Energy Market Bubbles under the Green Transition

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Abstract

Russia's weaponization of gas supplies has heightened concerns over the energy trilemma—security, affordability, and sustainability—emphasizing the need to reduce dependence on volatile fossil fuel markets. This paper investigates speculative price dynamics in energy markets during the recent energy crisis, focusing on gas, electricity, low-carbon hydrogen, and renewable Power Purchase Agreements (PPAs). We apply the Phillips, Shi, and Yu (2015) mild explosivity (PSY) test to daily and weekly benchmark price series to detect and date-stamp bubble episodes. Our analysis identifies two significant periods of widespread exuberance: one beginning in mid-2021 and another peaking in August 2022, coinciding with the Nord Stream I pipeline shutdown. These results provide empirical evidence of boom-and-bust cycles driven by both geopolitical supply shocks and market speculation. The findings stress the structural fragility of fossil-based energy systems and reinforce the urgency of accelerating the transition toward more stable, low-carbon energy alternatives.

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Keywords: bubble, gas futures, power futures, PPA, Low carbon hydrogen, green transition, global energy crisis, speculation
JEL: G18, D47, L94

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1. Introduction

The recent energy crisis has sent boom-and-bust cycles through global energy prices showing the vulnerability of the European energy system largely dependent on cheap energy sources from Russia. While benchmark European gas prices increased by a tenfold over the April 2021-August 2022, volatility rocketed by 500% over the same time period. Similar patterns were documented for European electricity prices. Gas is an important component of the energy mix in many countries worldwide as it is an essential part of a diversified energy mix (Portela *et al.* 2023). The contribution of gas-fired power plants into the electricity generation mix creates interdependence between gas and electricity prices. Gas prices affect the cost of electricity generation making them vulnerable to common shocks that have to be adequately managed. Chuliá *et al.*(2024) analyze shock transmission intensities between gas prices and local electricity prices. They differentiate between various energy mixes and regulations and find important disparities at cross-country level during the recent energy crisis.

These developments in energy markets have enhanced the needs for acceleration of the energy transition and the adoption of green alternatives, such as renewable electricity or low carbon hydrogen. Segarra *et al.* (2024) examine the impact of the recent energy crisis on the corporate performance of European and US utilities. It finds that the spike in gas prices led to an eight-fold increase in collateral requirement for EU power utilities holding one-year power futures contracts. A structural break in the volatility of European gas and electricity prices is identified in August 2021, after which the profitability of EU utilities is assessed against a counterfactual portfolio. The authors conclude that the crisis, along with the growing shift toward renewable energy, calls for a rethinking of traditional fossil fuel–linked pricing mechanisms to ensure that market signals align with long-term energy transition goals.

Fabra (2023) addresses the surge in gas and electricity prices due to the Ukrainian war underlying the consequences for rising inflation. The proposed framework introduces a market design that advocates an increased reliance on contract for differences (CFDs) tailored to the characteristics of generation technologies. This framework sheds light to concerns about whether current electricity market design is adequate for achieving the energy transition at low cost for the society. In doing this, Fabra (2023) proposes significant investments in new low carbon generation capacity to decarbonize the power sector. A greener and competitive power generation mix will increase energy security and lower inflationary pressures. The consequences of energy prices shocks on inflation in the US has been recently addressed by Kilian and Zhou (2023). The authors develop a vector autoregressive (VAR) model to quantify the joint effects of shocks to multiple energy prices on both headline and core CPI inflation. Their findings show that focusing solely on gasoline price shocks understates the inflationary pressures arising from the energy sector.

Natural gas markets have been subject to abnormal conditions since the second quarter of 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.[1] As a result, gas and power prices skyrocketed over the period from August 2021 to August 2022 delivering exuberant behaviour both in EU and the US.

Cincinelli and Pellini (2025) examine the presence of price bubbles in a panel of European day-ahead electricity markets. Their findings indicate that bubble dynamics are largely driven by geopolitical risks and weather-related factors. This is a plausible outcome given that clean energy now contributes over 60% of Europe's power mix.[2] Opoku *et al.* (2025) examine the impact of geopolitical risk and financial development on the energy trilemma.

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

[2] See Reuters article, "Europe on track to smash solar power output record in 2025", *Reuters*, 23 April 2025.

The analysis reveals a positive relationship between geopolitical risks and both energy security and energy equity, suggesting that heightened geopolitical tensions may prompt greater efforts to secure and distribute energy resources.

Building on this, the present paper provides a comprehensive analysis of gas, electricity, and alternative green energy sources—specifically carbon-neutral hydrogen and renewable Power Purchase Agreements (PPAs)—during the recent energy crisis. Following the methodology of Cincinelli and Pellini (2025), we apply the bubble detection approach of Phillips et al. (2015a) to identify boom-and-bust cycles and reassess the underlying drivers of the crisis using a reduced-form empirical framework.

Reduced-form approaches can offer valuable and complementary insights, particularly when there are concerns about the specification or properties of a given structural model—or of other potential structural frameworks. Such evidence is especially useful, for instance, when evaluating the possible role of speculation in the 2021-2022 energy crisis. We make several contributions to the literature on energy market dynamics and the application of bubble detection methodologies.

