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Article — Published Version

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European Financial Management

Provided in Cooperation with:

John Wiley & Sons

Suggested Citation: Horky, Florian; Bigerna, Simona; Polinori, Paolo; Dimitriou, Dimitrios; Magazzino, Cosimo (2025) : The Role of Financial Markets in Hydrogen Adoption, European Financial Management, ISSN 1468-036X, Wiley, Hoboken, NJ, Vol. 32, Iss. 1, pp. 359-382, <https://doi.org/10.1111/eufm.70012>

This Version is available at:

<https://hdl.handle.net/10419/335590>

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ORIGINAL ARTICLE OPEN ACCESS

The Role of Financial Markets in Hydrogen Adoption

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Received: 20 December 2024 | **Revised:** 1 August 2025 | **Accepted:** 12 August 2025

Keywords: financial development | financial ecosystem | financial markets | green transition | hydrogen | stock markets

ABSTRACT

This paper empirically investigates the role of financial markets (FM) and their development in promoting hydrogen adoption as a component of green and just transition. Hydrogen can play a significant role in the energy transition, especially for sectors that are otherwise hard to decarbonize. Utilizing a twofold methodology, we demonstrate that well-developed FM significantly drive hydrogen production. Moreover, the findings highlight the connection between individual hydrogen Exchange Traded Funds and high-tech stocks, while actual hydrogen pricing is connected to oil and gas. Policy implications highlight the need for clear regulatory frameworks, communication and blended financing support for hydrogen adoption.

JEL Classification: G15, G20, O13, Q42

1 | Introduction

Hydrogen is increasingly recognized as a key enabler of a just transition towards a green economy. This emerging technology potentially plays a significant role in the energy transition and can have broader implications for various sectors and markets. It offers a path to decarbonize industries that are difficult to electrify directly, such as air transport, heavy ship transportation and heavy industry like steel production, among others. Price estimates of about 0.8\$ to 1.6\$/kg of green hydrogen until 2050 would make it competitive against conventional fuels (Kane and Gil 2022). Thus, hydrogen potentially helps keep prices at fair levels and the green transformation bearable for the whole society. This is especially necessary for rural regions as many green transition policies lead to technology concentration in urban areas and traffic restrictions or price increases, which in turn affect rural regions that are already partly left behind (Rodríguez-Pose and Bartalucci 2024). However, transitioning from a conventional petroleum-based energy system to one that relies significantly on renewable energy sources, including hydrogen, involves numerous uncertainties. For the case of

hydrogen, these include the development of efficient fuel-cell technologies, challenges in hydrogen production and distribution infrastructure and the market response to petroleum and related commodities, among others (Tseng et al. 2005).

It is widely recognized that hydrogen can be produced using renewable sources of energy, including photovoltaic, wind, hydro-power, geothermal, biomass and even wave power. These green resources, along with the available environmentally friendly technologies, are increasingly being used to generate electricity. This electricity, in turn, can be used in the electrolysis process to split water into hydrogen and oxygen (Clark and Rifkin 2006). In periods of abundant renewable electricity production, excess energy can be efficiently channelled into green hydrogen production. Depending on the specific method used, the current efficiency of electrolysis ranges from approximately 70% to 90% (Nnabuiife et al. 2025), making hydrogen a promising solution for balancing the issue of nondispatchable renewable power generation (Qiu et al. 2023).

Despite its potential, green hydrogen currently represents only a small fraction of global hydrogen production. Approximately 4%

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of hydrogen worldwide is produced through electrolysis, while roughly 50% comes from natural gas, and the remainder is derived from petroleum and oil (Breunig et al. 2024). However, promoting hydrogen today lays the groundwork for the development of green hydrogen by stimulating market demand, encouraging technological advancements, building infrastructure and integrating renewables, all of which are essential for a sustainable energy future.

Storage and transportation technologies are additional considerable challenges for the large-scale economic adoption of hydrogen. To achieve efficient large-scale hydrogen production and further use, massive research and development (R&D) efforts need to be made, and policy support needs to be granted.¹ All this comes along with huge financing needs and is supposed to require a mix of different financing sources (Magazzino et al. 2024).

New technologies and innovations generally require substantial financial backing. Public R&D grants are crucial instruments of public finance. Acemoglu et al. (2016) developed a micro-economic model showing that the optimal policy for transitioning to a green economy should make heavy use of research subsidies and carbon pricing. Specifically for R&D grants, Howell (2017) makes a key contribution by demonstrating that R&D grants play a crucial role in advancing technology prototyping. Moreover, the timing of these grants is critical: Howell finds that early-stage grants raise the likelihood of securing future venture capital by 100%, while also having a positive effect on future revenue growth and patenting activity. Myers and Lanahan (2022) provide evidence that public R&D expenditures by the U.S. Department of Energy generate significant spillover effects, reporting that when small firms receive grants, this leads to the production of three additional patents by others. Moreover, it is shown that sudden policy shocks and withdrawal of support, as happened during the first Trump presidency, negatively affect the funding success of renewable technology campaigns (Cheng et al. 2025). Specifically for renewable energy sources in Germany, Ozkan et al. (2024) show that R&D spending for green technologies can substantially reduce energy-based carbon intensity.

However, the green transformation is too expensive to be driven exclusively by public finance initiatives. Companies that do not adapt properly face high potential costs via declining demands or stranded assets (Semieniuk et al. 2022). Markets will, therefore, not find a green direction on their own. This affects the whole bandwidth of the green transition. There is no guarantee that experimental green innovations will be profitable. To realize a decarbonized power system, governments and private investors must continue their commitment to funding research, demonstration projects, and early deployment (Polzin et al. 2021). Only if there is a stable and coherent direction of regulation will investment and innovation move in a green direction (Mazzucato and Kattel 2020). The transition must be supported by long-term, patient financing commitments and investors that are willing to take risks and able to mobilize and crowd-in other investors (Mazzucato and Semieniuk 2018). Kim and Park (2016) identify high upfront capital costs and potentially lower rates of return relative to competing conventional energy projects as the biggest obstacles to deploying renewable energy technology from a financing perspective. Another

obstacle they identify for most new technologies in the renewables area is the high information costs, specifically those associated with research and data capture. Accordingly, severe information asymmetry exists between firms and financiers. Thus, a well-developed financial system can be assumed to be essential for channelling investments into capital-intensive projects like green hydrogen production.

Risk-tolerant investors play a crucial role in driving technological innovation and energy transition. Relationship banks do not directly foster internal research in companies but rather fund relevant investments associated with the introduction and acquisition of new technologies (Maria Herrera and Minetti 2007). In fact, financial markets (FM) tend to be superior when there is significant diversity of opinion about the future prospects of an investment (Allen and Gale 1999), whereas debt financing plays only a minor role for small high-tech firms (Carpenter and Petersen 2002). From the perspective of FM, risk capital is crucially important for innovative tech-startups that are subject to high failure risk but also high innovation potential (Tian and Wang 2014). This is also reflected in the finding that the listing status of firms affects investment behaviour, that is, private firms potentially forgo valuable investment opportunities and sell these opportunities to public ones with better access to equity funding (Gilje and Taillard 2016). Digital financial initiatives in a country can also improve the availability of financing for green innovations, due to a broader access to risk-tolerant and young investors (Hossain et al. 2024).

Such mechanisms are especially important when considering the green transition of the economy in the context of the financial ecosystem. The role of banks is somewhat ambiguous, as evidenced in the literature. While some studies show that banks reduce loans to environmentally harmful businesses, particularly under regulatory pressure (Haushalter et al. 2023), other investigations reveal that environmental risk pricing in bank lending is partly driven by local beliefs and political attitudes (Erten and Ongena 2024). Specifically, in the case of renewable energy adoption, there is evidence that banks tend to support more conventional, brown energy production, while FM are more supportive of renewable energies, at least in regions with the respective political environments (Horky and Fidrmuc 2024). Focusing on the financial ecosystem, the distinction between financial institutions (FI) and FM is, however, crucial for understanding innovation and investment in the context of the green transition. Due to different risk appetites, traditional FI (banks) seem to lag in supporting renewable energy, while capital markets, at least in Europe, play an essential role. Overall, while increasing human development might increase an ecological footprint, inclusive financial development can help mitigate these effects (Nuta et al. 2025). Nevertheless, the role of financial development in the green transition and environmental pollution remains subject to further research and potentially varies across regions and technologies (Anton and Afloarei Nucu 2020; Sadorsky 2010).

Generally, the shift from fossil fuels to renewable energy has attracted global investments (Caporale et al. 2023; Lucey and Ren 2023). Investments in hydrogen projects are increasing, driven by policy plans, energy investments and new market trading opportunities.² Thus, investigations around the

financial and economic aspects of hydrogen adoption and production provide a timely opportunity for policymakers and investors to learn about implications and strategies in this new environment. Nevertheless, the current development of nearly all aspects of hydrogen technology is in the research phase and not yet on the large-scale implementation level (Kovač et al. 2021), which makes applied economic research hard to conduct. As already pointed out, an energy transition of any kind cannot happen without implementing a political solution, developing national strategies and action plans with a clear agenda, providing adequate legislation and establishing a financial structure. There is a consensus that more research is necessary on investment choices, support systems and regulatory frameworks for sustainability-driven ecosystems (Cumming et al. 2024). However, to the best of our knowledge, there is no research investigating the role of financial development from a cross-country perspective on hydrogen adoption and production.

This study addresses this empirical gap in the literature by utilizing an unbalanced panel of 35 countries already producing hydrogen, covering the period from 2006 to 2021. Also, we aggregate the per-country production of hydrogen³ by exploiting the International Energy Agency (IEA) hydrogen database (IEA 2019). The Hydrogen Production Projects Database covers projects to produce hydrogen for energy or climate change mitigation purposes. It includes projects that have the objective either to reduce emissions associated with producing hydrogen for existing applications or to use hydrogen as an energy carrier or industrial feedstock in new applications that have the potential to be a low-emissions technology option. The database is regularly used in research assessing the hydrogen economy (see, e.g., Pleshivtseva et al. 2023; De Kleijne et al. 2024). Therefore, our research also contributes to the conceptual gap, as we are directly focusing on green hydrogen production here. Moreover, we use the financial development indicators of the International Monetary Fund (IMF) to capture FM and FI development (Svirydenka 2016). Especially regarding the latter, it is important to acknowledge that FM are harder to understand and access for many people, potentially posing threats to a green transition.

Although hydrogen is in its early implementation steps for large-scale economic use, the literature and our results suggest a relevant role of FM for this new technological innovation. For a holistic assessment of financial developments and implications for hydrogen production and economic implementation, we do not stop at the country and macro perspective but also take a deeper look at the FM related to hydrogen in detail, coherently with the financial ecosystem approach. In fact, players participating in the hydrogen economy have undergone lively dynamics in recent years, especially given geopolitical upheavals and the pandemic crisis. One of these early studies directly considering hydrogen investments took the Coronavirus Disease 2019 (COVID-19) pandemic and the Russian invasion of Ukraine as central events to investigate market connectedness (Rubbiani et al. 2024). They found that while total dynamic connectedness experienced fluctuations, peaking during the initial days of the pandemic and surging again at the onset of the Russia-Ukraine war, the average connectedness throughout the two black swan events remained symmetric.

Additionally, they observe a persistent net transmitter role of the hydrogen economy index. In a similar line, Lucey et al. (2024) found that most assets had a weak to moderately positive connection with hydrogen, while extreme market conditions, such as those during the COVID-19 pandemic, can significantly impact the connection between hydrogen and other assets. On the basis of these findings, it seems hydrogen's connectedness may be more sensitive to market turmoil than conventional energy commodities. Thus, there is a potential need for policymakers to implement robust safeguards and monitoring measures, such as price stabilization mechanisms, resilience standards and contingency protocols, to manage uncertainty in hydrogen prices. This is especially important as hydrogen is still a nascent commodity that is not yet traded as such, but is only indirectly traded via indices. However, besides these mentioned studies, there is no research investigating the connectedness of hydrogen stocks/indices to general markets. Moreover, the latter two papers mention the role of extreme market events, which point to potential effects of global (policy) uncertainty and other behavioural factors like market attention, but do not include such measures.

This second empirical gap is addressed by investigating the connectedness of hydrogen with different markets, commodities and behavioural indices (i.e., policy uncertainty and Google Trends). The financial ecosystem is a complex network involving various entities, instruments and markets that interact and influence one another. As underlined, understanding the connectedness within this ecosystem is crucial for investors, policymakers and businesses alike. Moreover, from a social equity point of view, it is important to continuously provide and enhance knowledge about recent developments to make this complex network at least a bit more understandable for all socioeconomic groups. To analyze the connectedness of hydrogen with the main components of its financial ecosystem, the Time-Varying Parameter Vector Autoregressive (TVP-VAR) methodology, as initially proposed by Primiceri (2005) and refined by Antonakakis et al. (2020), is applied. TVP-VAR provides more flexibility for nonlinear and changing relationships as they potentially occur in recently developing and expanding markets. The hydrogen economy is proxied by two Exchange Traded Funds (ETFs) (Solactive and Global X) as well as the newly established EEX Hydrix Index, which should be a forerunner of a future commodity market listing.⁴

With our twofold analysis from both a cross-country macro perspective and a detailed FM perspective, significant contributions in three key areas are developed. First, we show that initial hydrogen production is primarily driven by FM development rather than FI development. This finding supports the importance of well-developed capital markets in facilitating the green transition, specifically for economic hydrogen use. Second, we analyze the connectedness of hydrogen indices with the overall market, incorporating behavioural aspects and the recently established EEX Hydrix. The analysis indicates that all three hydrogen measures are persistent but weak net transmitters of spillovers. Generally, we see connectedness to high-tech stocks (Nasdaq) for the ETFs and to Oil/Gas for the EEX Hydrix. This hints at the importance of technological development and the still-existing predominance of brown hydrogen production. However, this finding also indicates a potential mismatch

between “green” technology-driven expectations reflected in the ETFs and actual “brown” pricing dynamics reflected in the EEX Hydrix. Finally, the combined macroeconomic and FM analysis provides valuable insights for policymakers, investors and FI. These insights can guide early investors in the hydrogen economy and inform banks and FI on how to invest in this emerging sector effectively. Moreover, showing the importance of FM and differing dynamics, our results call for policy action via blended financing efforts and guarantees to support FI in channelling money towards green hydrogen investments to achieve a just transition. Further, it can be fruitful to potentially strengthen capital markets via measures, such as the European Savings and Investment Union.

