Price determinants in the carbon neutral hydrogen market

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Abstract

Green hydrogen is instrumental to the achievement of net zero objectives worldwide. Its development as an energy vector and a new commodity requires that production and consumption is guaranteed at large scale which requires the introduction of the appropriate market price signals. This paper uses the hydrogen price assessments provided by Standards and Poor´s Global and time series representing benchmark gas and power prices for the European and US markets to examine the determinants of green hydrogen transaction prices. Following Russia's invasion of Ukraine, the world has experienced a global energy crisis that caused gas and electricity prices to soar. Adopting the the generalized sup augmented Dickey-Fuller test proposed by Phillips Shi and Yu (2015) we show that there is a tight connection between gas, electricity and carbon neutral hydrogen prices in Europe that may arise due to power market policy design. Using daily price series for the December 2021-May 2023 period We document the existence of bubble behaviour in

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the European hydrogen, electricity and gas benchmark in April 2022 in the aftermath of the start of the war in Ukraine. Additional bubble behaviour is documented in August 2022 when gas and electricity prices reached maximum levels. We model as a byproduct the volatility of the spread between European hydrogen and power prices and show that long term volatility is lowest for the hydrogen benchmark suggesting that hydrogen will be a major factor towards the transition to a climate neutral economy.

Keywords: Low carbon hydrogen, green transition, global energy crisis, hydrogen electricity spread
JEL: G18, D47, L94

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1. Introduction

The development of low carbon hydrogen within the next decade will play a determinant role in achieving the net-zero goals. Hydrogen is used in industrial production processes worldwide, namely for oil refining and ammonia production. The most common form of hydrogen production requires the use of fossil fuels, such as natural gas and coal. This form is labeled as grey hydrogen. Production is largely through Steam Methane Reforming (SMR) or gasification. These production pathways developed through Steam Methane emit carbon into the atmosphere. The production of green hydrogen relies on renewable energy, such as solar or wind power to decompose water into hydrogen and oxygen. Green hydrogen is becoming instrumental as a decarbonization energy vector from energy market practitioners, investors, policymakers who bet on the the potential of hydrogen as key for energy generation and long term energy storage. Low carbon hydrogen acts as a green future fuel of long distance heavy transportation as well as a low-carbon substitute for natural gas in hard to abate industrial processes, as well as for residential heating.

The proposal of low carbon hydrogen as energy vector of the future at a global level can be seen in the number of countries that have adopted a hydrogen strategy. According to a recent report by Bloomberg New Energy Finance (BNEF) there are currently 42 countries with a Hydrogen Roadmap, 36 countries with a strategy in preparation and 63 countries with no activity.[1] The new interest in low carbon hydrogen is also manifested in the number of new projects that have been announced to date. According to the Financial Times [2] some 1000 projects have recently been announced at global level requiring an investment of $ 320bn. The same article highlights that there is only $ 29 bn of committed capital. An additional problem is that while there has been a clear development from the supply side there is no evidence that there is commintment from potential users in the demand side. The European Hydrogen Strategy (COM/2020/31) claims that achieving the EU ´S energy transition will require large scale hydrogen production and consumption. As underlined in the annual report of the chair for low Carbon hydrogen studies (ICAI-ICADE, Universidad Pontificia Comillas)[3].

The green transition must align with the European Green Deal, The New Industrial Strategy in Europe and the Recovery Plan. Note that this targets have recently been updated by the Fit for 55 Package and the RePowerEU designed to accelerate the transition as means of achieving energy security. In response to the net zero requirements and the recent energy crisis, the United States has delivered its green objectives under the Inflation Reduction Act4, which provides $370bn in energy security and climate change investments. The legislation has become a key catalyst for advancing green hydrogen production and domestic green manufacturing, indicating that competition for the low carbon transformation is advancing.

The achievement of economies of scale in the hydrogen market will allow hydrogen production at low cost levels. This will only be possible under the creation of a hydrogen market with the appropriate fundamental price signals. However, the current market for hydrogen is opaque with limited price discovery. In order to contribute to market transparency, Platts hydrogen assessments provide the market different ways to value the cost of hydrogen production to evaluate as a new energy vector. In this paper we use the

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[1] See Bloomberg NEF report "Hydrogen Strategies on the rise, Hydrogen strategies as of February the 9th 2023"

[2] See "Lex in depth: the staggering cost of a green hydrogen economy, Financial Times, May the 28th