- We identify key regime shifts during the recent energy crisis by applying the PSY bubble test methodology and the panel bubble approach introduced by Pavlidis *et al.* (2016) to a broad set of fossil fuel and green energy price series. Our results indicate that bubble behavior in energy markets emerged prior to the war in Ukraine, with a more pronounced impact observed in Europe than in the US. Using daily data, we show that gas supply shocks triggered synchronized bubble episodes in European gas, electricity, and carbon-neutral hydrogen price benchmarks. These findings are further supported by evidence from a longer sample of renewable Power Purchase Agreement (PPA) prices, revealing bubble activity from fall 2021 through 2022. Our analysis, thus, demonstrates a two-stage development of the crisis, which is consistent with the work of Cincinelli and Pellini(2025).
- We show that the PSY and panel PSY tests are effective tools for identifying and date-stamping periods of individual and common regime

shifts in energy markets. This contributes to the literature that has applied these methods to detect bubbles in energy prices, including studies such as Figuerola-Ferretti *et al.* (2020), who analyzed crude oil price determinants post-2008, and Sharma and Escobari (2018), who examined the crude oil–gas price relationship.

- We extend the application of the PSY methodology to gas, electricity, and green hydrogen benchmarks in both the US and Europe, along with European renewable PPA price trends. This allows us to detect common regime shifts and evaluate whether price signals from green alternatives are aligned with energy transition objectives. Our findings complement the work of Cincinelli and Pellini (2025) by adding new evidence on bubble behavior in benchmark electricity markets and expanding the scope to include green alternatives in the bubble commonality exploration. Our results therefore also shed light 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)).

- We contribute to the literature on energy market dynamics by offering new evidence on speculative behaviour. While Segarra *et al.* (2024) investigate structural breaks in energy price volatility, we extend this line of inquiry by applying both univariate and panel bubble tests to fossil fuel and green energy markets. Notably, our paper is the first to demonstrate that speculative behavior played a partial role in generating price bubbles in gas and electricity markets during the energy crisis, thereby contributing to the debate on speculation versus fundamentals.

This paper is organized as follows. Section 2 discusses the roles of hydrogen and PPAs as a new green energy sources. Section 3 describes the methods used in this paper including the PSY and the panel generalisation of Pavlidis *et al.* (2016) as well as the bubble fundamental test proposed by Pavlidis *et al.*(2017b) . Section 4 provides a preliminary analysis of the data. Section 5 reports results from estimating the PSY methodology and its extensions at daily level. Additionally, we also provide results for PPA data and for the differences between future spot and futures prices. Finally, we conclude in Section 6.

2. The roles of low carbon hydrogen and green PPAs as green energy sources

The 2020s are witnessing a rapid shift toward renewable electricity and battery electric vehicles. However, progress remains limited in hard to abate sectors where electrification is insufficient to reduce emissions—particularly industry, shipping, and aviation Johnson *et al.* (2025). [3]

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 for energy market participants, investors and policymakers who bet on the potential of hydrogen as key for energy generation and long term energy storage. Its potential has spurred growing academic attention and significant financial investment in positioning hydrogen as a fuel of the future. The development of low carbon hydrogen within the next decade will therefore play a determinant role in achieving the net-zero goals.

The global positioning of low-carbon hydrogen as a key future energy vector is reflected in the growing number of national hydrogen strategies. According to a 2024 report by Bloomberg New Energy Finance (BNEF), 53 countries have adopted a hydrogen roadmap, 30 are in the process of developing one, while 58 countries have yet to engage.[4] This growing interest is further evidenced by the volume of announced projects. As of October 31, 2024, the BNEF Hydrogen Observability Platform lists 269 purchase agreements, accounting for an estimated 13 million tonnes of annual green hydrogen and derivative demand.[5] However, only 6% of this capacity currently has an identified offtaker, underscoring the primary challenge for the low-carbon hydrogen market: stimulating demand to match anticipated supply.

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[3] The challenges and opportunities faced by green energy resources has been examined by Nabera *et al.* (2023). They demonstrate the technical feasibility and potential climate benefits of green production routes for industrial processes and chemicals.

[4] See Bloomberg NEF report, "Hydrogen Strategies on the Rise: Hydrogen Strategies as of February 9th, 2024".

[5] Data sourced from Bloomberg NEF's Hydrogen Observatory. Projects included have a minimum size of 20 megawatts or 2,800 metric tonnes of annual production capacity.

The development of green alternatives to fossil fuels thus depends not only on technological readiness but also on ensuring economic viability and reliability. Data from 2024 indicate that cost estimates for initial hydrogen projects have been revised upward, while existing subsidy mechanisms have fallen short of delivering the expected market performance.[6]

This gap between projected supply and limited demand is consistent with broader market dynamics. Current figures suggest that hydrogen and eFuels are, by 2025, emerging from the 'Trough of Disillusionment' phase, following a period of inflated expectations between 2020 and 2023, during which many countries announced ambitious hydrogen strategies. Notably, the European Commission's RePowerEU plan targeted 10 million tonnes of green hydrogen production and an additional 10 million tonnes of imports by 2030—equivalent to approximately 667 TWh—triggering a surge in project announcements. However, in the absence of binding regulatory frameworks, a significant number of these initiatives have since been canceled or postponed.

As emphasized by the energy trilemma, the transition to green energy must balance sustainability with both economic viability and operational reliability. Green hydrogen, a promising alternative, faces significant affordability challenges, largely due to persistent uncertainty on the demand side. The successful development and deployment of low-carbon hydrogen over the next decade will be critical to meeting net-zero emissions targets.

