero-carbon electricity ('green hydrogen') or using natural gas with carbon capture and storage ('blue hydrogen') (Energy Transitions Commission, 2021). Three key requirements must be satisfied to facilitate clean production. First, cost reduction and technological advancements are essential to ensure economic feasibility (Burton et al., 2021; Jia et al., 2016; Nastasi & Basso, 2016; Salvi & Subramanian, 2015). Improved access to financing for enterprises in the hydrogen sector plays a pivotal role in transforming the hydrogen economy from a concept to a reality (Bleischwitz & Bader, 2010; Lee et al., 2022). Second, to succeed, the hydrogen economy must be holistically developed, encompassing all stages of the value chain (Peyerl & van der Zwaan, 2024). However, in many countries, the current hydrogen value chain is economically unsustainable, with immature technologies requiring significant investments in research and development (Hong et al., 2023). Third, to stimulate market demand for hydrogen, significant efforts are needed to establish standards and regulations aligned with net-zero targets, such as Japan's public measures, to support the private sector in advancing carbon neutrality (Otaki & Shaw, 2023). Governments should implement policies that enforce environmental regulations, reduce economic uncertainty, and encourage long-term investments to accelerate sustainable development (Balsalobre-Lorente et al., 2024).

The successful implementation of a hydrogen economy depends on addressing these interrelated challenges with a balanced approach. The commitment of national hydrogen strategies is critical (Cheng & Lee, 2022; Otaki & Shaw, 2023) because hydrogen policy development often leads to increased resource input and generates positive spillover effects (Caferra & Falcone, 2023; Yuan & Tan-Mullins, 2023). However, overreliance on government policies poses a challenge to long-term sustainability, necessitating a balance between public support and private investment incentives (Lee et al., 2022). A significant share of investment must come from the private sector to ensure sufficient funding, support a thriving hydrogen economy, and enable the transition (Koneczna & Cader, 2024; Sharma et al., 2023). Thus, public policies must be carefully aligned, and private investments should be encouraged (Chintala & Subramanian, 2015).

The number of private investors shifting toward hydrogen investments is growing for several reasons. First, hydrogen has emerged as an appealing investment opportunity for socially responsible investors to contribute to climate-change mitigation (Elsenhuber & Skenderasi, 2020; Göllei et al., 2016). According to some studies, ESG investments generate positive societal and environmental impacts and exhibit superior performance compared to conventional alternatives (e.g. Cerqueti et al., 2021; Sherwood & Pollard, 2018). They also positively contribute to portfolio diversification (Dai, 2021; Lee et al., 2021), even during the COVID-19 pandemic (Broadstock et al., 2021; Omura et al., 2021; Rubbaniy et al., 2024). These findings strengthen the appeal of hydrogen-related investments for those seeking sustainable and impactful financial choices. Second, the hydrogen economy is emerging as a remarkable investment opportunity, even for conventional investors seeking to create value by incorporating assets into their portfolios that they expect to outperform. This is particularly evident within Lo's (2012) adaptive markets hypothesis and investor attention theory (Zhang & Wang, 2015), which suggest that investors adjust their strategies in response to a changing economic environment. Third, climate change has been recognized as a significant investment risk factor (Bansal et al., 2017; Krueger et al., 2020); thus, hydrogen-related assets offer an attractive alternative for any investor concerned about climate-related hazards and regulatory adjustments that might lead to financial losses for companies and impact stock returns (Bua et al., 2024; Cepni et al., 2022).

Because hydrogen is not a tradeable commodity, incorporating it into investment portfolios requires the inclusion of hydrogen-related financial securities, such as stocks (Corzo Santamaría et al., 2022). The careful selection of suitable companies for investment is essential (Arribas et al., 2019). For example, investment in hydrogen infrastructure carries significant risks in the absence of assured supply and demand, with investors who make the wrong choices potentially incurring substantial financial losses (van de Graaf et al., 2020). Despite its importance, research on hydrogen energy finance remains limited.

The key variables influencing the profitability of hydrogen-related investments and their roles in decarbonized equity portfolios remain underexplored (Andersson et al., 2016; Engle et al., 2020). This gap is critical because the realization of a hydrogen economy depends heavily on substantial investments (Lee et al., 2022). However, no comprehensive analysis has yet evaluated the profit/risk profiles of different types of hydrogen-related investments, further emphasizing the need for targeted financial research.

This study aims to address this gap by identifying the key factors influencing the financial performance of hydrogen-related investments. Specifically, it focuses on answering the following three research questions: 1. What factors significantly affect the financial performance of the hydrogen economy, and to what extent? 2. How do periods of instability impact the performance of the hydrogen economy? 3. How do hydrogen-related investments compare in performance to other market benchmarks? To that end, we analyze the yearly performance of 123 publicly traded companies between 2019 and 2022 to characterize the early-stage risk-return dynamics of the hydrogen economy. This assessment is based on a quantitative analysis of the Sharpe ratio (SR; Sharpe, 1966, 1994), one of the most widely used methods to assess risk-adjusted performance.

This analysis is based on three company dimensions: (i) Degree of diversification: Empirical studies argue that diversification enhances efficiency and profitability through improved coordination of specialized divisions (Chandler, 1993), greater debt capacity resulting from the coinsurance effect—which arises when businesses with imperfectly correlated earnings are combined (Lewellen, 1971)—and tax benefits from offsetting losses across segments (Majd & Myers, 1986). Conversely, others contend that diversification destroys firm value due to overinvestment in underperforming segments (Stulz, 1990), greater losses from unprofitable divisions (Meyer et al., 1992), higher information costs (Harris et al., 1982; Myerson, 1982), and lower operating profitability coupled with inefficient capital allocation in diversified firms (Berger & Ofek, 1995). (ii) Value chain involvement: The hydrogen sector requires a value chain approach to address the unique challenges and opportunities presented at each stage (European Investment Bank, 2022; Hjeij et al., 2022). (iii) Geographical factors: Geographical location is expected to be a relevant factor considering different national strategies, regional energy prices, demand conditions, and resource availability (Auer & Schuhmach, 2016; Badía et al., 2020; Cheng & Lee, 2022; Odell & Ali, 2016). Additionally, yearly intervals are analyzed to determine whether temporal dynamics significantly affect the risk-adjusted returns of hydrogen-related stocks. Including turbulent events such as the 2022 energy crisis, which disrupted energy supply chains, particularly in Europe (Otaki & Shaw, 2023), provides important insights into their impact on the financial stability of key players in the hydrogen economy.

Once the significant dimensions are identified, the study determines the optimal annual mean-variance portfolios (OPs) (similar to Yousaf et al., 2023, for DeFi assets). According to James and Menzies (2023), investors seeking profitable opportunities during turbulent times should adopt asset allocation strategies that have proven effective in previous market downturns. Thus, these OPs provide investors with valuable insights for informed capital allocation decisions. They also help uncover critical areas where public support may be essential. Finally, to assess the relative performance of hydrogen-related OPs, we compare their dynamics to those of more sustainable and diversified investment options.