The remainder of the paper is organized as follows. In Section 2, the twofold methodology used in the study and the associated data sets are presented. In Section 3, the macro results of the effects of financial (market) development on hydrogen production and adoption are shown. Section 4 continues with a detailed investigation of the FM, and Section 5 derives policy implications and concludes.

2 | Empirical Strategy

2.1 | Multicountry Panel Estimation for the Macroeffects of Financial Development on Hydrogen Production

Our first methodological approach involves a Two-Way Fixed-Effect (TWFE) model, which is designed to assess the impact of financial development as well as other economic and environmental factors on hydrogen adoption and production across countries. The choice of a TWFE model allows us to control for both country-specific and time-specific unobserved heterogeneity and is robustly estimable with unbalanced panels (Wooldridge 2010). Moreover, our data set features a large cross-sectional dimension (N) relative to the time dimension (T). When N is substantially larger than T , the asymptotic properties predominantly rely on the cross-sectional dimension. Fixed-effects models adequately capture individual and time-specific heterogeneity without incurring significant bias (Wooldridge 2010; Hsiao 2022). Similar studies investigating financial development effects over similar countries and time horizons also apply fixed-effects, specifically hinting at unobserved factors (geographical aspects, cultural aspects and institutional aspects) that are likely correlated with key variables (Anton and Afloarei Nucu 2020; Horky and Fidrmuc 2024). The general form of the model can be represented as follows:

$$\log(\text{Hydrogen}_{i,t}) = \alpha + \beta_1 FI_{i,t} + \beta_2 FM_{i,t} + \beta_3 R \& D_{i,t} + \beta_n Z_{i,t} + \delta + \tau + \varepsilon_{i,t}, \quad (1)$$

where *Hydrogen* is either one of our three distinct measures of hydrogen production capacity in country i at year t . To calculate these measures, we rely on data provided by the IEA, which covers all projects commissioned worldwide since 2000 for the production of hydrogen for energy or climate change mitigation purposes. Their objective is either to reduce the

emissions associated with the production of hydrogen for existing applications or to introduce hydrogen as an energy carrier or industrial feedstock in new applications where it is not currently widely used, and has the potential to be a low-emissions technology option (IEA 2019). We use the capacity of each project in Megawatt electric capacity (MWel), production capacity in normal cubic metres of hydrogen per hour ($\text{Nm}^3 \text{H}_2/\text{h}$) and production in kilotonnes of hydrogen per year ($\text{kt H}_2/\text{year}$). We then aggregate the capacities within a country by year. Hydrogen production is generally taken in log-values in the estimation phase. *FI* and *FM* are subindices of the IMF’s recent multifaceted financial development index. The overall IMF financial development indicator takes values between zero and one. Compared with other financial development measures, it has a very broad coverage and provides a multidimensional measure using eight financial variables (Svirydzenka 2016). The subindices themselves cover the depth and the accessibility of the FI and FM. These indicators are now widely used in a variety of applications where a measurement of financial development is needed (Struthmann et al. 2024; Errunza et al. 2024). Nevertheless, we acknowledge that financial development is complex to measure; therefore, for robustness, two different measures instead of *FI* and *FM* are included: the domestic credit to private sector, in % of gross domestic product (GDP) (*credit_ps*), as a proxy for FI development; and the stock market capitalization, in % of GDP (*stock_cap*), as a proxy for FM development as in Leung et al. (2018). Moreover, as R&D expenditure is important for new technologies development and adoption, R&D expenditure in % of GDP (*R&D*) per country and year, as provided by the World Bank, is also included in the analysis. Z is a set of control variables. These control variables capture broader macroeconomic, institutional and environmental factors that could influence hydrogen production. GDP per capita, inflation and unemployment reflect the overall economic conditions. The same or similar controls, like labour force, are also used in Horky and Fidrmuc (2024) or Apergis and Payne (2010). At the same time, Regulatory Quality Index (RQI), Fragile States Index (FSI) and Expanded Program on Immunization (EPI) provide measures of regulatory quality, political stability and environmental performance, reflecting the countries’ political environment. Policy measures are important factors to control when investigating renewable energies and the green transition in general (Fadly 2019). For high-tech facilities, it can be arguably assumed that some political stability is relevant. Moreover, as already indicated, some “green” policy efforts are likely to be important for hydrogen production developments, which is the main reason for including the EPI. Mean temperature is included to control for climatic variations that may affect (renewable) energy production and demand. Green hydrogen production relies on renewable energies. However, it is quite well-known that the renewable energy potential is connected to geographic and climatic regional aspects. And many of the relevant climatic aspects, for example, solar irradiance and wind speed, are correlated, though not in a trivial way (Bett and Thornton 2016). To avoid endogeneity, we aim to include a strictly exogenous climatic proxy, as, for example, in Bessin et al. (2025) with air temperature. Finally, δ and τ denote country and year fixed-effects to capture unobservable factors on these dimensions. The variable definitions and sources can be found in Table A1 in the Appendix. Table 1 presents the

TABLE 1 | Descriptive statistics of the macrolevel variables.

	N	Mean	Median	Minimum	Maximum
<i>cumulative_Capacity_MWel</i>	489	194.98	0.57	0.00	8001.14
<i>cumulative_Capacity_Nm</i>	489	111,909.70	149.67	0.00	3,890,855.00
<i>cumulative_Capacity_kt</i>	489	90.93	0.12	0.00	3033.47
<i>FI</i>	489	68.32	69.90	28.56	99.41
<i>FM</i>	489	57.50	60.38	2.93	98.90
<i>R&D</i>	489	1.73	1.67	0.16	3.73
<i>GDP per capita</i>	489	32,950.81	35,560.08	802.01	103,553.80
<i>Inflation</i>	474	2.37	1.96	-1.74	13.42
<i>Unemployment</i>	489	7.79	7.04	0.25	27.69
<i>RQI</i>	489	69.43	74.13	16.67	100.00
<i>FSI</i>	489	41.13	35.10	14.63	91.80
<i>EPI</i>	489	36.15	38.16	5.72	79.94
<i>Mean temperature</i>	459	12.70	10.90	-4.62	28.19
<i>credit_ps</i>	467	104.24	101.39	11.91	246.61
<i>stock_cap</i>	392	80.07	65.92	3.06	322.71
	SD	Skewness	Excess kurtosis		
<i>cumulative_Capacity_MWel</i>	1026.26	6.70	46.18		
<i>cumulative_Capacity_Nm</i>	430,138.00	5.63	38.52		
<i>cumulative_Capacity_kt</i>	336.03	5.57	37.95		
<i>FI</i>	16.49	-0.30	-0.67		
<i>FM</i>	23.25	-0.61	-0.42		
<i>R&D</i>	0.93	0.16	-1.07		
<i>GDP per capita</i>	21,716.59	0.42	-0.35		
<i>Inflation</i>	2.30	1.63	3.99		
<i>Unemployment</i>	4.82	1.88	3.96		
<i>RQI</i>	18.20	-0.69	-0.46		
<i>FSI</i>	18.85	0.89	-0.27		
<i>EPI</i>	14.99	-0.12	0.23		
<i>Mean temperature</i>	7.92	0.34	-0.43		
<i>credit_ps</i>	43.89	0.17	-0.47		
<i>stock_cap</i>	61.80	1.40	1.98		

Note: Descriptive statistics are calculated using the *psych* package in R.

Abbreviations: EPI, Expanded Program on Immunization; FI, Financial Institutions; FM, Financial Markets; FSI, Fragile States Index; GDP, gross domestic product; R&D, research and development; RQI, Regulatory Quality Index.

descriptive statistics for all variables used in the first part of the analysis.

To ensure the appropriateness of the econometric model, several diagnostic tests are performed to identify the relevant data patterns. The resulting test statistics are provided in Table 2. The Hausman test (Hausman 1978) results clarify the choice of a Fixed-Effects model, which is the preferable choice over all three general specifications. To check for Cross-sectional Dependence (CD), the Pesaran CD test (Pesaran 2021) is applied. The results indicate a significant CD for models 1 and 3, while no significant CD emerges for model 2. For serial correlation, the Breusch–Godfrey test (Breusch 1978; Godfrey 1978) is run,

yielding significant serial correlation across all three models. Finally, the Breusch–Pagan test for heteroskedasticity (Breusch and Pagan 1979) shows that it is also present in all three models.

On the basis of the diagnostic tests, significant CD, serial correlation and heteroskedasticity are observed in the data set, while the Fixed-Effects model should be preferred. To address these issues, a TWFE model with Driscoll–Kraay Standard Errors is estimated (Driscoll and Kraay 1998). This set of Standard Errors is robust to heteroskedasticity, serial correlation and CD, making them suitable given the violations detected in the data. Remarkably, as this country sample is not very large, the presence of CD calls for specific consideration (Hoechle 2007).

TABLE 2 | Diagnostic test results.

	Model 1	Model 2	Model 3
Hausman test	54.18***	123.97***	77.94***
Pesaran CD test	4.46***	0.92	6.10***
Breusch–Godfrey test	200.96***	164.78***	167.02***
Breusch–Pagan test	230.64***	94.40***	263.19***

Note: All tests are conducted using the *plm* and *lmtest* packages in R. The three models reflect the three different dependent variables capturing the hydrogen production, that is, Model 1 is specified as $\log(\text{cumulative_Capacity_MWe}_{i,t}) = \alpha + \beta_n \mathbf{X}_{n,i,t} + \delta + \tau + \varepsilon_{i,t}$, Model 2 is specified as $\log(\text{cumulative_Capacity_Nm}_{i,t}) = \alpha + \beta_n \mathbf{X}_{n,i,t} + \delta + \tau + \varepsilon_{i,t}$ and Model 3 is specified as $\log(\text{cumulative_Capacity_MWe}_{i,t}) = \alpha + \beta_n \mathbf{X}_{n,i,t} + \delta + \tau + \varepsilon_{i,t}$. Each model is estimated with the full set of control variables for the purpose of diagnostic testing.

Abbreviation: CD, Cross-sectional Dependence.

*, ** and *** denote statistical significance at the 10%, 5% and 1% levels, respectively.

The Driscoll–Kraay Standard Errors deliver consistent error estimates even when the cross-sectional dimension (N) is small while the time dimension (T) is moderate to large. To further verify that the findings obtained with the TWFE estimator are not an artefact of the covariance estimator, we re-estimated Equation (1) with a complementary approach. We applied panel feasible-generalized least squares (PFGLS), which is efficient in the presence of heteroskedasticity as well as contemporaneous and serial correlation when both the cross-sectional and the temporal error structure are unknown (Parks 1967). However, it has to be noted that in many cases, simple Ordinary Least Squares regressions with panel-corrected standard errors are the most efficient way to go (Beck and Katz 1995). Therefore, in an additional robustness attempt, we retained the original TWFE estimator but constructed inference by means of panel wild-cluster bootstrap resampling with 1000 replications, clustering once by country and once by year. This technique controls for heteroskedasticity and within-cluster error correlation but is feasible in samples with less than 50 clusters, unlike the traditional cluster-robust standard errors (Cameron et al. 2008). Across the baseline TWFE specification with Driscoll–Kraay standard errors, the PFGLS estimates and the two panel wild-bootstrap cluster variants, the estimated signs of our variables of interest remain mostly consistent.

2.2 | TVP-VAR for Hydrogen FM Connectedness

As a second methodological approach, the TVP-VAR is applied. Using our twofold approach, the TWFE and TVP-VAR enable us to capture both the macroeconomic structural determinants of hydrogen production and the evolving dynamics within hydrogen-related FM. Initially, the TVP-VAR was developed by Primiceri (2005) and used to model macroeconomic variables with parameters that evolve over time. TVP-VAR offers a way to better capture structural changes and account for economic dynamics that are not constant over time. Diebold and Yilmaz (2009, 2014) provide a rich toolbox to measure the connectedness of different time series, especially in FM. With these properties, the methodology gained track in FM research as market-based pricing relationships are not static, evolving in response to economic shifts, policy changes and unexpected shocks. Such dynamics are especially expected in new markets, which are not yet mature and prone to a variety of forces, such as the hydrogen economy.

Following Antonakakis et al. (2020) and Diebold and Yilmaz (2009, 2014), this new econometric technique is more adaptable and robust in capturing changes in data and regularly adopted for investigating spillovers, especially in recently established markets (Ahmed et al. 2024; Duan et al. 2023; Ngene and Tah 2023).