The achievement of economies of scale in the hydrogen market will allow hydrogen production at low cost levels. This requires 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 evaluate the cost of hydrogen production.

Current low-carbon hydrogen price benchmarks are primarily based on the Levelized Cost of Hydrogen (LCOH), which is in turn largely driven by the Levelized Cost of Electricity (LCOE). Green hydrogen producers typically

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[6] See "Lex in Depth: How the Hydrogen Hype Fizzled Out", *Financial Times*, May 20, 2024.

rely on electricity sourced from a dedicated solar or wind facility, or a hybrid configuration of both technologies. Alternatively, electricity may be procured through a renewable Power Purchase Agreement (PPA), or via a combination of dedicated generation and contracted PPA supply.

As a result, the price of renewable PPAs expressed in \$/MWh or €/MWh plays a critical role in determining the economic feasibility and market competitiveness of green hydrogen production.

The growth of PPAs has been significant in Europe and North America over the past decades. This growth has mainly been driven by lower renewable energy costs and policy pressure for decarbonization and energy transition. The role of PPAs as enhancers of energy market reforms, specially the unbundling of vertically integrated utilities, has been addressed by Acharya (2022). This market has enabled new value creation models, especially through PPAs in renewable energy. These agreements are currently a key financing tool for Independent Power Producers (IPPs). PPAs offer Long-term revenue certainty, improving project bankability without government subsidies.

The baseload PPA price often serves as a benchmark for assessing different PPA price exposures. A baseload agreement is a volume-based contract in which the buyer agrees to purchase a fixed quantity of electricity—typically on an hourly basis throughout the year. In this structure, the seller bears both the profile and volume risk, as they are obligated to deliver the agreed amount of energy regardless of actual production. If generation falls short, the seller must cover the deficit, usually by purchasing electricity on the spot market.

One common PPA risk metric is the capture factor, which represents the ratio between the price actually captured by the asset and the baseload price over a defined period. For solar projects, capture factors are typically close to 1.0 in winter and slightly lower in summer, when output is highest. For wind projects, capture factors are generally lower in winter, aligning with peak wind production. These factors help gauge how the average volume-weighted price compares to the baseload benchmark, indicating whether the asset is likely to earn above or below market average pricing.

Increased renewable penetration could derive in potential cannibalization risk for the energy pool as a whole as these new technologies could drive down market prices, thus resulting in declining revenues. This occurs when large volumes of solar PV generate electricity simultaneously, causing market prices during those hours to fall. As low-cost solar displaces more expensive generation technologies that would otherwise set higher prices, the revenue potential for solar assets is reduced. Solar and Wind projects could benefit from incorporating batteries in the design of the plants, enabling these projects to optimize their non-merchant related revenues by storing energy in hours of high supply and selling energy in hours of low supply.

Hydrogen storage (like long duration batteries) can potentially reduce cannibalization risk by absorbing excess renewable electricity during periods of low market prices—typically caused by high solar or wind output—and converting it into hydrogen for later use or sale. This enables renewable energy projects to shift production from oversupplied to undersupplied hours, helping to stabilize revenues. Moreover, hydrogen provides long-duration, dispatchable storage that enhances grid flexibility and resilience. This capability is particularly important in light of recent blackout events in Spain, highlighting the need for reliable backup solutions during periods of low renewable generation or unexpected grid stress. By supporting both market efficiency and system reliability, hydrogen storage plays a dual role in advancing the energy transition.

3. Methodology

We apply the detection procedure proposed by Phillips *et al.* (2015b, 2015c) that enables the identification of multiple mildly explosive periods which can be associated with bubbles.

The technique fits the following recursive regression:

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

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. In order to avoid size distortions, 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. This is equal to 6 days in a sample of two years of daily data, 7 days in the sample of 1260 observations of PPA data, 7 weeks in our sample of 424 weeks. Critical values are generated using both Monte Carlo and Wild-bootstrap (WB) methodologies (Harvey *et al.* 2016) . The latter approach is usually more stringent and, as suggested by Phillips *et al.* (2015b) it should be used to reduce size distortion when volatility is non-stationary and to control the size of the tests when there are near IGARCH effects in conditional volatility.

We analyze the extent to which there is commonality in the date stamped periods of mild explosivity by applying the panel bubble test developed by Pavlidis *et al.* (2016). This allows to determine potential co-movement of the proposed variables. We consider for this purpose the panel version of equation (1):

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

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 common period of mild explosivity 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. The panel BSADF statistic is thus defined as:

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

The GSADF statistic is derived as the supremum of the panel BSADF.

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

In order 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)).