[3] Report available at (`https://www.comillas.edu/catedra-de-estudios-sobre-el-hidrogeno`

benchmark hydrogen price assessments for Europe and the US and analyze their time series evolution during the recent energy crisis which triggered gas supply shortages in a context of energy transition. Low carbon hydrogen prices are compared with benchmark electricity and gas prices in Europe and the US. The Phillips Shi and Yu (2015) methodology is used for this purpose. This allows modelling time series with regime shifts from the unit root process to the explosive or bubble state. The sample frequency and sample choice is conditioned by the availability of hydrogen price data and ranges from December 2021 to May 2020. We find that there is bubble in the European low carbon hydrogen price series around the time that the European benchmarks reached maximum levels in August 2022. Mild explosivity is also seen in the same period the European gas benchmark. European electricity prices exhibited bubble behaviour in the immediate aftermath of the Russian invasion of Ukraine. We therefore show that European low carbon hydrogen and European gas and power prices are closely related. Indeed both can be classified as fundamentals. This is an important finding that has not been documented in the prior literature. As a byproduct we provide a time changing volatility analysis which suggests that long term volatility is lower for the EU low carbon hydrogen market than for the power and gas counterparts. This is the first paper in the literature that uses hydrogen price assessments for the study of the hydrogen market in a time series perspective. We show that the time series evolution of low carbon hydrogen prices has been subject to important regime changes that are also reflected in the electricity and gas fundamentals clearly affected by the consequences of the war in Ukraine. As a second contribution this paper models the volatility of the European low carbon hydrogen and power prices and shows that long term volatility is lowest for the green hydrogen benchmark.

The existence of a close linkage between European low carbon hydrogen prices and European gas prices is related to EU electricity market design. The wholesale market in the EU is a system of marginal pricing where once the full demand is satisfied, everybody obtains the price of the last producer from which electricity was bought. Natural gas combined cycle power plants (NGCC) are often considered the marginal electricity production technology and their operating costs are typically used to set electricity prices in the market. Our results show that the system of marginal pricing gives rise to the close link between hydrogen prices and gas prices. The zero marginal cost of producing power with renewables is not reflected in current low carbon

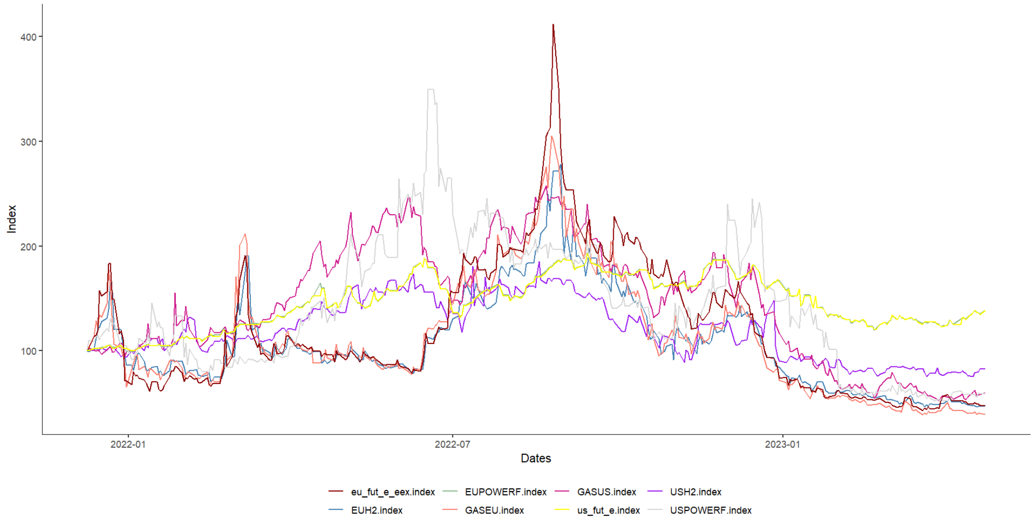

Figure 1: Historical performance of different commodities

hydrogen prices.

Natural gas markets have subject to abnormal conditions since August 2021 due to market tightening. Russia's invasion of Ukraine and its decision to suspend gas deliveries to several EU member states created significant disruptions that further intensified the race for local supply of energy.[4] As a result, gas, power (and low carbon hydrogen) prices increased tenfold over the period from August 2021 to August 2022. The link between the price of gas power and hydrogen markets for the EU and US can be seen in Fig 1 which illustrates the evolution of of daily prices for the EU gas power and low carbon hydrogen benchmark prices.

The remainder of this paper is organized as follows. The next section discusses the literature review. Section 3 introduces the method of study. Section 4 describes our data collection process . Section 5 outlines the research design of the paper and presents our empirical results. Section 6 concludes

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[4] Russia used to provide 40% of the gas supply to Europe at the start of the energy crisis. Since Russia has cut its gas exports to the EU by around 90% since the invasion, many European countries are having to redesign their energy strategy accelerating the adoption of green alternatives such as low carbon hydrogen.

the paper and highlights opportunities for future research in the area.