The main findings show that: (i) The financial performance of the hydrogen economy is significantly influenced by the value chain stage and geographical location of hydrogen-related companies, but not their degree of diversification. (ii) The 2022 energy crisis had a stronger negative impact on hydrogen financial performance than COVID-19, uniformly lowering SRs across geographies. However, its effect varies across the hydrogen value chain, leading to diverse financial outcomes. Conversely, during stable periods, companies behave quite differently across various regions. (iii) Optimal hydrogen-related portfolios have consistently outperformed global and sustainability benchmarks, particularly during times of crisis.

This study contributes to the literature on hydrogen investment strategies in several key ways. First, it identifies the critical factors that influence the risk-return profiles of hydrogen-related investments and offers a comparative analysis across various dimensions. Previous research has primarily focused on production costs or technological advancements within specific stages of the hydrogen value chain (e.g. Burton et al., 2021; Olabi et al., 2023; Zeng & Zhang, 2010; Zhao & Liu, 2024) and has often been limited to specific geographical regions (e.g. Gu et al. 2020; Huang et al., 2024; Kar et al., 2023; Kim et al., 2020). In contrast, this study evaluates investment risks and opportunities throughout the entire value chain, emphasizing the potential associated with each stage of hydrogen deployment (Noussan et al., 2020) and incorporating a global sample of firms. Second, it compares the financial impacts of both the

COVID-19 pandemic and the 2022 energy crisis on hydrogen-related investments, whereas existing research has typically examined these events in isolation (e.g. Nguyen et al., 2024; Okorie, 2024; Omura et al., 2021; Shaikh, 2022), being Rubbaniy et al. (2024) a notable exception. Finally, this study substantially advances the empirical literature concerning the financial viability of hydrogen investments. While financial research usually includes broad comparisons, only notable exceptions like Corzo Santamaría et al. (2022), Okorie (2024) and Rubbaniy et al. (2024) have examined specific hydrogen portfolios.

The rest of the article is structured as follows: Section 2 outlines the data and methodology used in the study. Section 3 presents and discusses the empirical findings. Finally, Section 4 summarizes the main conclusions, explores implications for investors and policymakers, and highlights limitations and suggestions for future research.

2. Data and methodology

2.1. Data collection

The 2019 release of The Future of Hydrogen report by the IEA marked a pivotal shift in the hydrogen economy, driving a surge in hydrogen-related businesses and investment opportunities. Governments worldwide have since implemented hydrogen strategies, and companies have significantly increased their investments in hydrogen production and management (IEA, 2019; van Renssen, 2020). The potential of hydrogen as an energy source has driven the emergence of companies dedicated exclusively to hydrogen development, fueling a substantial industry boom (International Renewable Energy Agency, 2019). Considering this structural shift, this study analyzes the performance of the hydrogen economy from January 1, 2019, to December 31, 2022, in order to capture the emergence and early market dynamics of hydrogen-related companies during a period marked by strong momentum.

Following Corzo Santamaría et al. (2022) validation of the main hydrogen-related stocks as reliable indicators of the hydrogen economy's performance, this study is based on Enerdata's Global Hydrogen Companies Database (version 4.0), as of August 2021 (https://www.enerdata.net). This non-open-access database provides up-to-date information on key players in the upstream hydrogen value chain, including 911 companies. Not all of these companies are solely involved in hydrogen-related activities, nor are they exclusively focused on green (renewable) hydrogen. Although only green hydrogen contributes to climate change mitigation (Göllei et al., 2016), non-green hydrogen projects remain critical for the energy transition from gray to blue and, ultimately, to green hydrogen (Corzo Santamaría et al., 2022; Lucey et al., 2024). Of the 911 hydrogen-related companies, 123 meet our inclusion criteria: (i) publicly traded during the four-year period analyzed and (ii) possessing liquid stocks with no extended periods of missing values exceeding 100 days (Amihud, 2002).

The 123 companies are classified based on their degree of diversification, involvement in the hydrogen value chain, and geographical location, following Enerdata's information. Of these, only nine companies exclusively focus on hydrogen-related activities (*Ballard Power Systems, Bloom Energy, Ceres Power, Doosan, Everest Kanto Cylinder, FuelCell Energy, Kitz, Plug Power, SFC Energy*), while the remaining 114 are diversified companies engaged in multiple activities that include hydrogen. Regarding the hydrogen value chain, 55 companies operate in Materials and Components (Materials), 82 in Fuel Cells manufacturing (Fuel Cells), 20 in H2 Production (Production), 25 in H2 Storage (Storage), and 27 in H2 Refueling (Refueling). Note that some companies may participate in multiple stages. Finally, in terms of location, 33 companies are situated in Europe, 25 in North America, and 65 in Asia. A more detailed analysis of Asian countries is conducted due to their greater dispersion in market maturity, differentiating between Japanese (43), South Korean (9), Chinese (7), Indian (3), and Taiwanese (3) companies.

2.2. Methodology

The first descriptive approach offers a comprehensive overview of the risk-adjusted returns of hydrogen-related stocks during the analyzed period. Considering the unprecedented impact of COVID-19 on financial markets (Albulescu, 2021; Anh & Gan, 2021; Bose et al., 2022; He et al., 2020) and following previous literature (e.g. Coccia, 2022; Jeong et al., 2023), our analysis is conducted on a yearly basis. We use USD closing prices from the Bloomberg Terminal to calculate daily log-returns, defined as ln (Pt/Pt − 1) for each stock. The annual SR is then estimated using the average daily return and the standard deviation of each stock. The average 10-year US government bond yield accounts for the annual, which we convert to a daily rate by dividing it by the trading frequency for accuracy (Prol & Kim, 2022).

Inferential analyses and linear regression models are then conducted to determine whether the degree of diversification, stage of the hydrogen value chain, and geographical location are relevant factors that significantly impact the risk-adjusted returns of hydrogen-related stocks. We run the following panel data regression models (Hsiao, 2007): Model 0 analyzes the year effect, with 2019 as the reference year. Model 1 incorporates the diversification dimension, using pure players as a reference group. Model 2 focuses exclusively on companies' participation in the hydrogen value chain (note that no reference group is used in Model 2, as some companies may participate in multiple phases). Model 3 addresses the geographical aspect, with Japan as the reference country due to its large number of companies. Finally, Model 4 combines all the variables. All models incorporate two control variables to address the influence of financial firm characteristics, consistent with prior research (Cai & Zhang, 2011; Hughen & Strauss, 2017; Modigliani & Miller, 1958). Return on equity (ROE) measures a firm's financial performance. Total debt-to-total-equity ratio (TDTE) assesses a firm's capital structure leverage.

We follow two key steps for all models. First, we assess the presence of multicollinearity by calculating the variance inflation factor (VIF), a widely recognized diagnostic tool (Thompson et al., 2017). The results indicate that multicollinearity is not a concern, as all mean VIF values remain below 2—well below the maximum threshold of 5 to 10, beyond which multicollinearity issues typically arise (Kim, 2019; Marcoulides & Raykov, 2019). Second, we conduct a Hausman test to determine whether random or fixed effects should be used for the panel data analysis. Since all *Hausman* tests yield *p*-values above 0.05, we adopt random-effects models. F-tests are conducted to validate the regression results regarding the significance (or lack thereof) of each dimension's impact on company performance.