The final step in the approach involves determining the extent to which the documented explosive behavior is speculative and therefore not justified in terms of fundamentals. If this is the case, explosiveness can be associated to speculative bubble behaviour. For example, Phillips *et al.* (2015b) reported explosivity in the NASDAQ price index not exhibited by the dividend yield, providing evidence for speculative bubble 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 explosiveness. We test for the existence of speculative bubble behaviour following the methods introduced by Pavlidis *et al.* (2017a). This requires the use of spot and futures' prices. Thus, the test cannot be applied to carbon neutral hydrogen prices and renewable PPAs as we do not have prices for different maturities. The bubble speculation test test will therefore concentrate on weekly European gas and electricity prices. Specifically, we apply the PSY test on the differences between the spot price at time $t + n$

and the future price with maturity $t+n$ for weekly gas and power prices.

$$s_{t+n} - f_{t,n} = (1+r)^n(\frac{1}{\pi^n} - 1)B_t + \epsilon^*_{t+n} \tag{6}$$

where (1+r) is the expected growth rate of the bubble, π the probability that the bubble grows and ϵ^*_{t+n} are two moving average processes [7]. Equation 6 defines $s_{t+n} - f_{t,n}$ as a linear function of a given bubble process specified as (B_t) and the sum of two moving average processes, implying that it is explosive. We can then apply the PSY test to this metric with the advantage that the test will not require the identification of fundamentals. A rejection of the null hypothesis of no bubble behaviour provides conclusive evidence of the existence of speculative bubbles. [8]

4. Data

This paper uses several data sources. This section describes our sample data and presents summary statistics as a preliminary analysis.

4.1. Gas and Power weekly price series

The Intercontinental Exchange (ICE) Dutch TTF natural gas futures' prices series are used as a gas benchmark in the EU market. Prices are measured in euros per megawatt hour (MWh). The Chicago Mercantile Exchange's Henry Hub prices are considered for the US. Prices are quoted in US dollars per MMBtu. All price series are downloaded from Bloomberg and transformed into US dollars for comparison purposes.[9]

This sample uses different contract maturities in order to perform the speculation driven bubble test based introduced by Pavlidis *et al.*2017b. One

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[7] See Pavlidis *et al.* (2017a) for further details on the method applied

[8] Note that the test requires the assumption of risk neutrality

[9] the conversion rates provided by Bloomberg are used for this purpose

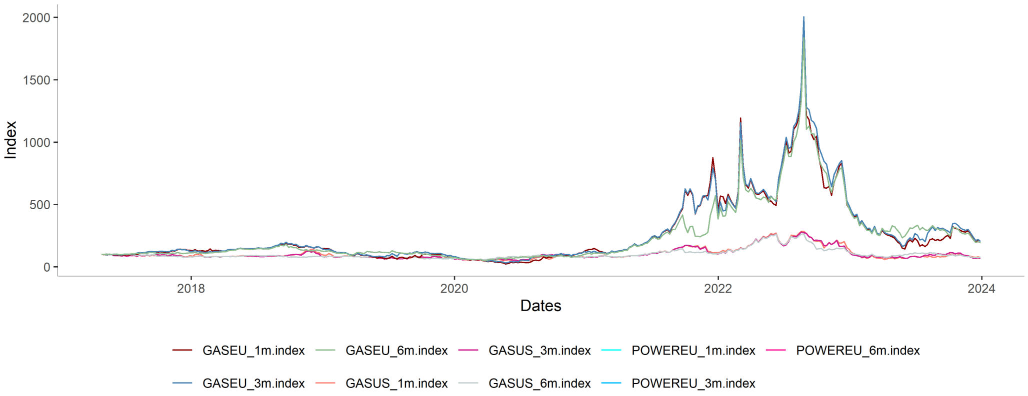

Figure 1: Time series evolution of gas and power weekly price benchmarks 2016-2023

month, three month and six month futures for EU and US are downloaded for this purpose. We therefore denote GASEU1m, GASEU3m, GASEU6m, GASUS1m, GASUS3m, GASUS6M as the one month and three month EU and US gas benchmarks respectively. One month prices are used as a proxy for spot prices.

Regarding electricity prices we restrict our analysis to the EU markets.[10] specifically, we use series of the German power futures (EEX Phelix DE/AT Baseload Quarterly Energy Future Continuation and EEX Phelix DE/AT Baseload Quarterly Energy Future Continuation) obtained from Bloomberg. We use front month and 3 and 6 month Futures . These will be denoted as POWEREU1m and POWEREU3m and POWEREU6m respectively. Prices are in euros per MWh and, again, transformed into US dollars for comparison purposes.

Fig 1 depicts the time series evolution of weekly European and US gas prices for the for the January 2016 - December 2023 period under the three maturities Considered. The series are indexed so that they take a value of 100 at the sample start date so that measures in different units can be comparable.

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[10] We failed to find a long and continuous series of electricity prices for the US

Indexed series are thus labeled with "index" as an extension.[11]. A close look at this figure shows that the European power and gas price series are closely linked and that front, three and six month gas price quotations increase by more than a tenfold during the recent energy crisis. Similar patterns are seen for the US power prices, however these are less pronounced. While the greatest spike is seen at the end of August 2022, we can observe three previous periods of boom and bust cycles. We shall see in the coming sections that the energy crisis starts in June 2021 and that the August run-up in prices coincides with the definite stop of gas flows from the North Stream 1 pipeline.

4.2. Daily sample of gas, power benchmarks and Hydrogen Price Assessments

This sample covers the second stage of the energy crisis. We analyze daily energy price data for the period ranging from January the 10th 2022 up to the December the 29th 2023 to be directly comparable with the Carbon neutral hydrogen benchmark. Front, three and six month European and US gas benchmarks are considered as well as the same references for European power prices.

The hydrogen price series is downloaded from Standard and Poors Platts. Platts Carbon Neutral Hydrogen 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 published in Euros or US Dollars per kilogram and per million British Thermal Units (MMBtu) for hydrogen, with 99.99% purity.