2. Literature Review

This paper is related to the literature that uses the algorithm developed by Phillips *et al.* (2015a), PSY algorithm from now on, to analyze the time series characteristics of energy prices. Important contributions in this area include the work of Figuerola-Ferretti *et al.* (2020) which analyzes determinants of crude oil prices in the aftermath of the 2007-2008 Global Financial Crisis and during the 2014 crude oil price collapse. Sharma and Escobari (2018) apply the same method for analyzing the relationship between crude oil prices and and gas prices. We contribute to this literature by providing the first analysis of the time series evolution of low carbon hydrogen prices in Europe and the US. Our paper provides results that are important for regulators. Specifically we add to the literature that has focused on policy design adapting power energy price signals to make them compatible with the energy transition (see e.g. Fitiwi *et al.* (2016), Joskow (2019) and Batlle *et al.* (2022)). This literature should consider implications for price formation of low carbon hydrogen prices. A related line of literature has analysed the impact of renewables on electricity prices (see Fabra and Reguant (2014) and Peña *et al.* (2020)). This paper studies the consequences of the recent energy crisis on the linkages between low carbon hydrogen, gas and power prices a context of net zero commitments. The paper also sheds light to the literature that addressed the effects of geopolitical risk in energy markets. Goldthau and Boersma (2014) underlined the increase of global exposure to geopolitical risk in a rapidly growing reliance on renewable sources. We contribute to this line of work by showing that the current policy design should consider the recent exposure of low carbon hydrogen gas and power markets to the 2021-2022 energy crisis. Reported results should thus be a reminder of the fragility of the current global energy system. Our work is also related to the output documented in the Energy International Agency EIA´s 2022 World Economic Outlook. The WEO's analysis finds evidence to support claims from that climate policies and net zero commitments contributed to the run-up in energy price. [5] This paper is related to the literature that analyzes the role of green hydrogen as a new energy vector. Azadnia *et al.* (2023) pursue green hydrogen supply chain risk identification concluding that high investment on capital expenditure for hydrogen production and delivery technology was the highest-ranked risk factor followed by the lack of enough electrolyser capacity, and policy and regulation development (see also Egerer *et al.* (2023). A related literature has compared different scenarios for a variety of electric fuels (Runge *et al.* (2019). This paper is also related to the literature on electricity pricing which has addressed the relationship between spot and futures electricity prices (Carmona et al., 2012; Cartea and Villaplana, 2008, Algieri, Leccadito and Tunaru, 2021) as well as the modelling of time changing volatility (see Escribano and Sucarrat 2017 and references there in). In an analysis of tail risk underlying futures contracts for the European and US markets Peña *et al.* (2020) conclude that the associated capital ratios to be required to investments in long positions on power futures contracts should be computed using GARCH-type methods.

Here we focus on analyzing the time series evolution of low carbon hydrogen prices by addressing first and second order processes of gas power and hydrogen in a context of energy crisis and energy transition.

3. Methodology

We apply the detection procedure proposed by Phillips *et al.* (2015a, 2015b) that enables the identification of multiple mildly explosive periods.

The technique fits the following recursive regression:

$$x_t = \mu_x + \delta x_{t-1} \sum_{j=1}^{J} \phi_j \Delta x_{t-j} + \epsilon_{x,t}, \quad \epsilon_{x,t} \sim NID(0, \sigma_x^2) \tag{1}$$

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[5] Full report available at `https://www.iea.org/news/world-energy-outlook-2022-shows-the-global-energy-crisis-can-be-a-historic-turning-point-towards-a-cleaner-and-more-secure-future`

First, we use a subset of $\tau_0 = nr_0$ observations, where $r_0 = 0.01 + 1.8/\sqrt{T}$. This subset is supplemented by successive observations in each regression, giving a sample of size $\tau = nr$ with $r_0 \leq r \leq 1$. This procedure yields a sequence of augmented Dickey-Fuller (ADF) t-statistics. To avoid size distorsions, we follow Vasilopoulos *et al.* (2022) with respect to the selection of j and set the number of lags to 0.

A test for the null hypothesis of no explosive behavior is based on the generalized supremum ADF (GSADF) statistic, constructed through repeated implementation for each $r_2 \in [r_0, 1]$.

Once this hypothesis has been rejected, the starting and ending points of a first mildly explosive period, $\hat{r}_{1,e}$ and $\hat{r}_{1,f}$, can be date-stamped via the backward supremum ADF (BASDF) statistic:

$$\begin{aligned} \hat{r}_{1,e} &= inf_{r_2 \in [r_0,1]} \left\{ r_2 : BSADF_{r_2}(r_0) > scv_{r_2}^{\beta_T} \right\} \\ \hat{r}_{1,f} &= inf_{r_2 \in (\hat{r}_e + ln(T)/T, 1)} \{ r_2 : BSADF_{r_2}(r_0) > scv_{r_2}^{\beta_T} \} \end{aligned} \tag{2}$$

where $scv_{r_2}^{\beta_T}$ is the right-sided critical value. A (mildly) explosive period is declared if the BSADF statistic is above its critical value for a minimum duration of $ln(T)$ observations (6 days in our case). For the calculation of the critical values we use both Montecarlo and Wild-bootstrap methodologies. The second one is usually more stringent and, as Phillips *et al.* (2015a) suggest it should be used to reduce size distortion when volatility is nonstationary and to control the size of the tests when there are near IGARCH effects in conditional volatility.