Finally, we examine the optimal hydrogen-related investment strategy for rational investors seeking to maximize their SR. According to Markowitz's Markowitz (1952, Markowitz, 1959) modern portfolio theory, investors aim to maximize expected returns at a certain risk level. By calculating the variance and covariance matrices, we determine the efficient frontier per year and select the optimal hydrogen portfolio that exhibits the highest SR. The objective is twofold. First, to delineate investment portfolios that optimize risk exposure to maximize returns. Second, to identify less-developed areas where public support should be directed.

Our analysis excludes transaction costs, leverage, and cash positions, allowing only for long positions. While alternative portfolio optimization methodologies exist, the fundamental mean-variance framework offers initial insights into hydrogen-related portfolios with sufficient accuracy (Brauneis & Mestel, 2019), as shown by Cucchiella et al. (2017) in their analysis of the optimal mix of renewable energy sources in Italy.

This empirical analysis concludes by comparing the optimal hydrogen portfolios with several market benchmarks to better understand their relationships with sustainable and diversified investment styles. Specifically, we choose three different indices: the MSCI World ESG Leaders Index (ESG Leaders), representing general ESG investments; the MSCI ACWI Index (ACWI), as a global equity benchmark; and the WilderHill Clean Energy Index (ECO), to compare hydrogen investment with pure clean energy stocks.

3. Results and discussion

3.1. Overall financial performance

The analysis of the SRs reveals a gradual decline in risk-adjusted returns (Table 1). Throughout the years, average returns have remained relatively stable, while average risk has displayed greater variability. The 2020 pandemic witnessed the highest deviation in returns, offsetting the increased average returns

Table 1. Summary statistics of the global sample by year.

	Risk free rate	Average return	Average min return	Average max return	Average St. deviation	Average Sharpe ratio
2019	0.0085%	0.0424%	−8.8554%	7.8949%	2.0845%	0.0222
2020	0.0035%	0.0619%	−14.8893%	13.6292%	3.2859%	0.0154
2021	0.0057%	0.0315%	−8.3375%	9.2070%	2.2781%	0.0100
2022	0.0117%	−0.0918%	−10.3393%	9.9422%	2.6216%	−0.0408

Source: own elaboration.

Table 2. Random effects panel data regression models.

	Model 0	Model 1	Model 2	Model 3	Model 4
Diversified		**−0.0121***			−0.0083
		(0.0067)			(0.0064)
Materials and components			−0.0051		−0.0061
			(0.0043)		(0.0040)
Fuel cells manufacturing			0.0013		0.0011
			(0.0044)		(0.0041)
H2 Production			**0.0137****		**0.0145*****
			(0.0065)		(0.0055)
H2 Storage			0.004		0.0003
			(0.0045)		(0.0043)
H2 Refueling			−0.003		0.0007
			(0.0066)		(0.0062)
Europe				**0.0119****	**0.0124****
				(0.0052)	(0.0049)
North America				**0.0141****	**0.0107***
				(0.0054)	(0.0057)
China				0.0011	0.0004
				(0.0031)	(0.0065)
South Korea				−0.0093	**−0.015****
				(0.0058)	(0.0063)
India				**0.0281*****	**0.0247*****
				(0.0052)	(0.0074)
Taiwan				**0.0292****	**0.0279*****
				(0.0132)	(0.0099)
2020	−0.0071	−0.0071	−0.0069	−0.0071	−0.007
	(0.0060)	(0.0059)	(0.0060)	(0.0060)	(0.0060)
2021	**−0.0129***	**−0.0130***	**−0.0129***	**−0.0127***	**−0.0127***
	(0.0066)	(0.0066)	(0.0067)	(0.0067)	(0.0067)
2022	**−0.0645*****	**−0.0646*****	**−0.064*****	**−0.064*****	**−0.064*****
	(0.0062)	(0.0062)	(0.0062)	(0.0062)	(0.0063)
ROE	**0.0003****	**0.0003*****	**0.0003****	**0.0002****	**0.0002****
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
TDTE	**−0.0001*****	**−0.0001*****	**−0.0001*****	**−0.0001*****	**−0.0001*****
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Intercept	0.0235	0.0344	0.0223	0.0169	0.0245
	(0.0050)	(0.0075)	(0.0066)	(0.0050)	(0.0093)
Obs	436	436	436	436	436
R2	0.2341	0.2372	0.2469	0.2615	0.2767
Mean VIF	1.15	1.99	1.54	1.26	1.92

Note: Inference based on robust cluster standard errors (standard errors in parentheses). ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: own elaboration.

achieved. Negative returns during the 2022 energy crisis align with Zhiznin et al. (2023), who highlight the growing geopolitical influence hindering the 'green transition', including the hydrogen economy.

3.2. Factors affecting the financial performance of the hydrogen economy

Inferential analyses and linear regression models are used to detect statistically significant differences in risk-adjusted returns among diversified and pure players, companies operating at different stages of the hydrogen value chain, organizations located in distinct regions and across different years. The results are summarized in Table 2. With all variables included and the highest R-squared value, Model 4 has the greatest explanatory capacity; therefore, the following analysis is based on these results.

Table 2 shows that being a pure player or a diversified company does not significantly impact the risk-adjusted returns of stocks, as confirmed by the F-test analysis (Prob $> \chi^2 = 0.1940$). However, despite the marginal evidence, the consistently negative coefficient across all models suggests that hydrogen-related diversified firms do not achieve the improvements suggested by Chandler (1993), Lewellen (1971), and Majd and Myers (1986). Possible reasons for this may include increased management complexity, resource misallocation, and a lack of strategic focus. These factors could offset the risk-reduction benefits typically associated with diversification, aligning more closely with the findings of Berger and Ofek (1995), Myerson (1982), and Stulz (1990). Regarding companies' participation in the hydrogen value chain, the regression and F-test results (Prob $> \chi^2 = 0.0208$) indicate that the stage in which companies participate significantly affects their performance. Notably, companies involved in Production exhibit a significantly higher SR compared to those in other segments.

Concerning the geographical aspect, it is important to note that a previous regression model categorized companies into three major regions: Europe, North America, and Asia (the results are not reported in this study but are available upon request). This first approach showed that European (0.0105; p-value <0.05) and North American (0.0109; p-value <0.05) hydrogen-related stocks perform significantly better than Asian stocks. However, considering the greater heterogeneity among countries in Asia compared to Europe or North America, we decided to segment the Asian regions. This is particularly pertinent considering the growing relevance of countries such as Japan and China in the hydrogen economy. Despite Japan's traditional dependence on foreign fossil fuels (Cheng & Lee, 2022; Noussan et al., 2020), it has started to actively invest in hydrogen technologies and infrastructure (Otaki & Shaw, 2023). Similarly, after years of inactivity in hydrogen regulations (Cheng & Lee, 2022; Yuan & Tan-Mullins, 2023), China emerged in 2022 as a prominent player in the hydrogen economy, partly because of its leadership in electrolyzer deployment (IEA, 2023).

The final detailed regression model also highlights the country effect, which is confirmed by the F-test analysis ($\text{Prob} > \chi^2 = 0.0000$). Companies from Europe, North America, India, and Taiwan outperform Japanese companies. It appears that the aforementioned Japanese investments in technology and infrastructure, along with the recently developed national strategy, have yet to bridge the lack of perceived relevance within the Japanese community highlighted by Yap and McLellan (2024). Only South Korean companies exhibit significantly lower SRs than Japanese ones. This can be primarily attributed to the institutional and political constraints that hinder the development of hydrogen energy within the country (Lee et al., 2022). To foster sustainable hydrogen technology in South Korea, more resources for research and development are needed to mitigate high production costs (Hong et al., 2023).