The TVP-VAR(p) model is described in the following equations:

$$y_t = A_t z_{t-1} + e_t, \text{ with } e_t | \Omega_{t-1} \sim N(0, \Sigma_t),$$

$$\text{Vec}(A_{t-1}) + \xi_t, \text{ with } \xi_t | \Omega_{t-1} \sim N(0, \Xi_t),$$

where Ω_{t-1} represents all information available until $t - 1$, and y_t and $z_{t-1} = (y_{t-1}^T, y_{t-2}^T, \dots, y_{t-p}^T)^T$ represent $m \times 1$ and $mp \times 1$ vectors, respectively. The evolution of the coefficient matrix A_t is modelled as a stochastic process, where $\text{vec}(\cdot)$ stacks the columns of A_t into an $m^2 p \times 1$ vector. e_t is an $m \times 1$ vector, and ξ_t is an $m^2 p \times 1$ vector, whereas the time-varying variance-covariance matrices Σ_t and Ξ_t are $m \times m$ and $m^2 p \times m^2 p$ dimensional matrices, respectively. By permitting both the coefficients and their variance-covariance structure to change over time, this framework is able to capture evolving spillovers, interconnectedness and regime shifts in economic and financial variables.

To capture the hydrogen economy features, three distinct financial time series are used. First, we use the Solactive Global Hydrogen Index,⁵ which emerges as a suitable proxy for investment products to track the hydrogen economy (Santamaria et al. 2022). Moreover, we use an alternative ETF (Global X⁶) replicating the Solactive Global Hydrogen Index for robustness reasons. Finally, we believe that Indices reflect the stock markets and associated companies. This is good for capturing the overall hydrogen economy, but it misses the view of hydrogen as a potential commodity. Yet, there is no already unified hydrogen commodity price, which makes it hard to assess this aspect. Other papers, like Lucey et al. (2024), used some hydrogen prices, usually one individual price series. Therefore, we rely on the more recently established EEX Hydrix Index.⁷ To make this weekly index comparable to other daily time series, the missing days are interpolated with cubic spline interpolation. The connectedness of these indices is measured with a variety of other FM products, capturing commodities (Aluminium, Steel,⁸ Oil, Gas, and Gold), general FM (Nasdaq 100 and S&P 500) and behavioural measures for economic policy uncertainty (EPU) and market attention (Google Trends).⁹ Especially for the latter two, the TVP-VAR approach is useful for investigating the connectedness between stock markets and behavioural aspects (Raza et al. 2023; Ngene and Tah 2023).

The data covers the period from 02.01.2020 until 30.09.2024, with the hydrogen data being available from 29.06.2021 for Solactive, 14.07.2021 for Global X and 04.05.2023 for EEX Hydrix. The TVP-VAR models start at these respective dates.

The variable definitions and sources are reported in Table A2 in the Appendix. Table 3 presents the descriptive statistics for all variables used in the second part of the analysis. Daily returns are calculated except for the Google Trends index and the EPU index, as these are calculated indices and not market-based.

TABLE 3 | Descriptive statistics of the (financial) market time series and diagnostic tests.

	N	Mean	Median	Minimum	Maximum	SD
<i>Global X</i>	734	0.00	0.00	-0.10	0.12	0.03
<i>Solactive</i>	744	0.00	0.00	-0.10	0.12	0.03
<i>EEX Hydrix</i>	324	0.00	0.00	-0.07	0.10	0.02
<i>Alu</i>	1092	0.00	0.00	-0.06	0.03	0.01
<i>Steel</i>	1092	0.00	0.00	-0.09	0.08	0.01
<i>Gold</i>	1092	0.00	0.00	-0.05	0.06	0.01
<i>Oil</i>	1092	0.00	0.00	-0.24	0.21	0.03
<i>Gas</i>	1092	0.00	0.00	-0.30	0.51	0.07
<i>Nasdaq</i>	1092	0.00	0.00	-0.12	0.10	0.02
<i>S&P</i>	1092	0.00	0.00	-0.13	0.09	0.01
<i>EPU</i>	1092	161.39	128.39	14.69	1026.38	112.38
<i>Trends</i>	1092	5288.12	5076.00	1364.00	10,000.0	1660.26
<i>Trends (Alternative)</i>	1092	5393.38	5240.00	1258.00	10,000.0	1723.82

	Skewness	Excess kurtosis	JB test	KPSS	ADF	PP
<i>Global X</i>	0.47	1.18	71.07***	0.02	-7.45***	-678.56***
<i>Solactive</i>	0.52	1.47	101.75***	0.03	-7.60***	-633.33***
<i>EEX Hydrix</i>	1.39	9.39	1316.4***	0.01	-8.45***	-178.73***
<i>Alu</i>	-0.58	2.95	461.89***	0.17	-9.64***	-924.04***
<i>Steel</i>	-0.45	5.84	1596.00***	0.27	-11.64***	-1053.2***
<i>Gold</i>	-0.19	3.51	570.00***	0.13	-10.28***	-1062.6***
<i>Oil</i>	-0.67	13.80	8779.00***	0.10	-10.19***	-968.19***
<i>Gas</i>	0.83	5.55	1535.3***	0.14	-10.37***	-1079.7***
<i>Nasdaq</i>	-0.26	5.76	1527.5***	0.10	-9.65***	-1321.2***
<i>S&P</i>	-0.55	12.43	7112.1***	0.04	-9.29***	-1391.4***
<i>EPU</i>	2.27	7.37	3426.8***	4.70***	-3.84**	-626.71***
<i>Trends</i>	0.52	-0.27	51.76***	2.15***	-3.58**	-42.52***
<i>Trends (Alternative)</i>	0.22	-0.43	16.859***	2.894***	-4.885***	-101.27***

Note: All tests are conducted using R with the *tseries* package. For the tests, the following functions are used: *jarque.bera.test()* for Jarque and Bera (1980), *kpss.test()* for Kwiatkowski et al. (1992), *adf.test()* for Dickey and Fuller (1979) and *pp.test()* for Phillips and Perron (1988).

Abbreviations: ADF, augmented Dickey-Fuller; Alu, aluminium; EPU, economic policy uncertainty; JB, Jarque-Bera; KPSS, Kwiatkowski-Phillips-Schmidt-Shin; Nasdaq, National Association of Securities Dealers Automated Quotations; PP, Phillips-Perron.

*, ** and *** stars denote significance at the 10%, 5% and 1% levels, respectively.

The descriptive statistics indicate that the mean returns for all market-based variables are effectively zero, which is typical for financial time series data. The standard deviations, skewness and kurtosis reveal varying levels of volatility, with natural gas (Gas) exhibiting the highest volatility (SD = 0.07) and gold showing the lowest (SD = 0.01), reflecting the diverse risk profiles and geopolitical events (Russian invasion in Ukraine and subsequent gas crisis in Europe) affecting these assets. The Jarque-Bera test statistics are significant at the 1% level for all variables, confirming the rejection of the null hypothesis of normality. To assess stationarity, we apply the ADF and PP tests. The results indicate that the null hypothesis of a unit root is rejected for all variables at the 1% significance level, implying that the return series are stationary. Complementarily, the KPSS test was employed to test the null hypothesis of stationarity. For most variables, the KPSS test statistics are not significant at conventional levels, supporting the stationarity conclusion drawn from the ADF and PP tests.

However, the EPU index and Google Trends data exhibit significant KPSS statistics (4.70*** and 2.15***, respectively), yielding potential nonstationarity. Given that the ADF and PP tests for these variables clearly suggest nonstationarity, and both indices, by construction, do not follow a random walk, we include them in their raw form in our TVP-VAR models.

3 | Financial Markets Development and Hydrogen Production

In this section, the estimation results for the multicountry panel estimation outlined in Section 2.1 are provided in Table 4. EPI shows a consistently positive and statistically significant impact on hydrogen production capacity across most specifications. This indicates that countries with stronger environmental policies tend to have higher hydrogen production capacities. This

TABLE 4 | Multicountry panel estimation for hydrogen production.

	<i>cumulative_Capacity_Mwel</i>			<i>cumulative_Capacity_Nm</i>			<i>cumulative_Capacity_Kt</i>		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
<i>EPI</i>	-0.017 (0.011)	0.094*** (0.036)	0.076* (0.039)	-0.025 (0.039)	0.163*** (0.039)	0.169*** (0.046)	0.013 (0.013)	0.101*** (0.027)	0.093*** (0.031)
<i>RQI</i>	0.000 (0.014)	0.004 (0.023)	0.008 (0.021)	-0.006 (0.021)	0.017 (0.021)	0.023 (0.036)	-0.002 (0.015)	-0.011 (0.018)	-0.007 (0.017)
<i>FSI</i>	-0.029*** (0.009)	-0.033 (0.025)	-0.038* (0.023)	-0.032 (0.023)	-0.039* (0.023)	-0.056 (0.035)	-0.015 (0.017)	-0.017 (0.036)	-0.024 (0.035)
<i>R&D</i>		-0.955*** (0.306)	-0.831*** (0.306)		-1.682*** (0.306)	-1.346*** (0.430)		-1.454*** (0.225)	-1.298*** (0.189)
<i>log(GDP per capita)</i>		-0.706 (0.766)	-0.397 (0.713)		-0.097 (0.713)	-0.399 (1.231)		-0.825 (0.683)	-0.731 (0.758)
<i>Inflation</i>		-0.014 (0.041)	-0.010 (0.039)		0.004 (0.039)	-0.016 (0.089)		0.036 (0.043)	0.033 (0.044)
<i>Unemployment</i>		0.077*** (0.029)	0.083*** (0.027)		0.212*** (0.027)	0.211*** (0.051)		0.017 (0.022)	0.020 (0.025)
<i>Mean temperature</i>		0.190* (0.112)	0.195 (0.123)		0.367*** (0.123)	0.429** (0.178)		0.159 (0.121)	0.178 (0.114)
<i>FI</i>			-0.044*** (0.014)			-0.026 (0.018)			-0.031*** (0.010)
<i>FM</i>			0.054*** (0.013)			0.114*** (0.024)			0.060*** (0.008)
<i>Observations</i>	489	444	444	489	444	444	489	444	444
<i>N</i>	35	32	32	35	32	32	35	32	32
<i>T</i>	5–15	5–15	5–15	5–15	5–15	5–15	5–15	5–15	5–15
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>R</i> ²	0.004	0.089	0.150	0.001	0.083	0.149	0.001	0.099	0.158
<i>F</i> statistic	0.69	4.81***	6.86***	0.28	4.45***	6.81***	0.22	5.36***	7.28***

Note: All estimates are conducted using the *plm* package in R. Driscoll–Kraay standard errors are reported in parentheses. Abbreviations: EPI, Expanded Program on Immunization; FE, fixed effect; FI, Financial Institutions; FM, Financial Markets; FSI, Fragile States Index; GDP, gross domestic product; R&D, research and development; RQI, Regulatory Quality Index. *, ** and *** denote significance at the 10%, 5% and 1% levels, respectively.

aligns with many countries and regions implementing hydrogen policy action plans, especially to enable the green transition. Such policies proxied by a country's general environmental performance seem to successfully promote hydrogen production. The FSI exhibits a negative and weakly significant effect on hydrogen production capacity in some models. Countries with higher levels of state fragility are, as expected, less likely to develop substantial hydrogen production capacities. Such high-tech investments usually require substantial political support and stability. Interestingly, the RQI has no significant impact. We would expect better regulatory quality to help promote hydrogen production. However, the hydrogen economy is still in its infancy and is characterized by initial investments. It seems that production quantity and the development stage are still too low for regulatory quality to make a real difference. The mean temperature exhibits positive coefficients, which are significant in some models, suggesting that countries with higher

average temperatures tend to have greater hydrogen production capacities. This can be reasoned as warmer climates are better suited to solar energy generation, which can be utilized for hydrogen production through electrolysis.

The core variables of interest, FI and FM, show contrasting effects as expected. FI shows a negative and statistically significant effect on hydrogen production capacity. Overall, three estimations show that a one-unit increase in FI score accounts for ~3%–4% decrease in hydrogen production. This aligns with the literature suggesting that FI may be risk-averse and hesitant to finance emerging green high-tech innovations due to uncertainty and unfamiliarity with the sector. In contrast, FM has a positive and significant impact, implying that well-developed FM supports larger hydrogen production capacities. This effect is comparably large, leading to ~5%–11% increase in hydrogen production for each unit increase in FM score. FM generally offer

more flexibility and risk tolerance when it comes to innovative products and business models. Our findings herewith confirm previous literature on renewable energy adoption, such as Horky and Fidrmuc (2024) and Anton and Afloarei Nucu (2020). More intricate is the strong negative and highly significant effect of R&D expenditure across all models. This suggests that higher national R&D expenditure is associated with lower hydrogen production capacity. One possible explanation is that substantial R&D investments are directed towards other advanced technologies perceived as more promising or offering immediate returns, such as digital technologies or other renewable energy sources like wind and solar. Alternatively, higher R&D expenditure may focus on early-stage research rather than commercialization and deployment, resulting in a lag before such investments translate into increased hydrogen production capacity. This is in line with the conclusion of Hailemariam et al. (2022), who state that “major economies allocated only a negligible share of GDP to energy R&D”, leaving substantial room for improvement.