S&P Platts carbon neutral price assessments include market valuations or estimations of the leveled cost of hydrogen in the absence of market transactions. In the production of low carbon hydrogen, 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

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[11] Full names for the graph are: GASEU1mIndex, GASEU3mIndex, GASEUm6ndex,GASUS1mIndex, GASUS3mIndex,GASUS6MIndex, POWEREU1mIndex, POWEREU3mIndex

hydrogen price assessments which essentially refer to Hydrogen produced using renewable resources. While these are available for six locations worldwide we focus on the US and European benchmarks for which there is a longer data availability i) the European benchmark defined as the Ex Works Northwest Europe reflecting hydrogen delivered at any production facility in the Netherlands and ii) US Gulf Coast benchmark labeled as Ex Works US Gulf Coast measuring hydrogen delivered at any production facility in Texas or Louisiana. Price units are Euros per MMBtu for the European benchmark (denoted as HEU) and in dollars per MMBtu for the US benchmark (denoted as HUS). Daily data are available for the series from January the 10th 2022 up to the December the 29th 2023. All prices are transformed into USD for comparison purposes. [12]

Note that the development of price signals in the hydrogen market has been extensive over the past years. Important benchmarks include the green hydrogen index of the Austrian Market (CEGH), the green hydrogen benchmark of the German EEX power market (HYDRYX) or the Iberian Mibgas Index, the S&P Global green hydrogen PPAs. [13] However, the benchmarks are the S&P Global carbon neutral hydrogen series have the longest available history.

Fig 2 illustrates the time series evolution of daily prices for the EU and US gas price benchmarks with 1, 3, and 6 month maturities respectively as well as the EU power benchmarks with the same maturities. Additionally, we illustrate the time series paths of carbon-neutral EU and US hydrogen benchmarks from January 22 to December 23. All series are indexed, so that they take a value of 100 at the start of the sample. A close look at the figure shows that there is an initial spike in the first quarter of 2022, a second and more pronounced shock August 2022 and a last and less significant turmoil in

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[12] The term ex works means that the price reference excludes transport cost. Other important global CNH benchmarks include (1) Ex Works California reflecting hydrogen delivered at any production facility in California, (2) Ex Works Middle East reflecting hydrogen delivered at any production facility in Saudi Arabia, (3) Ex Works Far East Asia reflecting hydrogen delivered at any production facility in Japan and (4) Ex Works Australia reflecting hydrogen delivered at any production facility in West Australia.

[13] See Cossent *et al.* (2025) for detailed analysis of the different green hydrogen price benchmarks

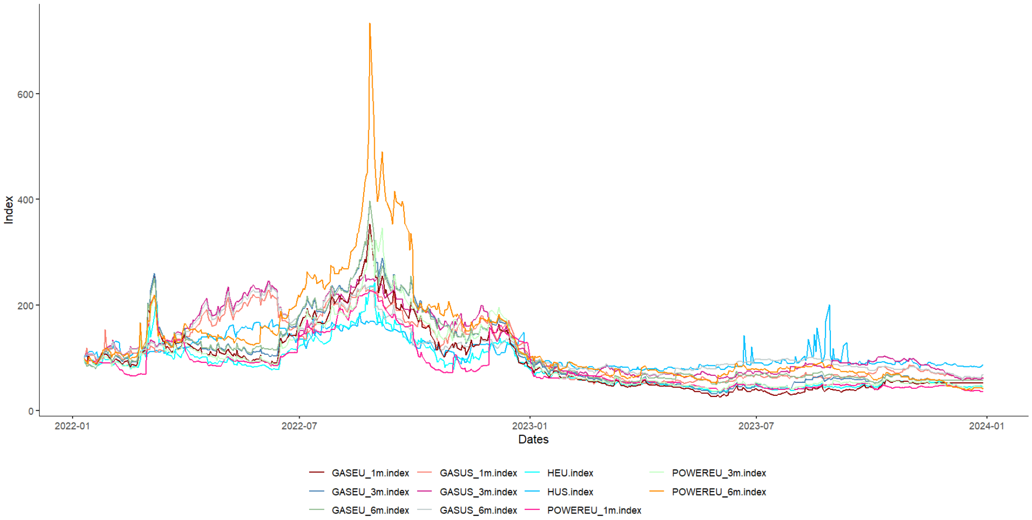

Figure 2: Time series evolution of gas, electricity and carbon neutral Hydrogen daily benchmarks for EU and the US for the 2022-2023 period

December 2022. While the first episode coincides with start and immediate aftermath of the war in Ukraine (24th of February of 2022) the second episode affecting US and European gas, power and hydrogen benchmarks in August 2022 takes place when gas supplies from the North Stream I are definitively suspended. Note that this pattern is also seen in Fig 1.

4.3. Renewable PPA data

We obtain daily price data for renewable PPAs prices at European wide and country specific level over the Feb 2019 - Dec 2024 period from Reuters Refinitiv which collects PEXAPARK PPA data. Market Trends provide an aggregated measure of the evolution of 10-year Pay-as-Produced (PAP) prices, based on a rolling average of the front and second year starting contracts.