The final step in the approach involves characterizing explosive behavior as speculative (bubble) or not, depending on the evolution of its fundamentals. For example, Phillips *et al.* (2015a) reported explosivity in the NASDAQ price index not exhibited by the dividend yield, providing evidence for speculative behavior. In contrast, Figuerola-Ferretti *et al.* (2015) found mildly explosive prices in non-ferrous metals to be tied to the behavior of the stock-to-use ratio, allowing them to conclude that fluctuating demand around inelastic supply, and not speculation, was driving price volatility.

In this case we will also use the methodology developed by Pavlidis *et al.* (2016) to determine potential co-movement of our variables. Consider the panel version of equation (1):

$$x_{i_t} = \mu_{x_i} + \delta x_{i_{t-1}} \sum_{j=1}^{J} \phi_{i,j} \Delta x_{i_{t-j}} + \epsilon_{x_{i_t}}, \quad \epsilon_{x_{i_t}} \sim NID(0, \sigma^2_{x_i}) \tag{3}$$

where i = 1,..., N denotes the panel index and the remaining variables are defined as before. The panel GSADF test examines the null hypothesis of a unit root in all series against the alternative of a potential bubble in a subset of series. This requires the introduction of a measure of overall explosiveness by averaging the individual BSADF statistics at each time period.

$$panel\ BSADF_{r_2}(r_0) = \frac{1}{N} \sum_{i=1}^{N} BSADF_{i,r_2}(r_0) \tag{4}$$

Then the panel GSADF statistic is defined as the supremum of the panel BSADF.

$$panel\ GSADF(r_0) = \sup_{r_2 \in [r_0,1]} panel\ BSADF_{r_2}(r_0) \tag{5}$$

To calculate the critical values, we use a a sieve bootstrap method to allow for cross-sectional error dependence (Further details are provided in the appendix of Pavlidis *et al.* (2016)).

4. Data

This section describes our sample data and presents summary statistics as a preliminary analysis.

4.1. Hydrogen Price Assessments

This paper uses several data sources. The hydrogen price series is downloaded from Standards and Poors Platts. Platts Carbon Neutral Hydrogen (CNH) assessments reflect valuations of minimum lot sizes of 20,000 kg for prompt delivery the calendar month that follows the trading date. Daily assessments are available since 2018 for most series and are published in Euros or US Dollars per kilogram and per million British Thermal Units for hydrogen, with 99.99% purity.

Platts CNH assessments include market valuations of hydrogen in which emissions have been: a) avoided where possible through the use of low emissions generation, b)removed through the use of carbon capture and storage, c) and offset through the use of carbon credits or equivalent instruments. We concentrate on the CNH assessments of type a. The following 6 locations of CNH assements are are available: (1) Ex Works California reflecting hydrogen delivered at any production facility in California, (2) Ex Works US Gulf Coast reflecting hydrogen delivered at any production facility in Texas or Louisiana, (3) Ex Works Northwest Europe reflecting hydrogen delivered at any production facility in the Netherlands, (4) Ex Works Middle East reflecting hydrogen delivered at any production facility in Saudi Arabia, (5) Ex Works Far East Asia reflecting hydrogen delivered at any production facility in Japan and (6) Ex Works Australia reflecting hydrogen delivered at any production facility in West Australia. We concentrate on European and US benchmarks with longest data availability (starting in December 2021) which are the Exwork US golf Coast reference and the Northwest Europe Reference.

4.2. Gas and Power price series

The Dutch TTF natural gas front month futures price is used as a benchmark in the EU market while the Henry Hub one is the benchmark for the US. We obtain daily time series for the Henry Hub Natural Gas Futures traded on the CME exchange and the Dutch TTF Gas Futures traded on the ICE exchange for the period ranging from January 2018 to May 2023.

Regarding electricity prices, we use forward and futures prices for different contract specifications and maturities for the US and EU markets. As a reference for EU long term power delivery contracts, we use a daily series of German power futures (EEX Phelix DE/AT Baseload Quarterly Energy Future Continuation) obtained from Reuters for the period ranging May 2003 to May 2023. EEX is the most liquid power futures market in Europe. We use power swap and power forward data as US long term delivery benchmarks. The Bloomberg fair value price for PJM Western Hub power swap for 1 to 4 month maturities is connsidered. Data for these contracts are available on a daily basis from January 2012 to April 2023. The rest of daily data on electricity forward contracts are downloaded from Bloomberg for the period ranging from January 2018 to May 2023.