Finally, both the regression and F-test results ($\text{Prob} > \chi^2 = 0.0000$) confirm a statistically significant link between SRs and the time dimension. The SRs of hydrogen-related stocks have consistently decreased since 2019. This negative trend becomes statistically significant in 2021 and 2022, suggesting that the 2022 energy crisis had a greater impact than COVID-19. Although statistically significant, the effects of the two control variables (ROE and TDTE) on risk-adjusted returns are minimal.

3.2.1. Robustness checks

Table 2 shows that the coefficients and their significance levels for each variable remain consistent across all five models, underscoring the robustness and validity of our findings. To further strengthen these results, we performed two additional robustness checks to further bolster the credibility of these results. First, we re-estimate our models by incorporating two extra control variables: return on assets (ROA), which measures firms' financial performance, and the total debt-to-total assets ratio (TDTA), which reflects capital structure leverage. Second, we employ the principal components technique to create two new composite variables: one that encapsulates the effects of the financial performance metrics (ROE and ROA) and another that represents the capital structure leverage metrics (TDTE and TDTA). The newly formulated financial performance variable accounts for 80.83% of the variance originally explained by ROE and ROA, while the capital structure leverage variable captures 74.5% of the explained variance. Re-estimating our models using these new variables confirmed the consistency of coefficients and significance levels across all five models, with F-test results further supporting the stability of our findings.

3.3. Yearly financial performance by value chain stages and geographies

Since the risk-adjusted returns of the hydrogen industry are significantly influenced by the stage of the hydrogen value chain and the location of companies, a deeper, yearly examination of these subsets is conducted. Identifying the most profitable opportunities for investors also highlights the important role of policies in advancing hydrogen development (Yuan & Tan-Mullins, 2023). In areas where financial attractiveness limits private investment, public support becomes essential to make hydrogen a key component of a decarbonized economy. The key statistical data are presented in Tables 3 and 4.

The production and utilization of hydrogen are complex processes that involve various stages, ranging from material procurement and production to transportation, storage, local infrastructure, and application phases (Hjeij et al., 2022). However, most academic research tends to focus only on hydrogen

Table 3. Summary statistics by hydrogen chain value stage and year.

	Average return	Average min return	Average max return	Average St. deviation	Average Sharpe ratio
2019 (Risk Free Rate 0.0085%)					
Materials and Components	0.0520%	−10.0325%	8.7017%	2.2218%	0.0273
Fuel Cells manufacturing	0.0516%	−9.5148%	8.1853%	2.1529%	0.0268
H2 Production	0.0316%	−9.9782%	9.7394%	2.3732%	0.0372
H2 Storage	0.0570%	−9.9626%	10.6352%	2.4789%	0.0329
H2 Refueling	0.0220%	−6.8491%	6.1210%	1.8108%	0.0145
2020 (Risk Free Rate 0.0035%)					
Materials and Components	0.0672%	−14.8410%	13.6141%	3.3452%	0.0116
Fuel Cells manufacturing	0.0755%	−14.7464%	13.5422%	3.3201%	0.0178
H2 Production	0.0898%	−14.5001%	14.9306%	3.4528%	0.0235
H2 Storage	0.0774%	−16.2460%	14.8104%	3.5656%	0.0201
H2 Refueling	0.0870%	−13.9518%	13.2744%	3.0427%	0.0214
2021 (Risk Free Rate 0.0057%)					
Materials and Components	0.0190%	−8.1859%	9.0553%	2.3110%	0.0095
Fuel Cells manufacturing	0.0162%	−8.6940%	9.2393%	2.2907%	0.0060
H2 Production	−0.0002%	−7.5466%	7.9591%	2.1961%	0.0029
H2 Storage	0.0298%	−8.7829%	9.1943%	2.5238%	0.0093
H2 Refueling	0.0235%	−7.2871%	9.2460%	2.1039%	0.0069
2022 (Risk Free Rate 0.0117%)					
Materials and Components	−0.1312%	−10.1551%	10.1879%	2.7157%	−0.0533
Fuel Cells manufacturing	−0.0887%	−9.7278%	9.7788%	2.6194%	−0.0412
H2 Production	−0.0329%	−9.4647%	9.2009%	2.5357%	−0.0185
H2 Storage	−0.1003%	−12.2667%	10.8136%	2.8797%	−0.0372
H2 Refueling	−0.0770%	−9.8050%	9.0172%	2.4300%	−0.0360

Source: own elaboration.

Table 4. Summary statistics by geographical location and year.

	Average return	Average min return	Average max return	Average St. deviation	Average Sharpe ratio
2019 (Risk Free Rate 0.0085%)					
Europe	0.0655%	−8.0265%	7.2687%	1.9090%	0.0327
North America	0.0608%	−13.5563%	11.6663%	2.7518%	0.0400
Japan	0.0326%	−6.8240%	6.0343%	1.6806%	0.0164
China	0.1015%	−9.6977%	8.8332%	2.8724%	0.0268
South Korea	−0.0938%	−8.1468%	7.1505%	2.1118%	−0.0423
India	0.0355%	−11.0018%	11.9579%	2.7807%	0.0168
Taiwan	0.0552%	−5.9295%	6.0055%	1.6287%	0.0279
2020 (Risk Free Rate 0.0035%)					
Europe	0.0220%	−17.8130%	13.3752%	3.3768%	0.0078
North America	0.1474%	−20.4622%	18.5612%	4.3643%	0.0260
Japan	0.0153%	−9.8303%	10.9266%	2.4842%	0.0063
China	0.1250%	−13.5557%	12.1659%	3.2293%	0.0386
South Korea	0.1197%	−14.8648%	16.1796%	3.7949%	0.0302
India	0.1022%	−15.8515%	13.8644%	3.6947%	0.0268
Taiwan	0.0950%	−11.0226%	9.5874%	2.9869%	0.0308
2021 (Risk Free Rate 0.0057%)					
Europe	0.0341%	−7.7846%	8.0876%	2.0484%	0.0155
North America	0.0117%	−10.2294%	11.0960%	2.6668%	0.0146
Japan	−0.0047%	−7.3739%	7.5450%	1.9211%	−0.0064
China	0.1499%	−10.4314%	12.0015%	3.1856%	0.0297
South Korea	−0.0114%	−7.5863%	11.8959%	2.5382%	−0.0100
India	0.3509%	−7.7630%	14.2516%	3.0127%	0.0989
Taiwan	0.2196%	−10.4052%	9.9664%	3.0497%	0.0714
2022 (Risk Free Rate 0.0117%)					
Europe	−0.0837%	−11.1295%	11.1879%	2.8637%	−0.0333
North America	−0.1284%	−12.9013%	11.3017%	3.0279%	−0.0433
Japan	−0.0691%	−8.2891%	8.2396%	2.1045%	−0.0407
China	−0.1212%	−10.5263%	9.8635%	2.9669%	−0.0562
South Korea	−0.0922%	−8.9920%	10.5096%	2.5906%	−0.0449
India	−0.1799%	−13.7638%	7.6811%	2.5942%	−0.0622
Taiwan	−0.0443%	−9.8625%	10.0584%	3.3006%	−0.0313

Source: own elaboration.

production costs, while ignoring the importance of considering all stages of the value chain. Any of these stages can result in significant losses and infrastructure challenges (Noussan et al., 2020).