In a PAP Agreement, the buyer commits to purchasing all electricity actually generated by the project, regardless of timing or quantity. In contrast, a baseload PPA specifies a fixed, pre-agreed amount of electricity (e.g., 50 MWh per hour) to be delivered consistently every hour, independent of the plant's actual generation. Under the Pay-as-Produced model, the buyer assumes the volume and profile risk, whereas in a baseload PPA, that risk shifts to the seller. The buyer of the PPA is the entity that is purchasing power from a renewables' generator (also known as off-taker, consumer or purchaser). It could be a corporate, a trader or a utility. The seller is typically the renewable energy generator or project company that owns and operates the power plant. This entity is responsible for generating and delivering electricity to the buyer (off-taker) under the terms of the PPA.

PPA trends displayed via Refinitiv track the evolution of renewable PPA prices. Trends do not reflect actual transaction prices, they have instead been designed to provide a cross-sectional overview of price movements . Depending on the type, they average trends on country level, technology level (on-shore, offshore or solar) or regionally (EURO Composite).

The PPA data used here includes PEXA Euro Composite[14], PEXA Euro wind offshore, PEXA Euro wind onshore, PEXA Euro Solar, PEXA France, PEXA Great Britain, PEXA Germany, PEXA Italy, PEXA Netherlands, PEXA Nordics, PEXA Poland, PEXA Portugal, PEXA Spain.

Fig 3 represents the time series evolution of different PPA benchmarks. A close look a this figure shows that there are significant boom and bust cycles during the 2021-2022 period resembling those documented for the gas, power and low carbon hydrogen benchmarks.

4.4. Summary statistics

In this section, we provide a preliminary analysis of the the time series evolution of price returns in the three samples considered.

Summary statistics for weekly returns are reported in Table 1. All figures are annualized apart from the skewness and kurtosis measures. The column corresponding to the Standard Deviation shows that gas and power European series exhibit higher volatility than the GASUS series. For instance, while the

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[14] The Euro Composite is an average of 10-year solar and wind pay as produced PPA prices across Europe for a commercial operation dated Y+1, and Y+2

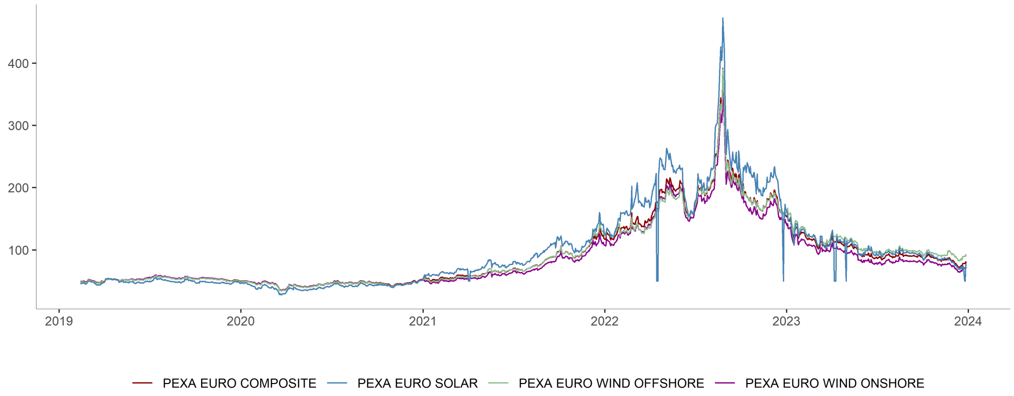

Figure 3: Time series evolution of PPA benchmarks by technology for the 2019-2023 period

Table 1: Descriptive Statistics for weekly returns

	Mean	Median	Max	Min	Std. Dev	Skew	Kurt
GASUS.1m.ret	0.12	0.01	12.69	-12.55	0.55	-0.17	3.72
GASUS.3m.ret	0.069	0.084	11.97	-13.99	0.50	-0.17	4.67
GASUS.6m.ret	0.045	0.10	9.17	-11.31	0.41	-0.31	5.28
GASEU.1m.ret	0.45	-0.074	51.07	-19.12	0.87	1.87	15.71
GASEU.3m.ret	0.41	-0.21	49.47	-21.15	0.81	2.11	18.31
GASEU.6m.ret	0.34	-0.11	44.39	-20.74	0.72	2.04	20.12
POWEREU.1m.ret	0.58	-0.26	98.38	-26.26	1.11	5.81	67.70
POWEREU.3m.ret	0.46	-0.24	43.14	-26.30	0.79	1.53	14.63
POWEREU.6m.ret	0.41	-0.20	52.02	-23.29	0.80	2.62	26.35

[1] All returns calculated from data in USD

[2] Data for front-month, 3 month and 6 month future contracts for US Gas (GASUS.1m.ret, GASUS.3m.ret and GASUS.6m.ret), EU Gas (GASEU.1m.ret, GASEU.3m.ret and GASEU.6m.ret) and EU Power (POWEREU.1m.ret, POWEREU.3m.ret and POWEREU.6m.ret) obtained from Bloomberg

[3] All metrics annualized except for Skew and Kurtosis

standard deviation for GASUS1m is 55% the same metric reported for the European counterpart (GASEU1m) is 87%. In general, volatility (as proxied by the standard deviation) declines with the time to maturity both in Gas and Power markets[15]. Kurtosis is also significantly higher in European gas benchmarks (GASEU1m, GASEU3m, GASEU6m) than in US based benchmarks. Note that kurtosis increases with time to maturity for the Gas series, while it decreases for Power. The highest volatility and kurtosis are reported for POWEREU1m.