4.3. Summary statistics

In this section, we analyze the time series evolution of benchmark low carbon hydrogen prices as well as the corresponding gas and electricity price counterparts. European and American low carbon hydrogen price benchmarks are denoted as EUH2 and USH2 respectively. The European and American gas benchmarks are denoted as GASEU and GASUS, European and American electricity forward prices are EUPOWERF and USPOWERF respectively. European and American power futures prices are labelled as EUFUT and USFUT. We have considered the period ranging from December 2021 to April 2023, which adds up to 354 days. We depict the time series evolution of all prices considered in Figure 1. A close look at the picture shows that there are abrupt price increases and collapses around August 2022.

We report summary statistics for the different series in Table 1. All prices for EU variables are higher than their US counterparts (except for forward electricity prices). The variable with the highest standard deviation is EUFUT, showing power prices in Europe were highly volatile during our sample period. The same table reports that there are two price series with a negative skew (EUPOWERF and USFUT) and four leptokurtic series (EUH2, GASEU, USPOWERF and EUFUT).

Table 1: Descriptive statistics for commodities

	Mean	Median	Max	Min	Std. Dev.	Skew	Kurt
EUH2	77,12	69,08	179,96	38,28	27,71	1,12	4,05
USH2	19,04	18,66	27,72	12,50	3,72	0,21	1,86
GASUS	6,13	6,20	9,76	2,39	1,80	0,04	1,97
GASEU	126,57	110,39	310,50	54,40	52,16	1,07	3,70
EUPOWERF	65,51	67,33	84,95	43,60	11,50	-0,42	2,04
USPOWERF	96,50	88,34	216,29	38,61	33,86	0,73	3,35
EUFUT	292.1	241.9	997.7	103.1	154.54	1.09	4.28
USFUT	64.13	64.00	85.00	44.00	11.04	-0.10	1.93

5. Empirical Analysis

First, we perform a PSY test on the different series. This allows us to detect any potential bubble during the period. We used the `exuber` package in R developed by Vasilopoulos *et al.* (2022). When applying critical values generated under the assumption of unit root (MC cv here after) with 5,000 simulations, we reject the H0 of no bubble behaviour for most of the series, except for USH2. In EUH2, GASUS, EUPOWERF and EUFUT, we reject at 1% significance level. For GASEU, we reject at 5%, while for USPOWERF and USFUT we reject the null at 10% significance level. Whe also perform the analysis using Wild Botstrapped critical values (WB cv here after) under 5,000 bootstrap samples. These critical values are robust to the existence of heteroskedastic errors implying that the test becomes more stringent than under the benchmark MC cv. Under this more restrictive version of the test we only reject the null hypothesis in GASUS (10% significance level) and EUFUT (5% significance level). In summary, we can conclude that there is significant evidence of explosiveness during the sample period considered.

The PSY methodology also allows us to date-stamp bubbles when the BSADF statistic surpasses the critical values. A summary of our results, using MC cv and a 5% significance level, can be found in Table 2. They show that there was mild explosivity in the time series considered during March (first bubble) and August (second bubble) of 2022. The table also presents the number of bubbles found, the average duration and the maximum duration.

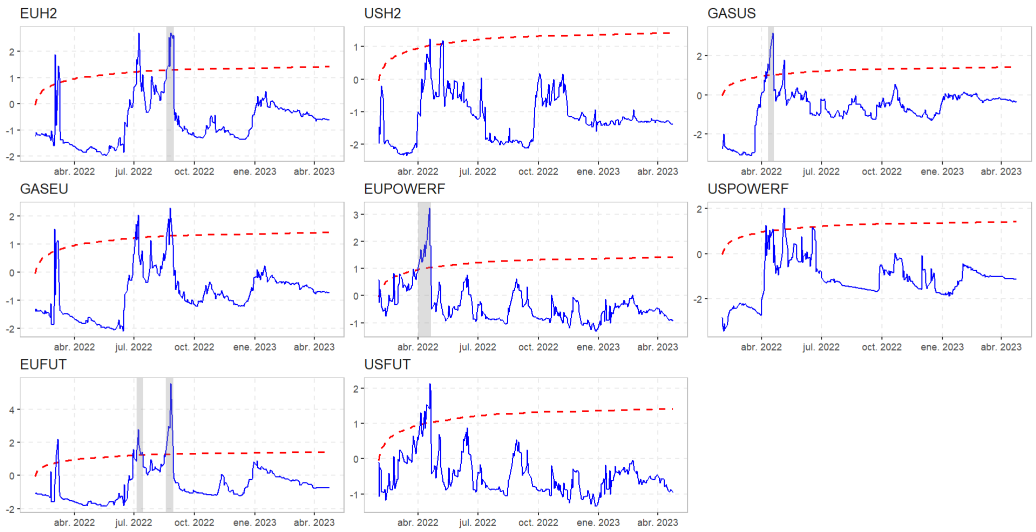


Figure 2: Datestamping on the basis of the BSADF statistic for all series considered under the MC critical values