Our results indicate that the risk-adjusted returns of different value chain stages have steadily decreased over time, with the pandemic serving as a catalyst for this trend. In 2020, elevated risk was the main driver of this decline, peaking in line with broader market trends (Chatjuthamard et al., 2021; Zaremba et al., 2020). This heightened risk offsets the benefits of higher returns and lower risk-free rates. A possible explanation is the moderately negative correlation between the VIX and hydrogen during the pandemic, noted by Lucey et al. (2024). Conversely, in 2021 and 2022, the primary driver behind the decrease in SRs was a decline in returns, which became negative by the end of the analyzed period. The energy crisis emerged as the time of the highest variability in risk-adjusted returns across the value chain stages.

The Production segment consistently outperforms the other segments in terms of SRs, except in 2021, despite the limited number of companies operating at this stage. It reflects the growing investor preference for hydrogen production over other activities (IEA, 2024), likely driven by advancements in electrolysis, which have improved efficiency and cost-effectiveness, demonstrating significant potential for hydrogen production (Zeng & Zhang, 2010). In contrast, Fuel Cells and Materials, despite encompassing the largest number of companies, consistently underperform—except for Materials in 2021, which recorded the highest SR. Storage and Refueling activities exhibit the most consistent patterns, with Storage carrying the highest risk and Refueling the lowest. The lower volatility of refueling-related stocks may stem from the strong dependence of refueling station investments on growing demand (Zhao & Liu, 2024), which has remained relatively stable.

The results highlight the differing impacts of the two crises on hydrogen companies. On one hand, the pandemic negatively affected the risk-adjusted returns of all stages, primarily due to an increase in risk. This observation aligns with Shaikh (2022), who reported the severe impact of the pandemic on the volatility of the energy stock market. An exception to this trend is Refueling, which manages to offset greater volatility with higher returns. Alongside a declining risk-free rate, this led to an increase in its risk-adjusted returns. Conversely, Materials stage suffered the most during the COVID-19 pandemic. On the other hand, despite the 2022 energy crisis having a less detrimental effect on market volatility than the pandemic, it caused a significant and widespread decrease in returns across all examined stages. This led to the lowest (or even negative) SRs. The year 2022 also marked a peak in the dispersion of SRs, accentuating divergent risk-adjusted returns between the Materials and Production stages. This contrasts with the more stable periods and the pandemic year, which seemed to homogenize the performance of all players within the hydrogen economy. This enhanced relationship between hydrogen-related stocks during the COVID-19 pandemic aligns with Okorie′s (2024) findings, which indicate that these stocks were influenced at that time by similar market information aimed at profit maximization and risk reduction. During the more stable periods (2019 and 2021), the overall average volatility was notably lower.

We also explore the geographical dimension of hydrogen companies, acknowledging the existing body of literature that addresses this aspect in analyzing the financial performance of sustainable investments (Auer & Schuhmach, 2016; Badía et al., 2020; Odell & Ali, 2016). This analysis is crucial because public hydrogen strategies are developed at the national level (KPMG., 2021), and significant divergences exist between countries and regions in their approach to the hydrogen economy (World Energy Council, 2021).

Taiwan emerges as a standout country, consistently delivering above-average returns, closely followed by Chinese companies until 2022. Gu et al. (2020) attribute China's rapid rise in hydrogen-related stocks to strong government support, particularly since hydrogen power development was included in the 2019 Annual Government Work Report. In contrast, North America presents above-average risks, whereas Japan exhibits the lowest risk levels. In terms of risk-adjusted returns, Taiwan continues to outperform, whereas South Korea and Japan lag behind on average. South Korea seeks to boost investment in key hydrogen technologies; however, existing legislation lacks comprehensive coverage of hydrogen-related facilities and safety standards (Kim et al., 2020). Notable differences in returns and risk-adjusted returns across various regions arose in 2021 compared to 2020, when the risk disparity was more prominent. By 2022, all three variables—returns, risk-adjusted returns, and risks—became more closely aligned across regions.

It is worth noting that while there seems to be a noticeable trend in the fluctuation of returns across various stages of the supply chain—with an increase in 2020, a decrease in 2021, and ultimately a negative turn in 2022—there was a lack of a consistent pattern in geographical performance until 2022. Some areas experienced rising returns, while others saw declines during the 2019–2021 period. Again, the returns of all regions became negative (or even more negative in the case of Japan and South Korea) in 2022.

Geographical heterogeneity may be influenced by the diverse government policies implemented across countries. Clear and stable policy frameworks are known to reduce uncertainty and risks, leading to better-informed investment decisions (Abad & Dodds, 2020; Kovač et al., 2021). In a recent study, Cheng and Lee (2022) categorized North America and India as countries with the lowest green hydrogen regulatory stringency. Our results show that the highest average risk is observed in these two countries (along with China, which was not included in Cheng and Lee (2022) study because national hydrogen strategies were not yet in place at the time of the research, despite having local-level strategies). This emphasizes the link between regulatory stringency and risk. Companies in North America and India remain heavily reliant on fossil fuels (Harichandan et al., 2023; Noussan et al., 2020) and face additional challenges, including cost reduction, infrastructure deficits, and supply chain expansion (Harichandan et al., 2023; Kar et al., 2023; Talus & Martin, 2022). In contrast, European countries exhibit a lower average risk, likely driven by explicit government commitments to green hydrogen and ambitious national strategies, which have encouraged investment in the industry (IEA, 2022; Noussan et al., 2020). As more hydrogen strategies are developed, increased resources are invested, accelerating industry growth and generating positive spillover effects (Yuan & Tan-Mullins, 2023).

Our analysis also reveals the contrasting impacts of the COVID-19 outbreak on hydrogen-related stocks across regions. China, South Korea, India, and Taiwan exhibited substantial improvements, primarily attributed to increased profitability. In contrast, the European, North American, and Japanese subsamples experienced notable declines in risk-adjusted returns. The case of North America is particularly noteworthy, as a rise in risk overshadowed a sharp increase in returns. Conversely, the global 2022 energy crisis had a uniform and severe impact on all regions, significantly reducing SRs.

3.4. Optimal portfolio

In this section, we compute the yearly hydrogen-related OPs to maximize SR and provide valuable information for portfolio managers. Identifying these portfolios highlights the most attractive investment opportunities for investors seeking exposure to the hydrogen economy. Furthermore, determining optimal portfolio weights offers a broader perspective on risk minimization (Chemkha et al., 2021; Yousaf et al., 2023) and is particularly useful for investors navigating future market turbulence (James & Menzies, 2023). This analysis contributes to a better understanding of how value chain stages, as well as geographical and temporal factors, influence the financial performance of hydrogen-related investments. The main daily financial statistics for the annual OPs and their compositions are summarized in Table 5.