Table 5 reports the PFGLS estimates. The results broadly confirm the patterns obtained with the TWFE model. The Environmental Performance Index remains positive and highly significant in every specification. State fragility again enters with a negative sign and, in most cases, statistical significance. As before, the RQI is mostly insignificant. Finally, national R&D expenditure retains its negative sign. The contrasting roles of the two financial-development dimensions are also preserved, but with some minor restrictions: FM continues to display a positive and mostly significant association with hydrogen capacity. A notable deviation between the two models occurs when investigating the FI dimension. While in the TWFE model this dimension has a negative sign, in the PFGLS it is positive, yet close to zero, and significant in at least one specification. Despite this sign change, the estimated coefficients for FM are consistently larger than those for FI. We therefore stick with our main interpretation that FM development remains the dominant financial driver of hydrogen-capacity expansion.

TABLE 5 | Multicountry panel estimation for hydrogen production alternatively estimated with panel feasible-generalized least squares regression.

	<i>cumulative_Capacity_Mwel</i>			<i>cumulative_Capacity_Nm</i>			<i>cumulative_Capacity_Kt</i>		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
<i>EPI</i>	0.009*** (0.002)	0.026*** (0.003)	0.070*** (0.008)	0.358*** (0.005)	0.287*** (0.016)	0.294*** (0.014)	0.048*** (0.011)	0.031*** (0.006)	0.053*** (0.011)
<i>RQI</i>	0.000 (0.001)	0.002 (0.002)	-0.005 (0.006)	0.007** (0.002)	0.02 (0.012)	-0.031** (0.010)	-0.007 (0.007)	0.020*** (0.004)	-0.01 (0.008)
<i>FSI</i>	-0.013*** (0.001)	-0.013*** (0.001)	-0.010* (0.006)	-0.134*** (0.005)	-0.044** (0.013)	-0.064*** (0.012)	-0.020* (0.010)	-0.039*** (0.005)	-0.005 (0.008)
<i>R&D</i>		-0.445*** (0.031)	-0.087 (0.107)		-0.615** (0.213)	0.403* (0.176)		0.019 (0.065)	0.123 (0.133)
<i>log (GDP per capita)</i>		-0.395*** (0.027)	-0.124 (0.192)		0.856* (0.350)	1.341*** (0.260)		-0.360** (0.114)	-0.027 (0.271)
<i>Inflation</i>		0.006*** (0.002)	-0.023** (0.008)		-0.077*** (0.016)	-0.057*** (0.016)		0.001 (0.004)	-0.020* (0.010)
<i>Unemployment</i>		-0.004* (0.002)	0.053*** (0.012)		0.100*** (0.024)	0.143*** (0.019)		0.063*** (0.010)	0.01 (0.014)
<i>Mean temperature</i>		-0.007 (0.009)	0.062* (0.028)		0.302*** (0.078)	0.379*** (0.079)		-0.024 (0.025)	0.055 (0.035)
<i>FI</i>			0.003 (0.006)			0.033*** (0.009)			0.003 (0.007)
<i>FM</i>			0.007* (0.003)			0.060*** (0.007)			0.015*** (0.004)
<i>Observations</i>	489	444	444	489	444	444	489	444	444
<i>N</i>	35	32	32	35	32	32	35	32	32
<i>T</i>	5–15	5–15	5–15	5–15	5–15	5–15	5–15	5–15	5–15
<i>Country FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>R²</i>	0.484	0.565	0.630	0.669	0.769	0.783	0.576	0.626	0.650

Note: All estimates are conducted using the *pfm* package in R. Abbreviations: EPI, Expanded Program on Immunization; FE, fixed effect; FI, Financial Institutions; FM, Financial Markets; FSI, Fragile States Index; GDP, gross domestic product; R&D, research and development; RQI, Regulatory Quality Index. *, ** and *** denote significance at the 10%, 5% and 1% levels, respectively.

Figure 1 summarizes the 95% confidence intervals obtained from our wild-bootstrap cluster standard errors based on Cameron et al. (2008), once clustering on the country dimension (upper panel) and once on the time dimension (lower panel). For each explanatory variable, the three slightly offset bars correspond to the hydrogen-capacity indicators (MWel to the left, centred Kt, and Nm to the right). The bootstrap intervals confirm the earlier conclusions drawn from the TWFE–Driscoll–Kraay and PFGLS estimations. However, expectedly, the significances are substantially lowered in this exercise. Most importantly, FM continues to exert a statistically significant positive effect, while the effect of FI is either insignificant or significant and weakly negative. Thus, this additional robustness exercise reveals no departure from the baseline results.

For a more in-depth analysis, the interaction effects between R&D expenditure and FI and FM scores are estimated. Given that R&D grants potentially signal support that is important for both FM and the securitization needs of FI, exploring these interaction effects is a potentially interesting analytical step. This analysis is depicted in Table 6. To increase the robustness of our analysis and check for potential threshold effects, we include specifications with an R&D dummy, equalling 1 if the R&D spending is equal to or above the median in a specific year in the respective country and 0 otherwise. On the basis of the estimation results incorporating interaction terms between R&D expenditure and FI and FM, we find that the interaction terms are not statistically significant in most cases. Specification number 6 is an exception, showing a significant positive

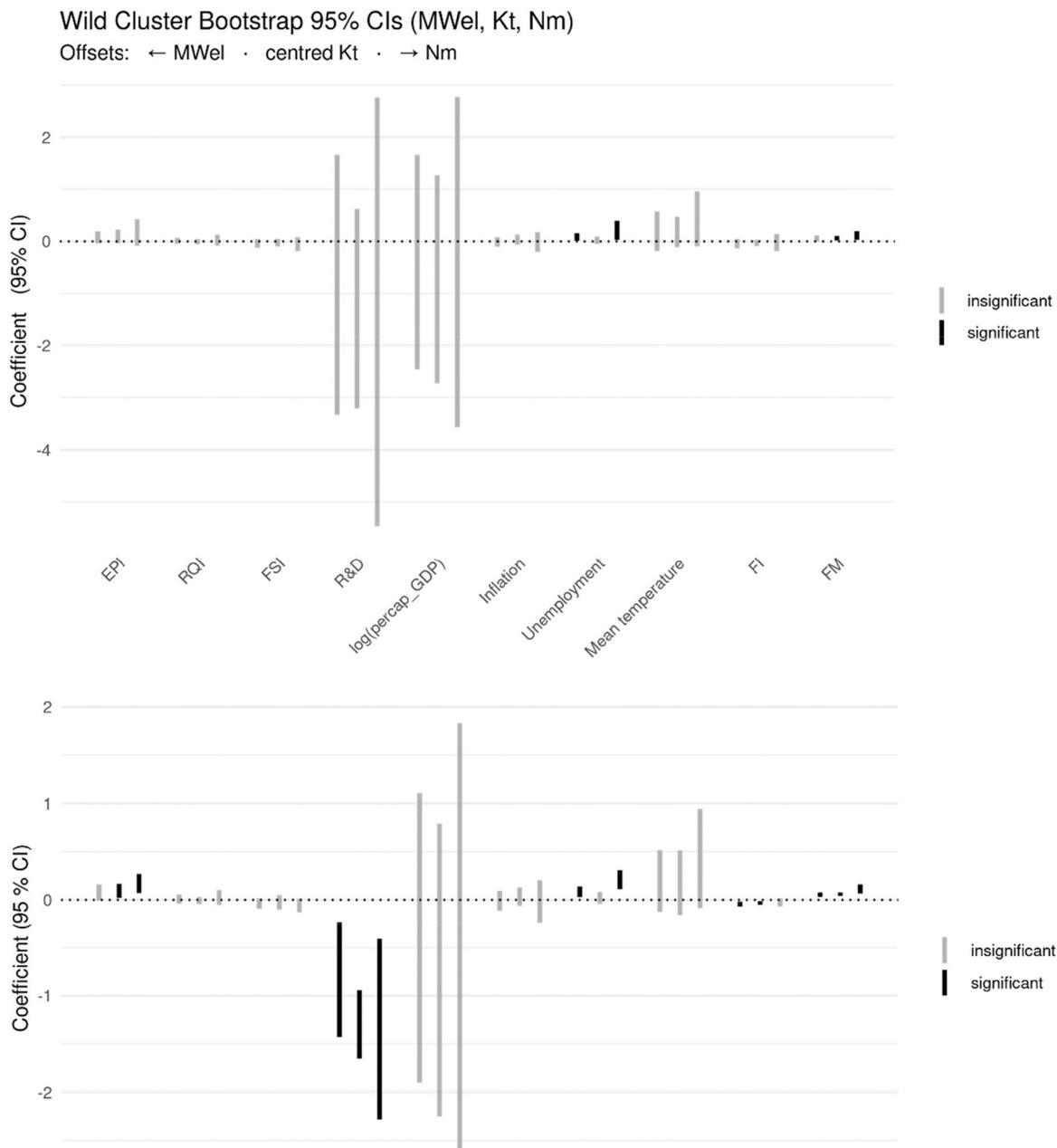


FIGURE 1 | Panel wild-bootstrap cluster standard error corrected coefficient plot. *Note:* The figure above shows the confidence intervals of the specifications with all control variables and the group wild-bootstrap cluster standard errors. The figure below shows the confidence intervals of the specifications with all control variables and the time wild-bootstrap cluster standard errors. The 95% confidence interval is shown. The estimates were performed using the clusterSEs package in R and 1000 replications each.

TABLE 6 | Interaction estimation of R&D and financial development.

	<i>cumulative_Capacity_Mwel</i>		<i>cumulative_Capacity_Nm</i>		<i>cumulative_Capacity_Kt</i>	
	(1)	(2)	(3)	(4)	(5)	(6)
<i>FI</i>	−0.044*** (0.015)	−0.065*** (0.019)	−0.077*** (0.026)	−0.062 (0.052)	−0.032 (0.021)	−0.082*** (0.010)
<i>FM</i>	0.043 (0.027)	0.073*** (0.022)	0.168*** (0.048)	0.133** (0.057)	0.056** (0.027)	0.085*** (0.014)
<i>R&D</i>	−1.226 (1.288)		−1.940 (1.774)		−1.432 (1.184)	
<i>R&D Median</i>		−1.083 (1.507)		−2.092 (3.812)		−3.990*** (1.056)
<i>FI * R&D</i>	0.001 (0.012)	0.030 (0.032)	0.032 (0.025)	0.050 (0.066)	0.001 (0.017)	0.074*** (0.021)
<i>FM * R&D</i>	0.006 (0.014)	−0.014 (0.021)	−0.029 (0.020)	−0.012 (0.054)	0.002 (0.013)	−0.018* (0.009)
<i>Observations</i>	444	444	444	444	444	444
<i>N</i>	32	32	32	32	32	32
<i>T</i>	5–15	5–15	5–15	5–15	5–15	5–15
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country and year FE	Yes	Yes	Yes	Yes	Yes	Yes
<i>R</i> ²	0.151	0.127	0.156	0.133	0.158	0.116
<i>F</i> statistic	5.74***	4.711***	5.96***	4.960***	6.04***	4.257***

Note: All estimates are conducted using the *plm* package in R. Driscoll–Kraay standard errors are reported in parentheses.

Abbreviations: FE, fixed effect; FI, Financial Institutions; FM, Financial Markets; R&D, research and development.

*, ** and *** denote significance at the 10%, 5% and 1% levels, respectively.

interaction between Financial Institutions Development and R&D spending and a negative one between Financial Markets Development and R&D spending. In line with the expected mechanism, this result at least weakly confirms that R&D backing seems to satisfy the securitization needs of FI to a certain degree. However, this specification might also hint at a crowding-out effect of FM when substantial R&D spending in one country is present. Overall, however, the results are too weak to strongly posit an effect of R&D connected with the level of development of FI or FM on hydrogen production capacity. Moreover, the coefficient of R&D remains negative but is no longer statistically significant. The coefficients on FI and FM remain consistent with prior results in terms of magnitude and significance.

We conduct two further sets of estimations to ensure the robustness of the results. First, we conduct a sample split, repeating the estimations with an exclusively EU country sample. In fact, it should be a comparably homogeneous country sample in terms of regulation and culture, thus providing a possibility to exclude nonquantifiable aspects stemming from cross-regional heterogeneity from the analysis. The results can be found in Table A3 in the Appendix. Second, we repeat the estimations for the whole country sample but with alternative measures of financial development, the domestic credit to the private sector (*credit_ps*) as a proxy for FI development and stock market capitalization (*stock_cap*) as a proxy for FM development. The respective results are shown in Table A4 in the Appendix.

In the EU subsample, the FM score remains positive and statistically significant across all models, which is consistent with the main analysis. This ensures the robustness of our conclusion that well-developed FM provide financing and support for greater hydrogen production capacity. However, complementary to the overall results, the FI score shows mixed results in the EU context. While FI is not significant in most models, it becomes positive and marginally significant in some specifications. This could hint at EU FI being more supportive of hydrogen investments compared with their global counterparts, possibly due to EU-wide initiatives and regulations promoting the green transition (EU Green Deal). Additionally, the interaction terms between R&D expenditure and FM in the EU subsample are negative and significant in some models. This suggests that the positive effect of FM on hydrogen production capacity may diminish when R&D expenditure is high. A potential explanation can be that in the case of R&D support, the respective projects (i.e., universities and start-ups) are not allowed to be unregulated and raise money in the FM.

The results using alternative measures of financial development are also widely consistent with our main findings. In the context of the financial ecosystem, the variable representing FI (*credit_ps*) exhibits a negative and significant coefficient in several models. Similarly, the alternative measure for FM (*stock_cap*) shows a positive and statistically significant coefficient in some models, consistent with the supportive role of FM in the hydrogen economy.