Summary statistics for the returns of the daily time series with hydrogen benchmarks are reported in Table 2. Daily Standard deviations show that there has been a significant degree of volatility during the period in all price series considered. Volatility, as proxied by the standard deviation, is also significant for the Carbon Neutral Hydrogen benchmark for US and EU (denoted as HUS and HEU respectively). Again, we can observe in the gas price benchmarks that volatility declines with the time to maturity.[16] However Power markets do not show such a clear term structure. Interestingly, the European Carbon neutral hydrogen benchmark (HUE) and the US gas benchmark daily series (GASUS1m, GASUS3m, GASUS6m) exhibit the lowest skew and volatility levels, while kurtosis is significant in all series with the POWEREU1m exhibiting the highest level.

We have additionally analysed the weekly differences between the spot price and the futures price for the 2016-2023 period. Results are presented in Table 3. We label the spot and future price differences for GASEU and GASUS and EUPOWER prices as *Diff1*$=s_{t+3}-f_{t,3}$ and *Diff2*$=s_{t+6}-f_{t,6}$. These take the front month future as a proxy for the spot price and the three month and six month futures respectively for the definition of *Diff1* and *Diff2*. Reported results show that all the difference measures exhibit negative means implying that markets have been generally in contango. Moreover we can see that the *Diff2* series presents the highest standard deviation, implying that the volatility of the basis is always highest for the difference constructed with the six month price. The highest volatility is reported for *Diff2* in POWEREU. This is not the case for the kurtosis data for GASUS and GASEU but it is for

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[15] This is a common feature in commodity markets known as the Samuelson effect

[16] This is a normal feature in commodity markets known as the Samuelson effect

Table 2: Descriptive Statistics for daily returns

Variable	Mean	Median	Max	Min	Std.Dev	Skew	Kurt
HUS.ret	0.71	0.00	154.64	-121.17	1.28	1.72	22.89
HEU.ret	0.053	0.00	88.40	-63.88	0.95	0.77	8.22
GASUS_1m.ret	0.12	0.00	117.13	-65.40	0.86	0.92	14.13
GASUS_3m.ret	-0.011	0.00	45.35	-42.91	0.68	0.095	4.45
GASUS_6m.ret	-0.0079	0.00	46.50	-53.01	0.60	-0.46	7.53
GASEU_1m.ret	0.32	0.00	123.90	-73.67	1.15	1.01	9.03
GASEU_3m.ret	0.27	-0.099	118.38	-73.96	1.06	1.36	11.93
GASEU_6m.ret	0.17	0.00	114.10	-73.15	0.96	1.12	12.27
POWEREU_1m.ret	0.06	-0.59	205.40	-110.93	1.15	5.49	65.06
POWEREU_3m.ret	0.09	-1.60	113.26	-67.83	1.01	1.27	10.29
POWEREU_6m.ret	0.067	-0.56	101.84	-82.46	1.01	1.02	12.41

[1] All returns calculated from data in USD
[2] Data for US Hydrogen (HUS.ret) and EU Hydrogen (HEU.ret) obtained from SP
[3] Data for future contracts for US Gas (GASUS.ret), EU Gas (GASEU.ret) and EU Power (POWEREU.ret) obtained from Bloomberg
[4] All metrics annualized except for Skew and Kurtosis

the EU power market which exhibits the greatest volatility and kurtosis of the six month basis. The evolution of the six difference series is illustrated in Fig 4. We can observe that these differences start diverging from zero from mid 2021 with the spread corresponding to POWEREU series exhibiting the most pronounced negative spike.

Table 3: Descriptive statistics for differences between Future spot and forwards

Variable	Mean	Median	Max	Min	Std. Dev	Skew	Kurt
GASUS.Diff.1	-0.086	-0.14	3.99	-3.60	1.05	0.47	6.13
GASUS.Diff.2	-0.049	-0.043	5.78	-5.02	1.57	0.71	5.87
GASEU.Diff.1	-2.17	-1.29	191.13	-195.48	28.78	-0.24	17.57
GASEU.Diff.2	-2.32	-3.83	266.22	-229.24	39.30	1.17	15.67
POWEREU.Diff.1	-20.76	-8.34	194.48	-464.52	68.48	-2.25	13.21
POWEREU.Diff.2	-30.51	-12.50	298.08	-1223.31	116.45	-4.55	41.19

[1] All metrics calculated from data in USD
[2] Diff.1 refers to the difference between future spot (proxied by front-month future) and 3-month future price; Diff.2 refers to the difference between future spot and 6-month future price