The highest (and similar) risk-adjusted returns are evident during the less turbulent years of 2019 and 2021. Despite the year-by-year decrease in SR seen in the global sample, the 2021 OP outperformed the 2020 one. Additionally, the energy crisis did not result in negative or risk-adjusted returns, unlike the average negative data in the global hydrogen sample. However, the 2022 crisis still negatively affected the financial performance of OPs in terms of the maximum SRs compared with COVID-19 (in line with the findings of Rubbaniy et al., 2024). As observed in the global sample, volatility had the strongest impact on OPs during the pandemic; however, this was offset by the highest average returns. Although the risk was not as high in 2022, OP returns were the lowest since the pandemic.

The number of OP components changes significantly over the years, along with the predominant geographies and stages of the hydrogen value chain they represent. The 2019 OP consists of 38 companies, but more than 35% of its portfolio is tied to only three securities (*Air Products*, *Ceres Power*, and *Sinoma Science and Technology*). During the pandemic, the number of components decreases sharply (45%), resulting in a 2022 OP comprising only eight companies, with three companies already representing 66% of the portfolio. This evidence underscores the importance of adjusting portfolio weights, especially during crises (Rubbaniy et al., 2024). The hydrogen industry is not exempt from external shocks;

Table 5. Optimal hydrogen-related portfolio by year.

	2019	2020	2021	2022
Return	0.1702%	0.3491%	0.2356%	0.2225%
St. Deviation	1.3440%	3.3754%	1.8504%	2.6061%
Sharpe ratio	0.1203	0.1024	0.1242	0.0809
N° of components	38	21	22	8

Source: own elaboration.

therefore, companies and investors must actively adjust their strategies to mitigate risks and minimize losses (Okorie, 2024).

Regarding the various stages of the value chain, on average, 60% of the companies in the OPs are involved in only one stage, yet they cover all stages. The inclusion of these players in OPs indicates their significant and valuable contributions to diversified portfolios. This is useful not only for private investors, who may consider them as part of their investment portfolios, but also for policymakers. If these companies are already involved in the hydrogen economy and considered attractive, public incentives to encourage their involvement in other stages of the value chain could generate substantial benefits by strengthening it. Figure 1 provides an overview of OP companies' involvement in the hydrogen value chain by displaying the stages that are either overweight or underweight in the annual portfolios compared to their weight in the global sample.

Most companies in the global sample (67%) focus on the development of Fuel Cells. However, this stage of the hydrogen industry is underweighted in the first part of the analysis period. Additionally, Materials (45% of the global sample) and Storage (20%) are consistently underweighted. In contrast, Production and Refueling seem to offer superior contributions to portfolio optimization in terms of returns and/or diversification.

These results further highlight the importance of investors' decision-making processes. Hydrogen-related stages and geographies do not yield uniform or consistent benefits, making careful and strategic investment choices essential. This becomes critical over time, as evidenced by the 2022 OP, which shows the greatest deviation from an equally weighted portfolio strategy, pointing to the need for a more selective allocation of hydrogen-related stocks.

There is no discernible pattern in the composition of OPs by geography, with 2020 (2021) witnessing the highest (lowest) dispersion among the weightings of the geographies included. This suggests a more demanding selection process among different geographies during the pandemic. The geographic distribution across the four OPs and their relative underweight/overweight status, compared with their participation in the global sample, are illustrated in Figures 2 and 3, respectively.

Asia's significance in hydrogen-related optimal portfolios (OPs) grows in 2020, driven by the increasing influence of Japan and China. Japan maintains a strong and consistent presence across all OPs, particularly in 2020, when 57.7% of its success is attributed to the performance of key Japanese companies (*Iwatani*, *Toho Gas,* and *Nidec* are among the highest scores). However, this high contribution is largely a reflection of Japan's dominant representation in the global sample (35%). Its relative relevance is only positive in 2020, while in other years, it is underweighted, averaging 31.2%. In contrast, China consistently holds a higher level of importance, averaging 10.8% despite comprising just 5.7% of the global sample. Several factors contribute to China's relevance. It is the world's largest hydrogen producer (Huang et al., 2024) and a leader in electrolyzer deployment (IEA, 2023). By 2020, China had introduced 49 national hydrogen policies (Yuan & Tan-Mullins, 2023) and implemented over 150 provincial policies and regulations between 2015 and 2021 (Zhang et al., 2022), reinforcing its strategic commitment to hydrogen development.

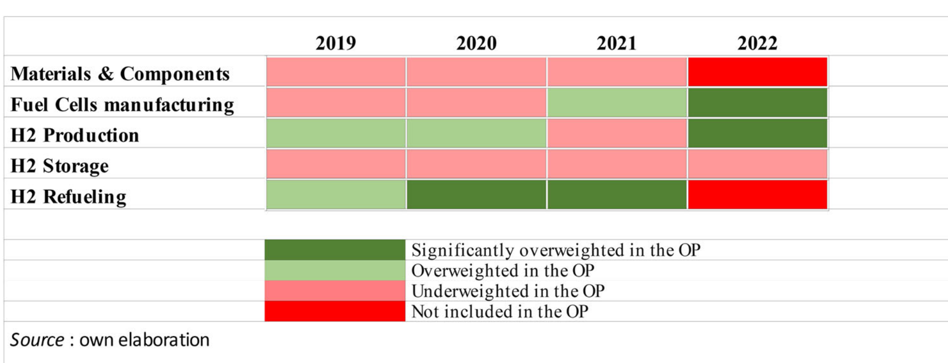

Figure 1. Optimal portfolio participation in the H2 value chain.
Source: own elaboration.

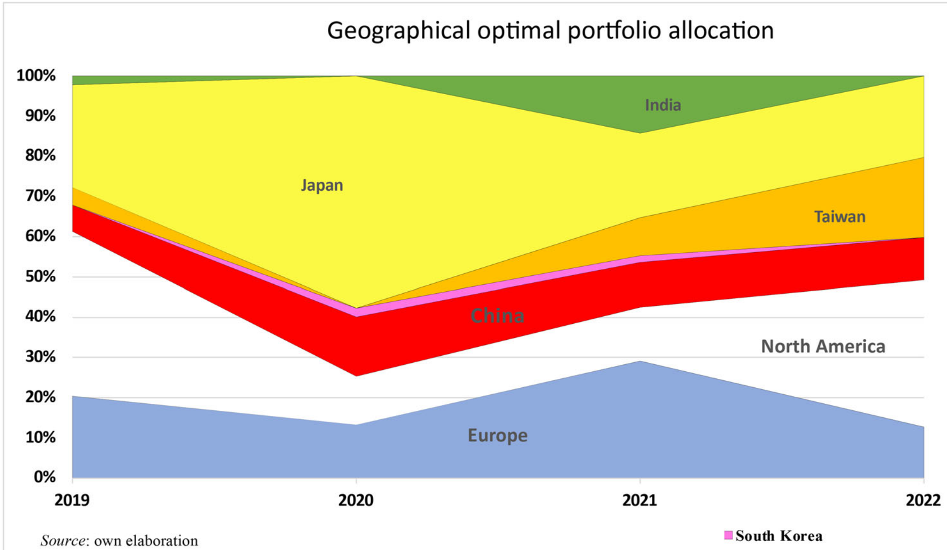

Figure 2. Geographical optimal portfolio allocation.
Source: own elaboration.