Interestingly, when considering the interaction effects, some interesting deviations occur. In particular, the interaction effect between FI's measures and R&D is positive and significant. This is somewhat in line with what we observe from the

EU subsample already. Complementary to the previously proposed mechanism, this result may hint at reduced perceived risk when countries invest more in R&D. Such a reduced risk perception may lead to FI becoming more willing to finance hydrogen projects.

To summarize, this first part of the empirical analysis highlights the critical role of FM development in supporting hydrogen production capacity across countries. The positive and significant impact of FM shows their potential to provide capital for the hydrogen sector, likely due to their greater risk tolerance. Conversely, traditional FI appear less supportive, possibly due to risk aversion and unfamiliarity with emerging technologies. These findings are consistent across various robustness checks, including an EU-specific sample and alternative measures of FM and institution development. Given the discovered role of FM in the hydrogen economy, it becomes essential to understand the dynamics between hydrogen-related financial instruments and prices and the overall FM to draw holistic policy and investment implications.

4 | Financial Market Connectedness of Hydrogen Stocks and Prices

The second step of the empirical analysis investigates in detail the FM's aspects. We employ TVP-VAR models to estimate the connectedness between hydrogen indices and prices and a

variety of other FM indices. We specifically try to cover a broad range of indices and assets, as the IMF's Financial Development Indicators are themselves aiming at covering the whole picture. So, this second part of the analysis should provide a more granular picture, complementing the macroeconomic aspects. In the dynamic spillover analysis presented in Table 7, the Solactive ETF is characterized as a weak net transmitter of spillover effects.

In the first row, Solactive's own variance explanation is about 60.55%, meaning most of its variance is explained by its own past values. This suggests a strong internal consistency and minimal dependence on external shocks. Furthermore, Solactive's effect on other variables is denoted by TO, with a value of 40.65 (i.e., meaning that 40.65% of the total variance of other variables can be explained by Solactive's returns), while FROM has a value of 39.45 (i.e., indicating that other factors can explain 39.45% of the variance in Solactive's returns). This outcome suggests that it is moderately influenced by external factors, resulting in a NET spillover effect of 1.21%. The highest spillover effects come from Nasdaq (15.69%) and S&P 500 (9.15%), followed by Gold (4.63%). This suggests that Solactive is particularly influenced by broader US equity, especially high-technology markets, and, to a lesser extent, by gold. Similarly, the highest spillover effect from Solactive is on the Nasdaq (11.68%) and S&P 500 (7.01%), followed by Gold (6.00%).

Figure A1 in the Appendix provides the time-varying connectedness dynamics and shows that Solactive has periods of positive net spillovers, especially noticeable in 2023 and early 2024. This suggests that during these phases, it exerted a stronger influence on other variables. These fluctuations may indicate shifts due to specific turmoil events (e.g., the Russia-Ukraine

TABLE 7 | Spillover connectedness (Solactive).

	<i>Solactive</i>	<i>Alu</i>	<i>EPU</i>	<i>Gold</i>	<i>Oil</i>	<i>Nasdaq</i>	<i>S&P 500</i>	<i>Steel</i>	<i>Gas</i>	<i>Trends</i>	<i>FROM</i>
<i>Solactive</i>	60.55	1.40	1.92	4.63	2.69	15.69	9.15	1.47	0.81	1.68	39.45
<i>Alu</i>	2.77	65.25	1.80	2.50	5.13	3.23	2.46	13.68	1.44	1.75	34.75
<i>EPU</i>	2.35	2.07	82.65	1.53	1.89	1.12	1.29	2.63	2.36	2.11	17.35
<i>Gold</i>	6.00	1.48	1.56	72.29	3.99	4.15	4.74	1.58	2.64	1.58	27.71
<i>Oil</i>	3.75	3.17	1.85	3.79	72.28	3.00	4.91	2.74	2.93	1.58	27.72
<i>Nasdaq</i>	11.68	1.63	0.84	2.33	2.14	46.45	32.00	1.44	0.60	0.88	53.55
<i>S&P 500</i>	7.01	1.66	0.83	2.84	3.17	33.12	48.02	1.57	0.91	0.86	51.98
<i>Steel</i>	2.45	14.22	2.32	2.22	2.65	2.64	2.42	68.05	1.81	1.22	31.95
<i>Gas</i>	1.79	2.44	2.56	3.00	3.15	2.20	2.21	2.75	77.65	2.26	22.35
<i>Trends</i>	2.85	2.09	3.20	2.18	1.39	2.05	1.40	1.03	2.57	81.23	18.77
<i>TO</i>	40.65	30.17	16.86	25.02	26.19	67.20	60.58	28.90	16.08	13.93	325.58
<i>Inc.Own</i>	101.21	95.42	99.52	97.31	98.47	113.65	108.60	96.95	93.73	95.16	cTCI/TCI
<i>NET</i>	1.21	-4.58	-0.48	-2.69	-1.53	13.65	8.60	-3.05	-6.27	-4.84	36.18/32.56
<i>NPT</i>	7.00	4.00	3.00	4.00	4.00	9.00	8.00	3.00	1.00	2.00	

Note: FROM represents the source of causal impacts received from each variable, TO stands for the destination of effects and positive (negative) values of NET reveal that the variable is a net transmitter (receiver) of spillover impacts. The numbers are on a 0 to 100 scale, showing percentages. They reflect how much of the variance in one variable is due to itself (diagonal) or others (off-diagonal). The Net Pairwise Transmission (NPT) in this table provides an ordinal ranking of each variable's net spillover position. Finally, cTCI and TCI denote the corrected Total Connectedness Index based on Chatziantoniou and Gabauer (2021) and the Total Connectedness Index, respectively. The same applies to Tables 7 and 8.

Abbreviations: Alu, aluminium; EPU, economic policy uncertainty; Nasdaq, National Association of Securities Dealers Automated Quotations.

war). All in all, Solactive seems to have a fluctuating pattern, moving between transmitter and receiver positions, which may indicate sensitivity to FM or economic conditions.

Table 8 provides the results of the dynamic spillover analysis for the second ETF (Global X), which is, similarly to Solactive, also identified as a weak net transmitter. Overall, the observed dynamics are nearly identical to the ones visible for Solactive. Global X's own variance explanation is about 59%–74% compared with 60.55% for Solactive. The largest spillovers also result from the high-tech sector (Nasdaq), followed by general markets (S&P 500) and gold. The same holds for spillover effects from Global X to other financial time series, with the strongest ones being observed in Nasdaq, S&P 500 and Gold. Considering the time-varying connectedness dynamics of Global X, as illustrated in Figure A2 in the Appendix, we can observe that Global X more consistently served as a net transmitter with less fluctuating patterns.

Finally, Table 9 provides the results of the dynamic spillover analysis for the EEX Hydrix, which aims at capturing hydrogen prices instead of being an index of stocks related to the hydrogen economy. Similar to the ETFs, Hydrix is a weak net transmitter of spillovers. The Hydrix index exhibits an even higher own variance explanation of 80.73%, suggesting a strong internal dynamic and an even lower relative dependence on external shocks compared with the already low levels exhibited with the Solactive and Global X ETFs. Analyzing the specific spillover relationships, Hydrix is most influenced by Oil (4.48%) and Gas (3.51%), highlighting that the fluctuations in these energy commodities impact hydrogen prices. This linkage is intuitive, given that hydrogen production and pricing are closely tied to the broader energy market and fossil fuel prices. However, this relationship is rather weak. Other variables like Aluminium, Gold, Nasdaq and S&P 500 have minimal spillover effects on Hydrix, each contributing less than 2%. Hydrix's

influence on other variables has the most substantial impact on Gas (4.21%) and Oil (3.76%). This reciprocal relationship confirms the previous finding of connectedness between hydrogen prices and traditional energy commodities. Figure A3 in the Appendix shows the time-varying connectedness dynamics of this model. We can observe some changing patterns, with Hydrix being a stronger net transmitter in its initial phase (2023) but mostly a net receiver in 2024. However, given the shorter span of data availability compared with the ETFs, an interpretation is rather inappropriate in this case.

For robustness purposes, we re-estimate the TVP-VAR models with an alternative Google Trends-based market attention measure. The results can be found in Tables A5–A7 and align with the previously presented results.

Overall, the second part of the analysis, using TVP-VAR models, shows distinct patterns in the connectedness between hydrogen-related financial instruments and other market indices. The hydrogen ETFs in our sample, Solactive and Global X, exhibit moderate spillover effects and are particularly connected to high-tech stocks, notably the Nasdaq index. This finding is consistent with existing literature that identifies strong linkages between renewable energy stocks and the high-technology sector (Zhang and Du 2017). The significant influence of the Nasdaq and, less important but still observable, the S&P 500 on these ETFs may hint at companies involved in the hydrogen economy being innovative high-tech firms. However, if this is the case, risks similar to those in the overall high-tech sector are potentially present. This means that companies are challenging to value, and there are potentially substantial crash and bubble risks. In contrast, the EEX Hydrix index demonstrates a considerably lower level of connectedness with broader FM. Its strongest connections are with traditional energy commodities, specifically natural gas and oil. This relationship is intuitive, given that a significant portion of hydrogen production

TABLE 8 | Spillover connectedness (Global X).

	<i>Global X</i>	<i>Alu</i>	<i>EPU</i>	<i>Gold</i>	<i>Oil</i>	<i>Nasdaq</i>	<i>S&P 500</i>	<i>Steel</i>	<i>Gas</i>	<i>Trends</i>	<i>FROM</i>
<i>Global X</i>	59.74	1.23	1.72	4.82	2.53	16.43	9.86	1.32	0.84	1.52	40.26
<i>Alu</i>	2.59	65.35	1.59	2.48	5.12	3.25	2.44	13.99	1.40	1.79	34.65
<i>EPU</i>	2.06	1.85	83.07	1.54	1.89	1.10	1.18	2.82	2.39	2.09	16.93
<i>Gold</i>	6.29	1.48	1.60	72.03	4.10	4.01	4.72	1.55	2.66	1.57	27.97
<i>Oil</i>	3.47	3.30	1.85	3.94	72.30	3.00	4.96	2.86	2.70	1.63	27.70
<i>Nasdaq</i>	12.80	1.63	0.80	2.32	2.06	45.78	31.68	1.46	0.58	0.89	54.22
<i>S&P 500</i>	8.20	1.70	0.81	2.87	3.09	32.80	47.22	1.58	0.86	0.85	52.78
<i>Steel</i>	2.22	14.46	2.43	2.19	2.82	2.67	2.44	67.72	1.85	1.20	32.28
<i>Gas</i>	1.88	2.50	2.57	2.98	2.97	1.79	1.86	2.92	78.17	2.36	21.83
<i>Trends</i>	2.72	2.16	3.08	2.14	1.42	2.00	1.33	1.09	2.60	81.45	18.55
<i>TO</i>	42.23	30.31	16.44	25.28	26.00	67.06	60.47	29.60	15.88	13.90	327.16
<i>Inc.Own</i>	101.97	95.67	99.51	97.31	98.30	112.84	107.69	97.32	94.04	95.35	cTCI/TCI
<i>NET</i>	1.97	−4.33	−0.49	−2.69	−1.70	12.84	7.69	−2.68	−5.96	−4.65	36.35/32.72
<i>NPT</i>	7.00	4.00	3.00	4.00	4.00	9.00	8.00	3.00	1.00	2.00	

Abbreviations: Alu, aluminium; EPU, economic policy uncertainty; Nasdaq, National Association of Securities Dealers Automated Quotations; NET, net transmitter; NPT, Net Pairwise Transmission.

TABLE 9 | Spillover connectedness (EEX Hydrix).

	<i>Hydrix</i>	<i>Alu</i>	<i>EPU</i>	<i>Gold</i>	<i>Oil</i>	<i>Nasdaq</i>	<i>S&P 500</i>	<i>Steel</i>	<i>Gas</i>	<i>Trends</i>	<i>FROM</i>
<i>Hydrix</i>	80.73	1.55	1.14	1.71	4.48	1.46	1.94	1.50	3.51	1.98	19.27
<i>Alu</i>	1.67	68.11	1.98	3.21	1.83	5.30	2.60	12.49	1.11	1.69	31.89
<i>EPU</i>	1.55	2.61	81.53	1.27	2.95	1.36	1.28	1.94	2.32	3.20	18.47
<i>Gold</i>	1.91	1.32	1.36	75.86	2.00	4.37	4.31	2.28	4.67	1.92	24.14
<i>Oil</i>	3.76	1.40	2.34	1.66	79.40	2.45	2.53	2.87	1.89	1.70	20.60
<i>Nasdaq</i>	1.70	2.14	0.76	2.60	1.69	53.02	34.59	1.87	0.65	0.98	46.98
<i>S&P 500</i>	1.23	1.41	1.01	2.61	1.50	34.70	53.13	2.37	1.23	0.81	46.87
<i>Steel</i>	1.27	10.94	1.66	2.35	1.58	6.76	6.25	65.67	1.41	2.10	34.33
<i>Gas</i>	4.21	1.13	2.10	3.39	3.47	0.97	2.18	1.26	79.89	1.40	20.11
<i>Trends</i>	3.36	4.19	1.52	1.54	2.11	1.67	1.65	1.87	1.47	80.63	19.37
<i>TO</i>	20.67	26.68	13.87	20.33	21.61	59.04	57.34	28.45	18.26	15.77	282.03
<i>Inc.Own</i>	101.40	94.79	95.40	96.19	101.01	112.06	110.47	94.13	98.15	96.40	cTCI/TCI
<i>NET</i>	1.40	-5.21	-4.60	-3.81	1.01	12.06	10.47	-5.87	-1.85	-3.60	31.34/28.20
<i>NPT</i>	6.00	3.00	1.00	2.00	6.00	8.00	8.00	4.00	4.00	3.00	

Abbreviations: Alu, aluminium; EPU, economic policy uncertainty; Nasdaq, National Association of Securities Dealers Automated Quotations; NET, net transmitter; NPT, Net Pairwise Transmission.

currently relies on natural gas through methods like steam methane reforming. Nevertheless, the divergence between hydrogen-related ETFs and actual attempts to capture hydrogen prices suggests a structural disconnect between the FM's perception of hydrogen economy companies and the current state of hydrogen as a commodity. While the stocks represent optimism about the future of green hydrogen and technological advancements, Hydrix reflects the practical challenges and current reliance on fossil-based production methods. This misalignment could pose issues for the sector and call for further policy action and investor attention. The overall weak connectedness observed, especially for the EEX Hydrix index, suggests that hydrogen markets are still in the process of establishing themselves within the global financial system.