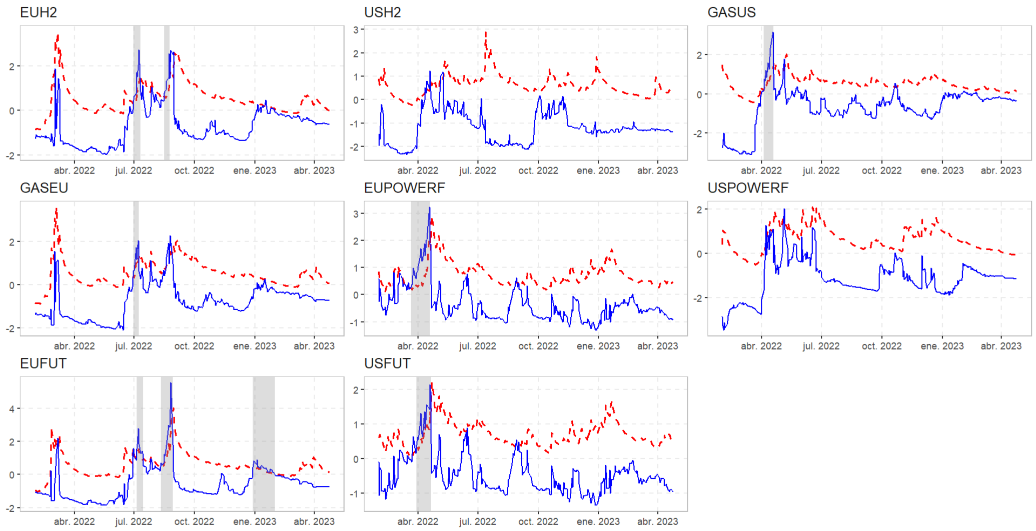


Figure 3: Datestamping for commodities' series with WB critical values

We refer to bubbles or mild explosivity when we find that the statistic surpasses the critical value. Phillips *et al.* (2015a) require that the number of periods is higher than the log of T and therefore 6 consecutive days. We report within parenthesis, the number of bubbles with duration higher than

6 days. A graphical representation of the different bubbles can be seen in Figure 2, under the MC cv, and in Figure 3 for WB cv.

Results reported in Table 2 suggest that the series considered exhibit common periods of bubble behaviour. We formally test for this presumption by performing a panel test following the methods proposed by Pavlidis *et al.* (2016) underlined under equation (3). Results reported in Table 3 are consistent with the figures reported in Table 2 and show that there is a common bubble satisfying the minimum bubble condition in August 2022. Shorter episodes are date stamped in April and July 2022.

Table 2: Multiple bubble test results for price series

	EUH2		GASUS		GASEU		EUPOWERF		EU FUT	
	Bubble period	Duration (days)	Bubble period	Duration (days)	Bubble period	Duration (days)	Bubble period	Duration (days)	Bubble period	Duration (days)
	03/22	1	04/22	1	03/22	1	01/22	1	03/22	3
	03/22	3	04/22	6	03/22	2	02/22	1	06/22	2
	07/22	4	05/22	2	07/22	1	02/22	1	07/22	8
	08/22	8			07/22	2	03/22	1	08/22	8
					08/22	1	03/22	1		
					08/22	3	04/22	13		
Number of bubbles		4 (1)		3 (1)		6 (0)		6 (1)		4 (2)
Average duration		4,00		3,00		1,67		3,00		5,25
Max. Duration		8,00		6,00		3,00		13,00		8,00

Table 3: Multiple bubble test results for panel of commodities

	Panel	
	Bubble period	Duration (days)
	04/2022 - 04/2022	4
	07/2022 - 07/2022	4
	08/2022 - 08/2022	6
Number of bubbles		3 (1)
Average duration		4,67
Max. Duration		6,00

5.1. Volatility in the gas, power and low carbon hydrogen markets markets.

We have seen in the last section that reported results change significantly when accounting for the existence of heteroskedastic errors. This reflects the existence of non constant volatility in the analyzed time-series. Time changing characteristics observed in the the second order process of the time series considered arise under tight fundamentals linked to geopolitical and regulatory conditions in a context of energy transition.

In what follows we analyse the long term non constant volatility processes using an AR-GARCH approach that introduces residuals that are t-distributed (which are often observed in financial time-series). The following specification is applied for this purpose:

$$\begin{aligned} R_{t+1} &= \Phi_0 + \Phi_1 \, R_t + u_{t+1} \\ u_{t+1} &= \sqrt{h_{t+1}} \, \epsilon_{t+1} \quad \epsilon_{t+1} \sim t_\nu \\ h_{t+1} &= \kappa + \alpha \, u_t^2 + \beta \, h_t \end{aligned}$$

Where R_t is the return of the given time-series. The long term volatility is the value at which the volatility reverts in a distant horizon, defined as the $\frac{\kappa}{1-(\alpha+\beta)} \cdot \sqrt{\frac{\nu}{\nu-2}}$. Table 4 reports parameters estimates for the US gas, the EU gas, the EU electricity future and the EU hydrogen price.