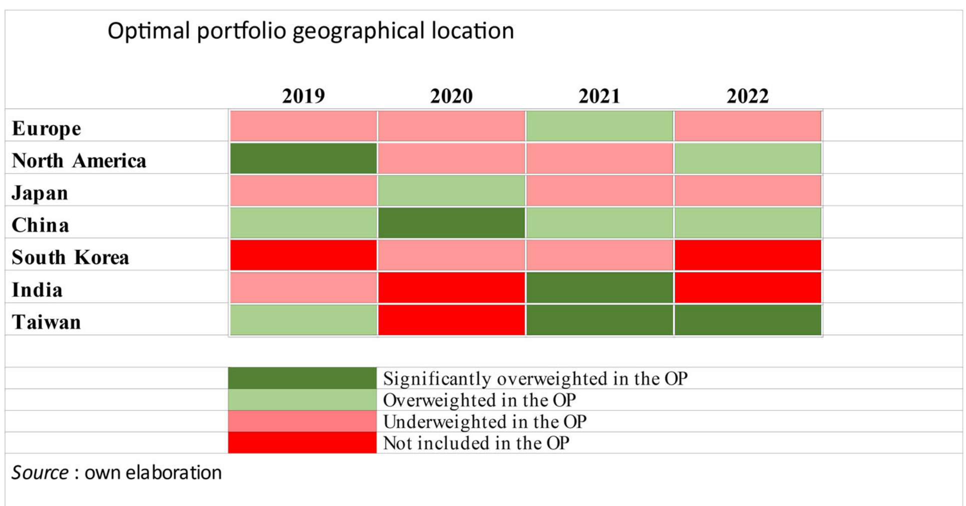

Figure 3. Optimal portfolio geographical location.
Source: own elaboration.

South Korea has maintained a minor presence in hydrogen-related OPs, averaging less than 2% weighting over the years. Indian companies participate only in the 2019 and 2021 OPs. The relevance of Taiwanese and Indian companies stands out in 2021, with a joint weight of 23.8% far exceeding their 5% share in the global sample. European companies see a decline in OP participation between 2019 and 2022, with 2021 being the only year in which their weighting (29.2%) surpasses their global sample representation (26.8%). Talus et al. (2024) argue that the EU's exclusive focus on renewable hydrogen, rather than embracing a broader range of hydrogen pathways, hinders the rapid development of a hydrogen market. Additionally, Steinbach and Bunk (2024) highlight the need for EU policymakers to enhance the profitability of hydrogen business models to drive investment and market growth.

North America plays a leading role in 2019 and 2022, although its dominance is primarily attributed to a small number of stocks. Notably, *Lockheed Martin* accounts for 35% of 2022 OP. Similarly, Taiwan is overrepresented in several OPs, but one unique Taiwanese company (*Kaori*) accounts for 19.9% of the 2022 OP. These instances illustrate that the OP is significantly influenced by outliers by the end of the period under review, further underscoring the vast diversity among hydrogen sector players.

Table 6. Market indexes characteristics.

	2019	2020	2021	2022
MSCI ESG World				
Return	0.0897%	0.0484%	0.0796%	−0.0899%
St. Deviation	0.6268%	1.8119%	0.6953%	1.2896%
MSCI ACWI Index				
Return	0.0829%	0.0513%	0.0597%	−0.0849%
St. Deviation	0.6193%	1.7287%	0.6762%	1.2176%
WilderHill Clean Energy Index				
Return	0.1772%	0.3896%	−0.1431%	−0.2471%
St. Deviation	1.3550%	3.4682%	2.8811%	3.3986%

Source: own elaboration.

3.5. Portfolios' relative performance evaluation

In line with previous research comparing a specific investment style with its counterparts based on SRs (as seen in El Ghoul et al., 2023, who found that socially responsible investments underperform non-socially responsible investments), we compare the annual OPs (Table 5) with the market benchmarks mentioned in the methodology section (ESG Leaders, ACWI, and ECO) to offer investors and policy-makers an all-encompassing assessment of hydrogen-related stocks. Table 6 summarizes the performance of the three indices in terms of daily returns and volatility over the examined period.

In terms of returns, OPs consistently outperform both the ESG Leaders and the ACWI indices, while exhibiting comparable performance to the ECO index throughout 2019–2020. However, in the following two years, the ECO index experiences a significant decline, resulting in negative returns that diverge from the OP's trajectory. This contrasts with the findings of Nguyen et al. (2024), who report that renewable energy companies experienced a greater increase in returns than their non-renewable counterparts in 2022. During the energy crisis, only the hydrogen-related portfolios avoid negative returns.

The volatility patterns of the three indices and OPs align with those observed in the global sample, peaking in 2020 due to pandemic-induced uncertainty. Over the four-year period, the ECO Index consistently displays the highest level of risk, while the global benchmarks (ESG Leaders and ACWI) exhibit lower volatility. Although volatility decreases across all four baskets in 2021, it does not return to pre-pandemic levels and rises again during the 2022 energy crisis. Overall, the risk profile of hydrogen-related stocks is more closely aligned with clean energy stocks.

Portfolios composed of hydrogen-related securities consistently outperform benchmarks in terms of risk-adjusted returns, particularly during periods of market turbulence. The risk-adjusted performance of all portfolios is superior during the COVID-19 pandemic compared to the energy crisis, as noted by Rubbaniy et al. (2024) in their analysis of the hydrogen economy, renewable energy markets, equities, and energy commodities. The authors argue that the hydrogen economy was a more effective hedging instrument during the health crisis than during the 2022 energy crisis, as hydrogen investments performed more strongly during the pandemic. However, the similar gap between the ESG and ACWI Sharpe ratios relative to hydrogen's risk-adjusted performance, as shown in Figure 4, suggests comparable hedging effectiveness across both crises. Overall, investing in hydrogen presents a compelling opportunity, highlighting its potential to diversify and enhance the performance of investment portfolios.

Our findings challenge previous claims that ESG investments outperform traditional portfolios (Cerqueti et al., 2021; Dai, 2021; Sherwood & Pollard, 2018; Tripathi & Bhandari, 2015), exhibit consistently lower volatility (Beloskar & Rao, 2023; Ouchen, 2022) and demonstrate greater resilience during crises (Broadstock et al., 2021; Lee et al., 2021; Omura et al., 2021; Rubbaniy et al., 2024; Wu et al., 2017). In contrast, certain hydrogen investments may outperform both ESG and non-ESG investments. These insights provide valuable guidance for investors seeking to optimize their portfolio strategies.