Regarding the total connectedness of the three systems, we notice that the corrected Total Connectedness Index (cTCI) presents a relatively moderate value (i.e., 36.18% for Solactive, 36.35% for Global X and 31.34% for EEX Hydrix), suggesting a moderate interdependence among our variables, which can be interpreted as moderate cross-market risk transmission.¹⁰ This finding practically implies that investors can achieve diversification benefits since the assets are not excessively interconnected.

5 | Conclusions

This study has investigated the role of FM and their development in the adoption of hydrogen in the wake of the necessary green transition. Utilizing both cross-country panel data for a macro perspective and TVP-VAR models for a detailed investigation of the FM, we provide a holistic financial ecosystem approach to inform policymakers and investors alike. To the best of our knowledge, we provide one of the first yet the broadest attempts at researching the connections of the hydrogen economy with financial development and FM, also considering the role of

institutions. We find several notable results: First, FM development is crucial for supporting increased hydrogen production capacity on a country level. This is in line with the literature on FM, which highlights the willingness to take risks for potential profits promised by innovative products and business models. On the other hand, traditional FI (i.e., banks) exhibit a more cautious approach, likely due to their preferred risk profile. Second, the connectedness analysis revealed overall weak relationships between hydrogen-related indices and broader financial and commodity markets. This finding indicates the still-developing stage of a hydrogen economy from an FM's perspective, especially when considering hydrogen as a commodity. Third, while hydrogen stocks, as captured by the Solactive and Global X ETFs, are mostly connected to the general FM (S&P 500) and especially high-tech stocks (Nasdaq), the Hydrix, which captures the hydrogen price, is mostly still weakly, connected to natural gas and oil. These findings suggest a structural misalignment between market expectations reflected in hydrogen stocks and the practical realities represented by actual hydrogen prices.

Our results allow us to draw relevant implications for policymakers and investors, suggesting how to coordinate diverse financial instruments, institutions and markets to support hydrogen adoption. For policymakers, it is important to acknowledge the importance of blended financing solutions to effectively channel investments for the green transitions. This means that supportive measures by governments and funding agencies need to be implemented to overcome the risk aversion exhibited by FI. Both banks and markets have unique strengths, but are individually insufficient to meet the financing needs of green transformation and hydrogen adoption. Nevertheless, hydrogen investments are potentially risky and are in the early development stages. Therefore, the FM necessary to support such businesses must be adequately large to provide sufficient financing. In the European case, the planned European Savings and Investment Union could be beneficial in overcoming the

fragmentation and, therefore, enable such a necessary large FM. Similar measures could potentially be adopted across world regions. Moreover, we suggest a proper information channel between policy makers, FI and the business sector involved in green hydrogen production to reduce frictions, which ultimately contributes to an increased socioeconomic technology divide. There should be a general consensus in supporting any technology that could help mitigate the potential increasing inequality caused by green policies. The observed misalignment between the dynamic market connectedness of hydrogen stocks and actual hydrogen pricing also signals the need for a clearer regulatory framework and communication. Policymakers should provide as explicit guidance as possible on the role of hydrogen as a complement to existing energy solutions for the green transition. This helps avoid speculative bubbles and ensures that investments align with realistic deployment goals. Finally, establishing hydrogen as a traded commodity, supported by appropriate indices, could bring transparency and stability. Policymakers and regulators can support such a process.

For investors, the hydrogen sector presents both opportunities and risks inherent to a market in its early stage. The divergence between hydrogen stock connectedness and the actual pricing of hydrogen and its connectedness implies potential risks due to wrong expectations. Investors should proceed with caution, keeping in mind that current valuations may not accurately reflect the fundamental values and economics of hydrogen production. This discrepancy also suggests that early investment strategies should focus on diversified portfolios that can mitigate risks associated with potential mispricing and overly strong market optimism. In particular, private investors should target this market with caution and seek professional investors' responsible and informed advice.

In the end, it should be noted that the present study is, of course, not without limitations. While our twofold approach provides a comprehensive view, there are some methodological limitations that warrant attention. For instance, our fixed-effects panel model might fail to capture potential nonlinearities or structural breaks due to regulatory changes potentially present in emerging markets like hydrogen production. Similar constraints hold for the TVP-VAR framework. Future research could, therefore, address these issues by specifically investigating nonlinearities and considering methodological approaches that account for or detect structural breaks. Another limitation, especially concerning the TVP-VAR approach, is our measurement of market attention. While market attention measures are usually important in nascent markets as they drive investor awareness, it is not really measurable. We made an attempt to capture it using Google Trends. However, the search volumes seem to be generally low. Also, given our results, the question remains whether the hydrogen economy and related investments have already reached the stage where attention can be regarded as a reasonable driver. In the future, maybe other sources like more tech-savvy Reddit threads or news articles can be used to measure hydrogen market attention.

The use of aggregate country-level financial indicators may further overlook the highly individual nature of each hydrogen production project. Currently, every hydrogen production project

is still highly dependent on regulatory and political considerations. Future research could, therefore, explore more granular data to examine the influence of specific financial and funding information for individual hydrogen production projects. An investigation into different R&D schemes and policies across countries could be especially interesting. Further research prospects include comparing green hydrogen production projects with those employing other production mechanisms to determine whether differences in financing structures and outcomes exist. Additionally, the hydrogen market's dynamics are evolving rapidly; thus, more frequent updates to connectedness and spillover analyses covering a wider range of other assets and world regions could provide relevant additional insights. Finally, specific use cases of hydrogen and its initial financing situations (such as green steel production) provide a valuable starting point for potential further research, especially in terms of a just transition.

Acknowledgements

We thank Jarko Fidrmuc, Florentina Paraschiv, Carolina Rachel, Jan Klacso and Tullia Gattone for valuable comments during the writing process. We further benefitted from helpful comments from the participants of the 7th Ethical Finance and Sustainability Conference in Leeds (EFS—2024) and the ZF-Symposium for future megatrends at the Zeppelin University. The views represented are the authors' and not necessarily the ones of the Slovak National Bank, the Eurosystem or any other institution the authors are affiliated with. Open Access funding enabled and organized by Projekt DEAL.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data are generally publicly available from the sources mentioned in the paper. A curated data set is available from the authors with a reasoned request.

Endnotes

¹ Across the globe, hydrogen became the subject of various policy plans. For example, the EU Commission developed a European hydrogen strategy in 2020, which was included and further developed in the comprehensive REPowerEU plan in 2022 (European Commission 2022). China included hydrogen as a frontier innovation area in its 14th 5-year plan from 2021 to 2025. India implemented a national green hydrogen mission to make India “the Global Hub for production, usage and export of Green Hydrogen and its derivatives” (India Ministry of New and Renewable Energy—National Green Hydrogen Mission|Ministry of New and Renewable Energy|India [mnre.gov.in]). The U.S. Department of Energy also released a comprehensive hydrogen action plan with a focus on R&D in 2023. These policy plans only include a small selection of relevant players.

² Germany provides “several billion euros” for R&D as well as implementation of hydrogen generation, necessary infrastructure, and its use in corporate contexts. Australia and the US have announced tax incentives for green hydrogen production with a volume of 6.7bn A\$ (~4.3bn \$) in the Australian case. Such government money flows are also visible as we investigate a growing number of hydrogen ETFs in recent years, with a clear acceleration after the COVID-19 pandemic and the Russian invasion of Ukraine. Moreover, efforts culminate in plans to establish hydrogen as a commodity on exchanges, with the first attempts being, for example, the EEX Hydrix, which is also used in this study.

- ³The IEA collects and categorizes the most comprehensive sample of planned and already implemented hydrogen production projects we make use of IEA (2019). The IEA covers 44 member and association countries, making up ~70% of global energy demand, and therefore provides good coverage of the global hydrogen efforts. However, it has to be acknowledged that several African and Arab countries with potentially relevant impacts are uncovered.
- ⁴EEX Hydrix is an index aiming at providing the price of green hydrogen offered in Germany. The index value is the unweighted arithmetic mean of price data provided by companies supporting this index and published once a week every Wednesday. It is said to be the first “market-based only” pricing index of green hydrogen and should serve as a predecessor of potential hydrogen commodity trading in the future (<https://www.eex-transparency.com/de/wasserstoff>).
- ⁵The Solactive Global Hydrogen Index (ISIN: DE000SL0DNU9; WKN: SL0DNU) is a USD-based Index composed of securities of companies that have business operations in the production or use of hydrogen as a fuel source. It was initiated at a base value of 1000 points on 29.06.2021 (<https://www.solactive.com/Indices/?index=DE000SL0DNU9>).
- ⁶The Global X Hydrogen ETF (ISIN: US37960A4206; CUSIP: 37960A420) seeks to provide investment results that correspond generally to the price and yield performance, before fees and expenses, of the Solactive Global Hydrogen Index (<https://www.globalxetfs.com/funds/hydr/>).
- ⁷EEX as provider states: “HYDRIX is the first hydrogen index based on supply and demand prices. The index provides much-needed price transparency for the hydrogen market. Today, there is neither over-the-counter nor exchange trading in hydrogen, but there are already price indications from bilateral supply contracts. EEX calculates the HYDRIX on a weekly basis, as an average value of supply and demand” (<https://www.eex-transparency.com/de/wasserstoff>).
- ⁸Hydrogen is perceived as an important energy carrier in greening the production of steel and other metals.
- ⁹We include two alternative measures of market attention captured via Google Trends. For our standard measure, we use the topic “Hydrogen”, while for our alternative measure, we use the search term “Hydrogen energy”.
- ¹⁰The TCI is a measure of the overall interconnectedness in a TVP-VAR and is specified as the sum of directional connectedness from all other variables to each variable, normalized by the total number of variables. The cTCI is slightly adjusted, since we want to know the average amount of network comovement in per cent (based on Chatziantoniou and Gabauer 2021).

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Appendix

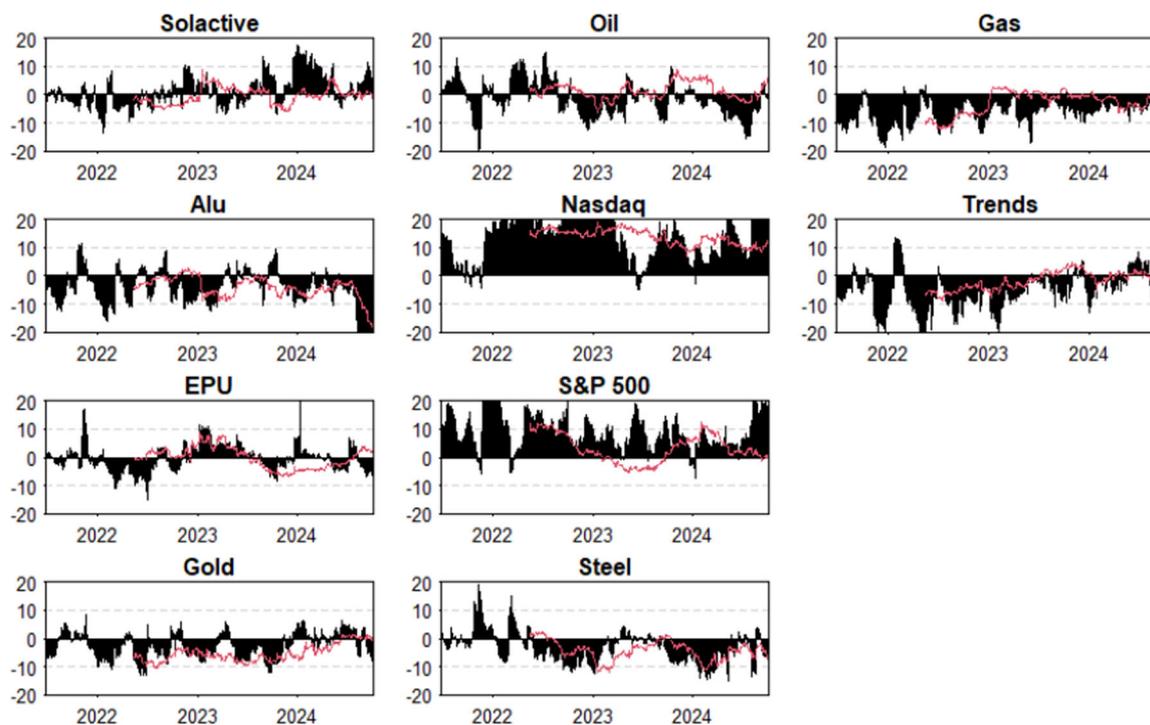


FIGURE A1 | Dynamic net total and net pairwise directional connectedness (Solactive). *Note:* The dynamic total connectedness based upon the TVP-VAR is presented by the black area, while the red line represents the dynamic total connectedness of a 200-day rolling-window VAR. The “ConnectednessApproach” package in R is used to estimate the TVP-VAR model. The same applies to Figures A2 and A3. Alu, aluminium; EPU, economic policy uncertainty; Nasdaq, National Association of Securities Dealers Automated Quotations; TVP, Time-Varying Parameter; VAR, Vector AutoRegressive.