Table 4: Parameter estimation of the AR-GARCH model for the US gas, the EU electricity future, the EU hydrogen price and the EU electricity future and the EU gas.

	GAS US	EU FUT	EUH2	GAS EU
Φ_0	0.141	-0.384	-0.106	-0.348
Φ_1	-0.063	0.110	0.092	0.023
κ	2.789	3.104	4.076	12.26
α	0.067	0.077	0.125	0.232
β	0.773	0.731	0.677	0.583
ν	6.761	3.648	5.143	340.1

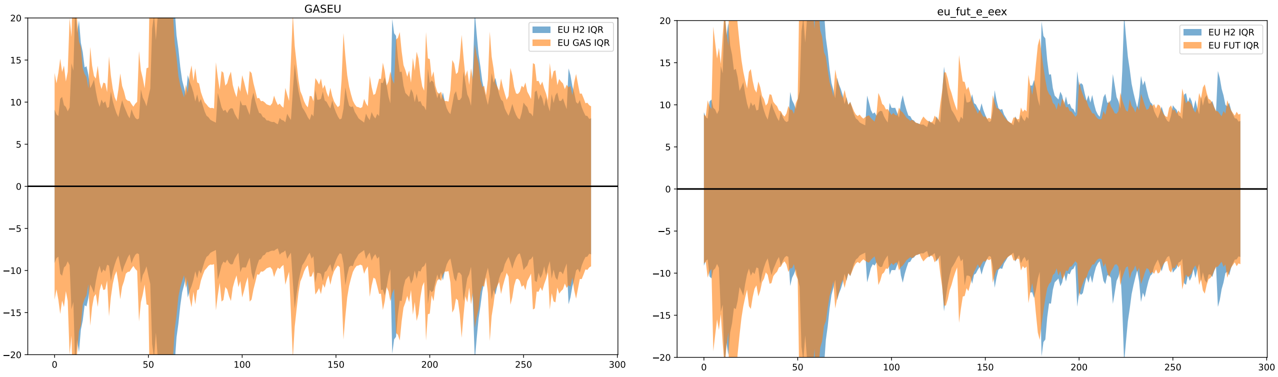
The analysis in the previous section suggests that the documented bubble behaviour may be closely linked to periods of increased volatility. Table 5 shows that there is a positive relationship between the number of documented and the level of long term volatility.

Table 5: Comparison long term volatility and bubbles.

	Long term vol	Num Bubbles
GAS US	20.96	3
EU FUT	24.24	4
EUH2	26.49	4
GAS EU	66.91	6

A close look at Table 5 also shows that while there are similar long term volatility levels the European power and the European green hydrogen is similar the figure reported for the European gas is substantially higher. Figure 4 illustrates a historical volatility comparison (using the AR-GARCH estimates) between H2 and Gas and between H2 and European power futures.

Figure 4 (Left) confirms that the gas market is more volatile than the H2 market. Figure 4 (Right) does not show any significant difference in volatility between European H2 and European power futures. This suggest that the high volatility seen in the European gas market over the last few years has not been fully transmitted into power and low carbon hydrogen prices.



(a)

Figure 4: Heterokedasticity in the hydrogen, gas and electricity prices.

The previous analysis shows that Low carbon hydrogen prices (H2) and power prices in Europe are closely linked over the period analyzed.