4. Conclusions

This comprehensive analysis examines the risk-adjusted returns of portfolios focused on hydrogen-related investments, aiming to enhance the understanding of investment opportunities and financing needs within the hydrogen economy. Specifically, the study examines the early consolidation phase of the hydrogen sector, identifying key factors influencing the financial performance of the hydrogen

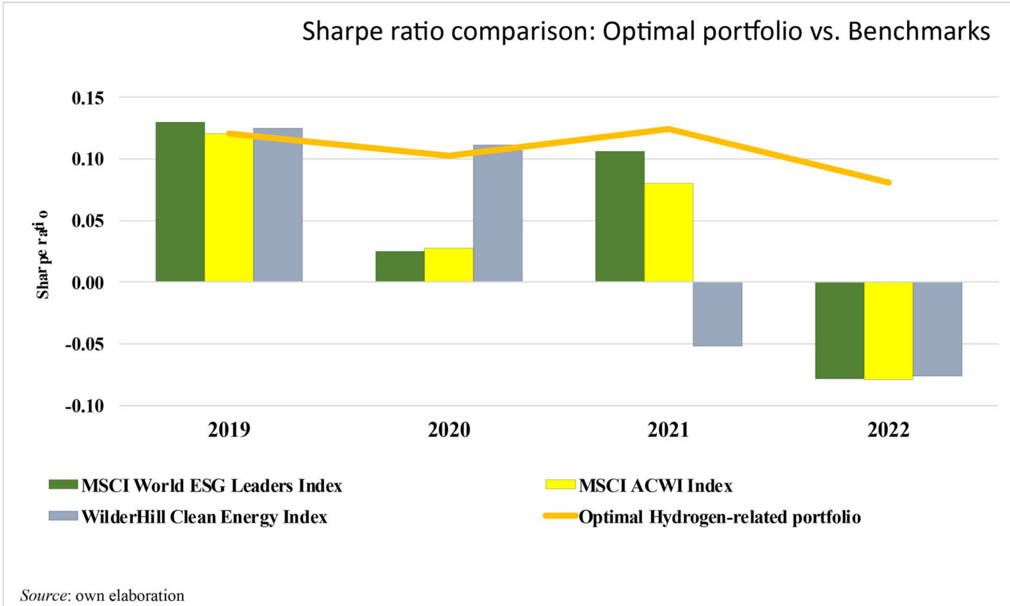

Figure 4. Sharpe ratio comparison: Optimal portfolio vs. Benchmarks.
Source: own elaboration.

industry and the effects of unstable periods on such performance. Additionally, it compares hydrogen-related investments to other market benchmarks. The analysis is based on a sample of 123 publicly traded hydrogen-related companies from 2019 to 2022.

First, the findings reveal that the financial performance of hydrogen-related companies is influenced by both the location and the stage of the hydrogen value chain in which they operate, whereas diversification does not yield a statistically significant effect. Second, the results indicate that the 2022 energy crisis hindered the progress toward a green hydrogen economy more severely than the 2020 pandemic. The 2022 energy crisis led to uniform deterioration across regions, whereas the pandemic's effects were more heterogeneous. Third, despite volatility, optimal hydrogen-related investment portfolios consistently outperform global and sustainability benchmarks, particularly during crises, highlighting the potential for strategic investment.

This study contributes to the assessment of the financial viability of hydrogen investments across the entire value chain and in a global context. While prior studies have focused on hydrogen production costs or technological advancements, this study adopts a holistic approach. Additionally, this study provides a comparative analysis of different crisis periods and offers evidence of the influence of external shocks on the performance of hydrogen-related stocks and portfolios. Finally, this research also advances the understanding of sustainable finance by comparing the performance of the hydrogen economy with other market benchmarks.

4.1. Practical implications and policy recommendations

The successful implementation and acceleration of a hydrogen economy requires strong public support and stimulated private investment. Our study's findings offer significant and actionable implications for a diverse range of stakeholders, including investors, corporations, and policymakers.

For traditional and socially responsible investors: Our insights enable investors to diversify their portfolios and align their investments with sustainability goals while exploring the nascent hydrogen economy. The study highlights the influence of value-chain positioning and geographical factors when evaluating hydrogen-related assets. Our findings suggest that investing in hydrogen can yield superior risk-adjusted returns, especially during turbulent periods, and improve overall portfolio diversification. This underscores the importance of active portfolio management and provides investors with the necessary knowledge for more informed decision-making.

For corporations: Corporations can refine their strategic approaches by leveraging our findings, particularly given the financial disparities observed across value chain stages and regions. Hydrogen firms should strategically position themselves within favorable policy environments to mitigate investment risks, enhance competitive advantage, and emerge as leaders in the decarbonization process. Non-hydrogen companies are encouraged to consider integrating hydrogen into their operations and investment strategies to foster long-term financial resilience and sustainability benefits.

For policymakers: Based on our empirical evidence, we propose the following recommendations to effectively accelerate the transition to a hydrogen-powered economy: (i) Strategically target public support and incentives towards less-profitable segments of the hydrogen market where private investment is limited. (ii) Implement clear and stable policy frameworks to reduce regulatory uncertainty and investment risks, promoting informed decisions and long-term stability in hydrogen investments. (iii) Design targeted interventions to address market inefficiencies observed across regions and stages of the hydrogen value chain. This includes financial incentives such as subsidies and tax breaks to enhance the economic viability of hydrogen projects; government-backed risk-sharing mechanisms to alleviate investor concerns and stimulate private sector participation; and fostering public-private partnerships to pool resources and expertise for large-scale hydrogen development and infrastructure. (iv) Strengthen international cooperation and policy harmonization to foster global market stability and boost cross-border investor confidence in the interconnected hydrogen economy.

4.2. Limitations and future research directions

Despite its contributions, this preliminary study has some limitations. First, the analysis is constrained to publicly traded hydrogen-related companies, overlooking private firms that may also play a crucial role in the hydrogen economy. Second, while this study captures the emergence and early market dynamics of hydrogen-related companies—including the effects of two major crises—longer-term financial trends and post-2022 developments remain unexplored. Future research could benefit from examining changes in the sector's composition and the evolution of key players as the hydrogen economy matures. Third, the methodology employed in this study could be subject to scrutiny, and alternative approaches could be considered for a more comprehensive analysis.

As the hydrogen economy evolves, further empirical research is crucial for navigating its financial complexities and maximizing its role in decarbonization. Longitudinal studies over extended periods will help assess the impacts of economic cycles, technological advancements, and regulatory changes, enabling the identification of long-term trends. As the industry matures, future research should focus specifically on green hydrogen companies. Additionally, future studies should explore the relationship between policy interventions and financial performance to gain deeper insights into how regulatory measures affect investment attractiveness. Methodologically, more advanced econometric techniques, such as dynamic panel models or machine learning algorithms, could help capture other relevant factors influencing companies' financial performance. Additionally, given that investors may consider including hydrogen stocks in their portfolios alongside other investments, it would be valuable to explore the diversification properties of hydrogen investments relative to traditional assets.

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Authors' contributions

CRediT: **Karin Martin-Bujack**: Conceptualization, Data curation, Project administration, Visualization, Writing – original draft, Writing – review & editing; **Carmen Bada**: Data curation, Formal analysis, Visualization, Writing – review & editing; **Susana De los Ríos-Sastre**: Visualization, Writing – review & editing; **Ana Daguerre-Torres**: Conceptualization, Data curation, Formal analysis.

Disclosure statement

The authors report there are no competing interests to declare.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

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Data availability statement

All the time series data used in the analysis have been obtained from Bloomberg, but the study has been mainly built on the Global Hydrogen Companies Database of Enerdata, a non-open-access source. Due to the private nature of the database, data cannot be shared. Nevertheless, anybody interested may visit https://www.enerdata.net/research/h2-database.html, where all the key features and contents are explained, and a Demo and Free Trial is available. The portfolio optimization processes are available upon request.

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