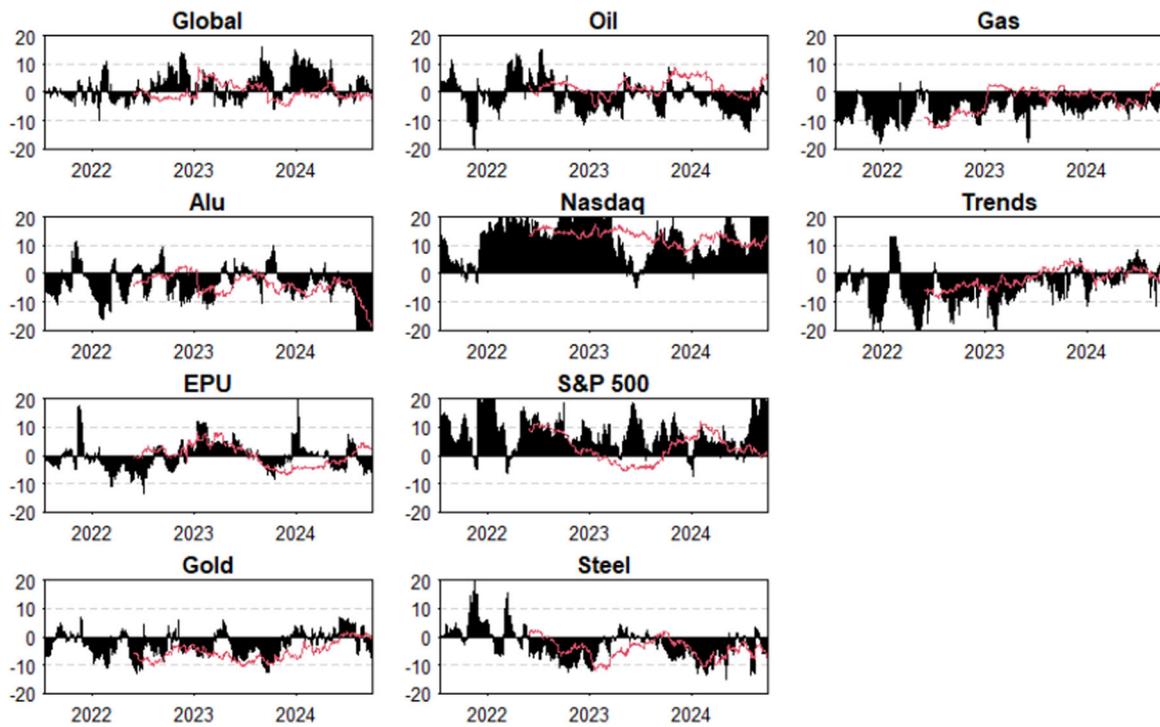


FIGURE A2 | Dynamic net total and net pairwise directional connectedness (Global X). *Note:* See Figure A1. Alu, aluminium; EPU, economic policy uncertainty; Nasdaq, National Association of Securities Dealers Automated Quotations.

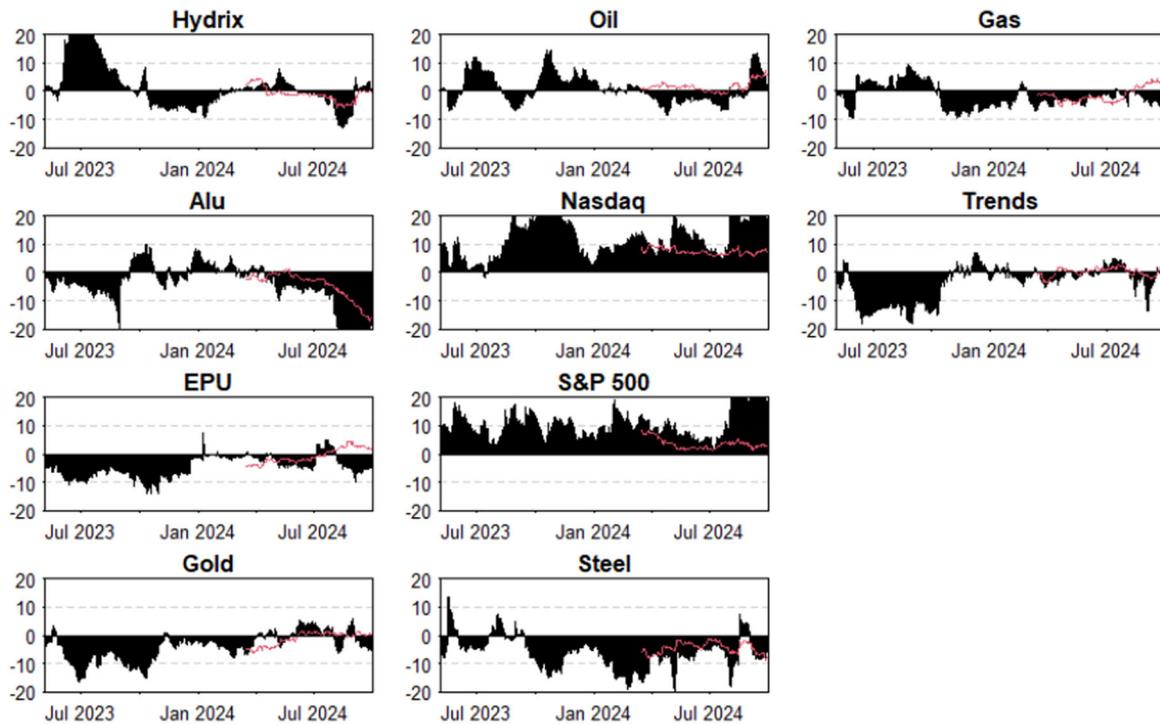


FIGURE A3 | Dynamic net total and net pairwise directional connectedness (EEX Hydrix). *Note:* See Figure A1. Alu, aluminium; EPU, economic policy uncertainty; Nasdaq, National Association of Securities Dealers Automated Quotations.

TABLE A1 | Overview of the variables used in the macroeconomic analysis.

Variable	Definition	Source
<i>cumulative_Capacity_MWel</i>	Aggregated and summed up the production capacity of the individual listed production projects by year and country. Measured in MWel	International Energy Agency (IEA)
<i>cumulative_Capacity_Nm</i>	Aggregated and summed up the production capacity of the individual listed production projects by year and country. Measured in Nm ³ H ₂ /h	IEA
<i>cumulative_Capacity_kt</i>	Aggregated and summed up the production capacity of the individual listed production projects by year and country. Measured in kt H ₂ /year	IEA
<i>FI</i>	Financial Institutions—ranging from 0 to 1, recalculated to a range from 0 to 100	International Monetary Fund (IMF)
<i>FM</i>	Financial Markets—ranging from 0 to 1, recalculated to a range from 0 to 100	IMF
<i>R&D</i>	Research and development spending as a share of GDP. Spending includes current and capital expenditures (public and private) on research	Our World in Data—World Bank
<i>GDP per capita</i>	GDP per capita (current US\$)	World Bank database
<i>Inflation</i>	Inflation, consumer prices (annual %)	World Bank database
<i>Unemployment</i>	Unemployment, total (% of total labour force)	World Bank database
<i>RQI</i>	Worldwide Governance Indicators—Regulatory Quality Index subindicator, ranging from 0 to 100	Worldwide Governance Indicators
<i>FSI</i>	Fragile states index—ranging from 0 to 120	Fragile States Index Database
<i>EPI</i>	Environmental Performance Index (own calculation based on four subindicators) Environmental Performance Index: CO exposure, Environmental Performance Index: NO _x exposure, Environmental Performance Index: SO ₂ exposure, Environmental Performance Index: VOC exposure	Environmental Performance Index—Yale University
<i>Mean temperature</i>	Annual mean temperature measured across the countries	Kaggle—scraped from World Bank Climate Knowledge https://climateknowledgeportal.worldbank.org/
<i>credit_ps</i>	Domestic credit to private sector (% of GDP)	World Bank database
<i>stock_cap</i>	Stock market capitalization to GDP (%)	World Bank database

Abbreviations: GDP, gross domestic product; VOC, volatile organic compound.

TABLE A2 | Overview of the variables used for the financial market analysis.

Variable	Definition	Source
<i>Global X</i>	Global X Hydrogen ETF—HYDR.O	Refintiv
<i>Solactive</i>	Solactive Global Hydrogen Index—SOLGHYD	Refintiv
<i>EEX Hydrix</i>	EEX Hydrix index—interpolated to daily data using cubic spline interpolation	https://www.eex-transparency.com/de/wasserstoff
<i>Alu</i>	SHFE Aluminium Commodity Future Continuation 3—SAFc3, converted to EUR	Refintiv
<i>Steel</i>	SHFE Hot Rolled Coil Future Continuation 1—SHHCc1, converted to EUR	Refintiv
<i>Gold</i>	COMEX Gold Electronic Commodity Future Continuation 1—GCc1	Refintiv
<i>Oil</i>	ICE Europe Brent Crude Electronic Energy Future—LCOc1	Refintiv
<i>Gas</i>	Intercontinental Exchange UK NBP Natural Gas Electronic Monthly Energy Future—NGLNMc1	Refintiv
<i>Nasdaq</i>	Nasdaq 100 Index—NDX	Refintiv
<i>S&P 500</i>	S&P 500 EUR—GSPCE	Refintiv

(Continues)

TABLE A2 | (Continued)

Variable	Definition	Source
<i>EPU</i>	US Daily News Index	www.policyuncertainty.com
<i>Trends</i>	Google Trends index for the topic “Hydrogen”, worldwide. For the robustness check, we use the search word “Hydrogen energy”, worldwide. Daily values are calculated by using daily observations for 1 month * monthly observations for the whole period. This allows one to capture long-term patterns on a daily basis. Index ranges from 0 to 10,000	Google Trends

Abbreviations: EPU, economic policy uncertainty; ETF, Exchange Traded Fund.

TABLE A3 | Multicountry panel estimation for hydrogen production for the EU subsample.

	<i>cumulative_Capacity_Mwel</i>			<i>cumulative_Capacity_Nm</i>			<i>cumulative_Capacity_Kt</i>		
<i>EPI</i>	-0.064 (0.107)	-0.033 (0.112)	-0.144 (0.112)	-0.230 (0.188)	-0.197 (0.201)	-0.318* (0.185)	-0.173 (0.109)	-0.145 (0.105)	-0.252** (0.121)
<i>RQI</i>	-0.019 (0.024)	-0.008 (0.022)	0.005 (0.026)	0.020 (0.056)	0.049 (0.045)	0.049 (0.054)	0.003 (0.031)	0.012 (0.029)	0.023 (0.033)
<i>FSI</i>	-0.095*** (0.034)	-0.068** (0.031)	-0.074*** (0.026)	-0.063** (0.118)	-0.055 (0.106)	-0.021 (0.125)	-0.095 (0.069)	-0.068 (0.077)	-0.071 (0.073)
<i>R&D</i>	-2.060*** (0.470)	1.774 (2.086)		-2.038 (0.824)	-2.424 (3.517)		-1.960*** (0.412)	1.907 (1.828)	
<i>R&D Median</i>			-107.530* (58.219)			-339.246*** (107.320)			28.370 (62.821)
<i>log(GDP per capita)</i>	-1.243 (1.347)	-2.553* (1.380)	-0.778 (1.481)	-3.946 (2.653)	-5.887* (3.116)	-3.332 (2.935)	-4.285** (1.971)	-5.455*** (1.827)	-3.937 (2.393)
<i>Inflation</i>	-0.145 (0.117)	-0.141 (0.107)	-0.168* (0.097)	-0.105 (0.272)	-0.037 (0.242)	-0.202 (0.236)	0.077 (0.133)	0.076 (0.117)	0.055 (0.112)
<i>Unemployment</i>	0.092 (0.057)	0.068 (0.050)	0.119** (0.057)	0.247*** (0.074)	0.226*** (0.074)	0.276*** (0.082)	0.061* (0.035)	0.038 (0.034)	0.084* (0.046)
<i>Mean temperature</i>	0.302 (0.249)	0.361 (0.241)	0.036 (0.307)	-0.029 (0.686)	0.152 (0.693)	-0.536 (0.671)	-0.039 (0.331)	0.007 (0.326)	-0.192 (0.413)
<i>FI</i>	-0.019 (0.031)	0.022 (0.034)	-4.850* (2.649)	0.079 (0.068)	-0.043 (0.090)	-15.189*** (4.872)	0.064* (0.035)	0.114** (0.056)	1.421 (2.848)
<i>FM</i>	0.067*** (0.014)	0.135*** (0.035)	3.500* (1.837)	0.118*** (0.027)	0.261*** (0.067)	10.860*** (3.396)	0.063*** (0.006)	0.120*** (0.029)	-0.827 (1.988)
<i>FI * R&D</i>		-0.037 (0.025)	4.861* (2.638)		0.053 (0.045)	15.304*** (4.867)		-0.040* (0.023)	-1.325 (2.846)
<i>FM * R&D</i>		-0.037* (0.021)	-3.415* (1.845)		-0.076** (0.036)	-10.729*** (3.408)		-0.031* (0.016)	0.908 (1.990)
<i>Observations</i>	225	225	225	225	225	225	225	225	225
<i>N</i>	15	15	15	15	15	15	15	15	15
<i>T</i>	15	15	15	15	15	15	15	15	15
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>R</i> ²	0.27	0.31	0.20	0.23	0.25	0.23	0.26	0.29	0.20
<i>F</i> statistic	7.20***	6.95***	3.88***	5.60***	5.26***	4.66***	6.68***	6.28***	3.97***

Note: All estimates are conducted using the *plm* package in R. Driscoll-Kraay standard errors are reported in parentheses. Abbreviations: EPI, Expanded Program on Immunization; EPU, economic policy uncertainty; ETF, Exchange Traded Fund; FE, fixed effect; FI, Financial Institutions; FM, Financial Markets; FSI, Fragile States Index; GDP, gross domestic product; R&D, research and development; RQI, Regulatory Quality Index. *, ** and *** denote significance at the 10%, 5% and 1% levels, respectively.