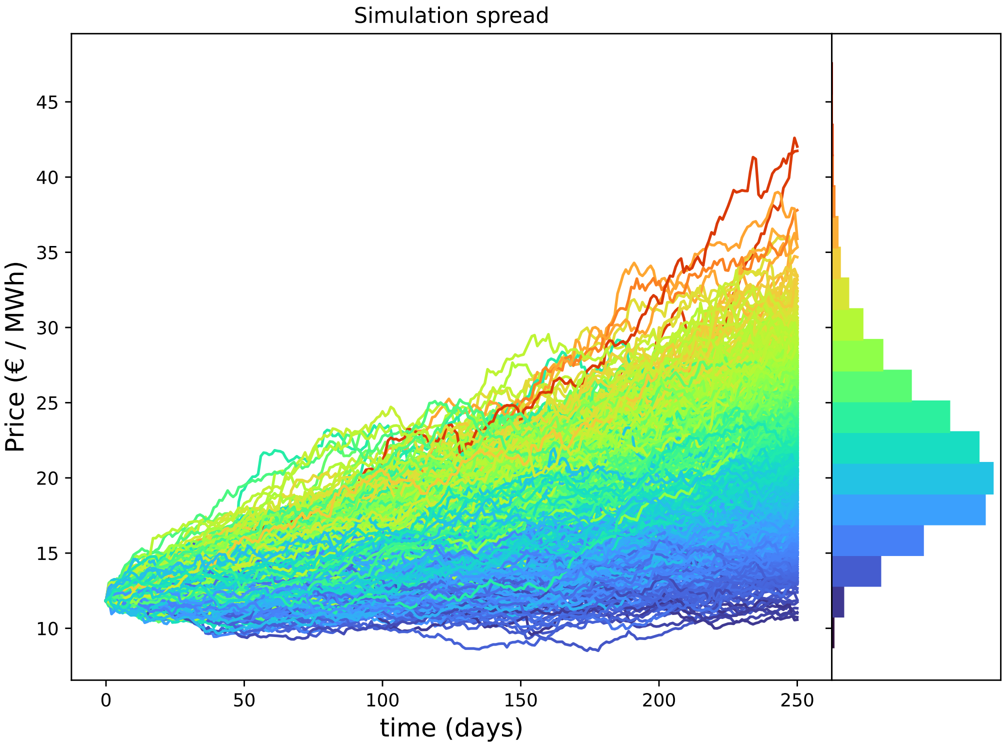


Figure 5: fancy simulation

In what follows we formally analyze their relationship by considering the spread between H2 prices and European electricity futures. The AR-GARCH model is fit on the spread process for this purpose. This framework is used in a second stage to produce forward simulations of the spread (in terms of € / MWh). Figure 5 shows the simulation over 1-year forward and the resulting distribution over the last period. It's clear that the spread is statistically different from 0. While the H2 is produced from electricity and their volatility is similar the differences between the two series is important suggesting lower volatility for the H2 process. Note that while this could potentially indicate that the adoption of H2 could reduce the volatility in the energy sector, it may also reflect that price assessments or transaction prices are not as volatile as market traded derivatives prices.

6. Conclusion

The adoption of green hydrogen is a key strategy to decarbonising the global economy in response to climate change. The emergence of the energy crisis with focus in Europe has accelerated the need for introduction of green hydrogen as an alternative energy vector and new traded commodity.

Natural gas markets worldwide have been tightening since August 2021. Russia's invasion of Ukraine and its decision to suspend gas deliveries to EU member states created important disruptions that further intensified the the need to foster local supply of energy. Russia used to provide 40% of the gas supply to Europe at the start of the energy crisis. Given that Russia has cut its gas exports to the EU by around 90% since the invasion, many European countries are having to redesign their energy strategy accelerating the adoption of green alternatives such as low carbon hydrogen. As a result, gas, power and carbon neutral hydrogen prices have experienced bubble behaviour. In this paper we use the benchmark hydrogen price assessments for Europe and the US and analyze their time series evolution during the recent energy crisis triggered gas supply shortages in a context of energy transition. Hydrogen prices are compared with benchmark electricity and gas prices in Europe and the US. The Phillips *et al.* (2015a, 2015b) methodology is used for this purpose. This allows modelling time series with regime shifts from the unit root process to the explosive or bubble state. We find that there is bubble in the European low carbon hydrogen price series around the time that the European and (also gas) benchmarks reached maximum levels in August 2022. Mild explosivity is also seen in the same period the European gas benchmark. European electricity prices exhibited bubble behaviour in the immediate aftermath of the Russian invasion of Ukraine. We therefore show that European low carbon hydrogen and European gas and power prices are closely related. Indeed both can be classified as fundamental variables of the hydrogen benchmark. As a second contribution this paper provides a long term volatility analysis based on GARCH estimates and shows that bubble behaviour is associated with high volatility regimes. Moreover long term volatility is lower for the EU low carbon hydrogen market than for the gas and power counterparts. We find to possible explanations for this findings. On one side this might imply that low carbon hydrogen is less exposed to geopolitical tensions than power and gas. Low carbon hydrogen price signals can be the basis for a low carbon hydrogen price index and for the creation of low carbon hydrogen long term contracts on the buyer side. We contend that alternatively the results might reflect the fact that low carbon price assessments are transaction prices and not derivative prices. While transaction prices are less transparent than exchange traded prices they may be seen as less volatile Figuerola-Ferretti and Gilbert (2005).

A series simulations on the hydrogen-power spread suggest that spread divergences will increase in the long term basis implying that the underlying fundamentals for future scenarios will be significantly different suggesting future changes in energy inter linkages supply costs, and energy security.

In summary, it is crucial for policy makers academics and market practitioners to understand behaviour of green hydrogen as a new energy vector under the need to accelerate the energy transition under increased geopolitical tensions driven by war in Ukraine. Government regulations during the energy crisis will therefore have crucial financial implications for the adoption of new green technologies.

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