TABLE A4 | Multicountry panel estimation for hydrogen production with alternative financial development measures.

	<i>cumulative_Capacity_Mwel</i>			<i>cumulative_Capacity_Nm</i>			<i>cumulative_Capacity_Kt</i>		
<i>EPI</i>	0.082** (0.032)	0.060*** (0.017)	0.087** (0.033)	0.164*** (0.030)	0.132*** (0.029)	0.155*** (0.028)	0.095*** (0.023)	0.073*** (0.014)	0.088*** (0.022)
<i>RQI</i>	0.000 (0.018)	-0.008 (0.017)	-0.000 (0.020)	-0.065*** (0.025)	-0.078*** (0.025)	-0.061** (0.026)	-0.055*** (0.012)	-0.064*** (0.012)	-0.055*** (0.012)
<i>FSI</i>	-0.006 (0.013)	-0.030*** (0.010)	-0.005 (0.013)	-0.014 (0.020)	-0.056** (0.024)	-0.020 (0.021)	-0.012 (0.025)	-0.042* (0.022)	-0.011 (0.023)
<i>R&D</i>	0.355 (0.226)	-6.696** (2.896)		0.095 (0.472)	-11.873*** (3.829)		-0.370* (0.213)	-8.635*** (1.756)	
<i>R&D Median</i>			0.589 (2.039)			-4.160 (4.612)			-2.202*** (0.784)
<i>log(GDP per capita)</i>	0.451 (0.435)	0.005 (0.312)	0.328 (0.407)	0.909 (0.795)	0.232 (0.771)	0.722 (0.803)	0.346 (0.477)	-0.117 (0.444)	0.429 (0.473)
<i>Inflation</i>	0.063** (0.028)	0.027 (0.026)	0.063** (0.025)	-0.011 (0.065)	-0.060 (0.069)	-0.012 (0.065)	0.019 (0.029)	-0.014 (0.026)	0.011 (0.030)
<i>Unemployment</i>	0.096*** (0.027)	0.069** (0.034)	0.090*** (0.029)	0.146*** (0.051)	0.104** (0.051)	0.132** (0.050)	0.008 (0.030)	-0.021 (0.029)	0.010 (0.030)
<i>Mean temperature</i>	0.107 (0.090)	0.183*** (0.065)	0.118 (0.080)	0.268* (0.152)	0.379*** (0.140)	0.263* (0.154)	0.050 (0.142)	0.126 (0.130)	0.039 (0.148)
<i>log(credit_ps)</i>	-0.836*** (0.301)	-2.405*** (0.715)	-0.725*** (0.265)	1.117* (0.665)	-1.753 (1.348)	0.049 (1.165)	-0.404 (0.337)	-2.400*** (0.375)	-0.560** (0.244)
<i>log(stock_cap)</i>	0.345* (0.177)	-0.627** (0.311)	0.344 (0.257)	0.788*** (0.267)	-0.453 (0.731)	0.942 (0.622)	0.648*** (0.168)	-0.180 (0.197)	0.421*** (0.158)
<i>log(credit_ps) * R&D</i>		1.083* (0.557)	-0.091 (0.315)		2.082** (0.878)	1.355 (0.995)		1.454*** (0.349)	0.135 (0.146)
<i>log(stock_cap) * R&D</i>		0.539*** (0.189)	0.010 (0.305)		0.623 (0.406)	-0.336 (0.716)		0.411*** (0.118)	0.295** (0.137)
<i>Observations</i>	330	330	330	330	330	330	330	330	330
<i>N</i>	27	27	27	27	27	27	27	27	27
<i>T</i>	3-15	3-15	3-15	3-15	3-15	3-15	3-15	3-15	3-15
<i>Country FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>R²</i>	0.16	0.24	0.16	0.12	0.17	0.14	0.11	0.18	0.12
<i>F statistic</i>	5.61***	7.45***	4.49***	4.13***	4.82***	3.77***	3.77***	5.12***	3.12***

Note: All estimates are conducted using the *plm* package in R. Driscoll-Kraay standard errors are reported in parentheses.

Abbreviations: EPI, Expanded Program on Immunization; FE, fixed effect; FSI, Fragile States Index; GDP, gross domestic product; R&D, research and development; RQI, Regulatory Quality Index.

*, ** and *** denote significance at the 10%, 5% and 1% levels, respectively.

TABLE A5 | Spillover connectedness (Solactive).

	<i>Solactive</i>	<i>Alu</i>	<i>EPU</i>	<i>Gold</i>	<i>Oil</i>	<i>Nasdaq</i>	<i>S&P 500</i>	<i>Steel</i>	<i>Gas</i>	<i>Trends</i>	<i>FROM</i>
<i>Solactive</i>	64.65	1.21	3.10	3.89	2.73	13.41	6.72	1.57	0.75	1.97	35.35
<i>Alu</i>	0.82	46.17	1.99	1.06	1.85	1.77	1.35	8.62	0.76	35.61	53.83
<i>EPU</i>	2.18	2.39	82.88	1.77	1.99	1.24	1.12	2.12	2.18	2.13	17.12
<i>Gold</i>	4.32	2.68	4.45	69.74	3.42	3.77	3.65	2.42	2.30	3.24	30.26
<i>Oil</i>	3.17	2.87	2.68	3.47	74.59	2.54	3.31	2.08	2.47	2.81	25.41
<i>Nasdaq</i>	10.16	1.92	3.63	2.57	1.73	46.06	30.80	1.50	0.62	1.00	53.94
<i>S&P 500</i>	5.46	1.85	3.15	2.65	2.26	32.31	48.27	1.73	0.84	1.48	51.72
<i>Steel</i>	1.57	12.48	2.21	2.17	1.87	2.00	2.31	66.73	1.44	7.41	33.27
<i>Gas</i>	0.93	1.40	2.73	2.55	2.81	0.93	1.27	1.98	84.16	1.24	15.84
<i>Trends</i>	1.38	37.58	1.47	1.24	1.87	0.83	0.99	5.05	0.68	48.92	51.08
<i>TO</i>	29.98	64.39	25.40	21.36	20.53	58.80	51.35	27.08	12.03	56.89	367.81
<i>Inc.Own</i>	94.63	110.5	108.29	91.11	95.12	104.87	99.63	93.80	96.19	105.81	cTCI/TCI
<i>NET</i>	-5.37	10.56	8.29	-8.89	-4.88	4.87	-0.37	-6.20	-3.81	5.81	40.87/36.78
<i>NPT</i>	3.00	9.00	7.00	2.00	1.00	6.00	5.00	4.00	0.00	8.00	

Note: These are the TVP-VAR estimations with the alternative Trends measure. FROM represents the source of causal impacts received from each variable, TO stands for the destination of effects and positive (negative) values of NET reveal that the variable is a net transmitter (receiver) of spillover impacts. The numbers are on a 0 to 100 scale, showing percentages. They reflect how much of the variance in one variable is due to itself (diagonal) or others (off-diagonal). The Net Pairwise Transmission (NPT) in this table provides an ordinal ranking of each variable's net spillover position. Finally, cTCI and TCI denote the corrected Total Connectedness Index based on Chatziantoniou and Gabauer (2021) and the Total Connectedness Index, respectively. The same applies to Tables A6 and A7. Abbreviations: Alu, aluminium; EPU, economic policy uncertainty; Nasdaq, National Association of Securities Dealers Automated Quotations; TVP, Time-Varying Parameter; VAR, Vector AutoRegressive.

TABLE A6 | Spillover connectedness (Global X).

	<i>Global X</i>	<i>Alu</i>	<i>EPU</i>	<i>Gold</i>	<i>Oil</i>	<i>Nasdaq</i>	<i>S&P 500</i>	<i>Steel</i>	<i>Gas</i>	<i>Trends</i>	<i>FROM</i>
<i>Global X</i>	62.13	1.19	2.37	4.38	2.44	15.28	8.18	1.37	0.81	1.86	37.87
<i>Alu</i>	0.82	45.72	1.03	0.92	1.88	1.53	1.28	9.96	0.77	36.10	54.28
<i>EPU</i>	1.96	1.93	83.80	1.69	2.00	0.93	1.24	2.15	2.27	2.04	16.20
<i>Gold</i>	5.19	1.98	4.79	70.74	3.97	3.18	3.59	1.75	2.10	2.71	29.26
<i>Oil</i>	2.90	2.87	2.54	3.97	73.43	2.64	3.82	2.61	2.38	2.85	26.57
<i>Nasdaq</i>	11.96	1.70	0.77	2.17	1.79	46.80	31.79	1.50	0.56	0.97	53.20
<i>S&P 500</i>	6.73	1.70	1.12	2.56	2.62	32.92	48.39	1.75	0.84	1.38	51.61
<i>Steel</i>	1.40	13.92	2.23	1.48	2.27	1.99	2.18	66.23	1.44	6.88	33.77
<i>Gas</i>	1.09	1.47	2.73	2.32	2.77	0.95	1.34	1.98	84.11	1.24	15.89
<i>Trends</i>	1.33	38.12	1.21	1.32	1.94	0.76	0.96	5.17	0.67	48.53	51.47
<i>TO</i>	33.36	64.89	18.77	20.80	21.69	60.17	54.36	28.24	11.82	56.03	370.13
<i>Inc.Own</i>	95.49	110.6	102.57	91.54	95.12	106.96	102.76	94.46	95.93	104.56	cTCI/TCI
<i>NET</i>	-4.51	10.61	2.57	-8.46	-4.88	6.96	2.76	-5.54	-4.07	4.56	41.13/37.01
<i>NPT</i>	4.00	9.00	5.00	1.00	2.00	7.00	6.00	3.00	0.00	8.00	

Note: See Table A5.

Abbreviations: Alu, aluminium; cTCI, corrected Total Connectedness Index; EPU, economic policy uncertainty; Nasdaq, National Association of Securities Dealers Automated Quotations; NET, net transmitter; NPT, Net Pairwise Transmission; TCI, Total Connectedness Index.

TABLE A7 | Spillover connectedness (EEX Hydrix).

	<i>Hydrix</i>	<i>Alu</i>	<i>EPU</i>	<i>Gold</i>	<i>Oil</i>	<i>Nasdaq</i>	<i>S&P 500</i>	<i>Steel</i>	<i>Gas</i>	<i>Trends</i>	<i>FROM</i>
<i>Hydrix</i>	80.33	2.02	2.16	1.75	3.66	1.92	1.54	1.03	3.02	2.57	19.67
<i>Alu</i>	1.28	47.52	1.30	0.61	1.03	1.71	1.00	9.39	0.59	35.57	52.48
<i>EPU</i>	1.52	1.53	86.87	0.81	2.84	0.81	0.84	1.01	1.57	2.19	13.13
<i>Gold</i>	1.78	1.47	2.96	79.78	2.00	3.22	2.74	1.48	1.97	2.60	20.22
<i>Oil</i>	3.64	1.93	3.23	1.81	80.09	2.50	2.48	1.48	1.57	1.27	19.91
<i>Nasdaq</i>	1.32	2.01	2.83	2.19	1.79	52.57	33.57	1.61	0.76	1.35	47.43
<i>S&P 500</i>	1.08	1.30	3.41	1.86	1.71	33.67	52.66	1.88	1.17	1.25	47.34
<i>Steel</i>	0.96	13.42	2.51	1.38	1.33	2.16	2.32	69.40	1.10	5.41	30.60
<i>Gas</i>	3.33	1.01	2.39	2.00	1.68	1.06	1.73	1.27	84.65	0.89	15.35
<i>Trends</i>	1.68	37.90	1.19	1.30	0.61	1.11	0.91	3.92	0.50	50.88	49.12
<i>TO</i>	16.61	62.60	21.98	13.71	16.65	48.16	47.11	23.08	12.26	53.09	315.26
<i>Inc.Own</i>	96.94	110.1	108.85	93.49	96.74	100.73	99.77	92.47	96.91	103.97	cTCI/TCI
<i>NET</i>	-3.06	10.12	8.85	-6.51	-3.26	0.73	-0.23	-7.53	-3.09	3.97	35.03/31.53
<i>NPT</i>	2.00	9.00	7.00	1.00	3.00	6.00	5.00	4.00	0.00	8.00	

Note: See Table A5.

Abbreviations: Alu, aluminium; cTCI, corrected Total Connectedness Index; EPU, economic policy uncertainty; Nasdaq, National Association of Securities Dealers Automated Quotations; NET, net transmitter; NPT, Net Pairwise Transmission; TCI, Total Connectedness Index.