Summary statistics for the daily PPA return measures are reported in Table

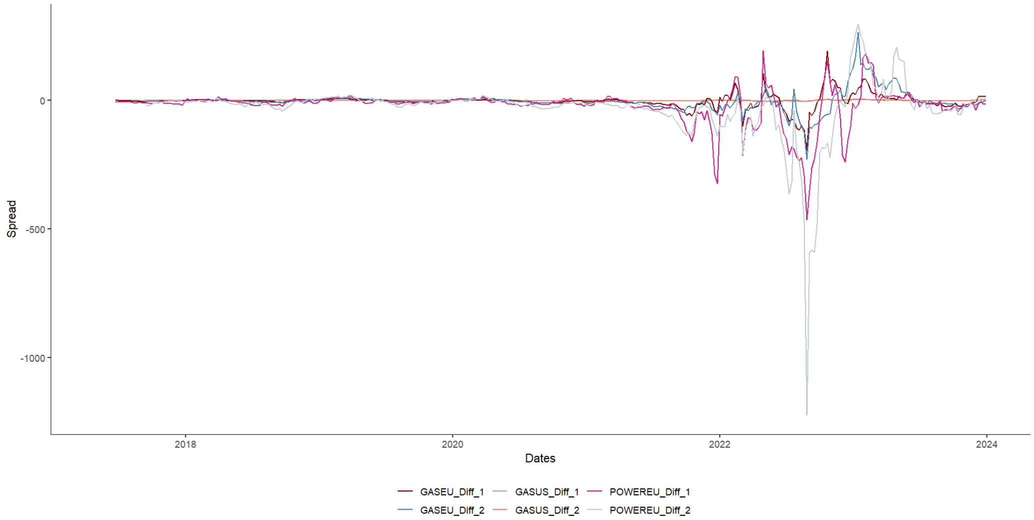

Figure 4: Time series evolution of the differences between (future) Spot and futures energy prices

4.As expected, PPA prices behave very similar to the EU power benchmark with volatilities ranging from 37% for the case of Euro Composite benchmark to 64% for the case of Great Britain and Netherlands. We can observe that volatility for Solar technology is higher when compared to Wind. Interestingly, kurtosis levels are highest for Poland and Italy.

Table 4: Descriptive Statistics for PPAs daily returns

Variable	Mean	Median	Max	Min	Std.Dev	Skew	Kurt
EURO_ret	0.16	0.00	33.70	-34.72	0.37	-0.066	8.26
EURO_Wind_on_ret	0.14	0.15	33.97	-36.74	0.37	-0.086	8.21
EURO_Wind_off_ret	0.19	0.12	35.02	-34.50	0.37	-0.22	8.98
EURO_Solar_ret	0.23	0.00	43.45	-44.86	0.52	0.27	8.03
France_ret	0.23	0.23	106.56	-46.39	0.52	1.58	28.58
UK_ret	0.27	0.00	66.12	-59.44	0.64	0.38	10.40
Germany_ret	0.19	0.017	46.17	-47.62	0.43	-0.032	9.87
Italy_ret	0.32	0.18	144.51	-88.31	0.59	1.94	62.67
Netherlands_ret	0.22	0.22	77.82	-74.91	0.64	0.27	14.31
Nordics_ret	0.24	0.056	100.65	-34.15	0.39	3.22	61.79
Poland_ret	0.26	0.12	155.40	-116.21	0.57	1.99	93.00
Portugal_ret	0.12	0.14	64.46	-44.47	0.48	0.54	15.83
Spain_ret	0.14	0.00	67.29	-46.85	0.48	0.44	17.60

[1] All returns calculated from data in EUR
[2] Data obtained from PEXA
[3] All metrics annualized except for Skew and Kurtosis

5. Empirical Analysis

We perform a PSY test on all different price series considered. This allows us to detect any potential explosive periods during the weekly and daily samples analyzed. We used the `exuber` package in R developed by Vasilopoulos *et al.* (2022). The test is implemented for critical values simulated under the unit root hypothesis and under wild-bootstrap. These critical values are robust to the existence of heteroskedastic errors implying that the test becomes more stringent than under the benchmark MC cv. [17] We refer to the former as Monte Carlo critical values (MC) while the later are denoted as (WB).

In what follows, we refer to "explosive signals" as a statistical results in which the test statistic is above the critical value. We call "bubbles" to explosive signals where the test statistic surpasses the critical values for a number of periods (either weeks for the weekly series or days for the daily ones) greater than log(T) where T is the total number of observations. If the bubble cannot

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[17] $5,000$ simulations are used for this purpose.

be explained by fundamental price behaviour we refer to it as a speculative bubble.

We first test for bubbles (also denoted as mild explosivity) in weekly electricity and gas prices. We will present periods in which bubbles are date stamped under 5% significance critical values. Results for critical values simulated at the 10% significance levels are provided as means of robustness in the Appendix.

5.1. Mild explosivity and bubbles for weekly gas and power prices

Estimated GSADF statistics which are reported in Table B.19 in the appendix indicate rejection of the null hypothesis (H_0) of no general bubble behaviour for all series at the 1% significance level.

Fig. 5 illustrates in a shaded area the episodes for which the statistic exceeds the 5% critical value. We refer to these periods as explosive signals that are identified as "bubbles" if the minimum bubble condition is fulfilled. We can see that there is a predominant period of explosiveness across all weekly series around the second, third and fourth quarters of 2021. There are also periods of mild explosivity during 2022. Shorter periods of explosiveness are documented in 2018.

Table 5 reports exact bubble periods under Montecarlo simulated critical values for European gas prices (GASEU1m, GASEU3m, GASEU6m). While some short explosive periods are documented in 2018 for three month and six month benchmarks,[18] bubbles fulfilling the minimum bubble condition are only documented during the energy crisis. Specifically, we find bubbles in the three GASEU benchmarks, as well as in GASUS6m and all the POWEREU price series considered. The GASEU1m series exhibits a bubble during 18 weeks from June to October 2021 and a 6 week bubble from November 2021 to December 2021. A similar pattern is followed for GASEU3m and GASEU6m. The six month European gas benchmark (GASEU6m) does however show an

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[18] Five week and three weeks explosive episodes are found in GASEU3m and GASEU6m in the second and third quarters of 2018

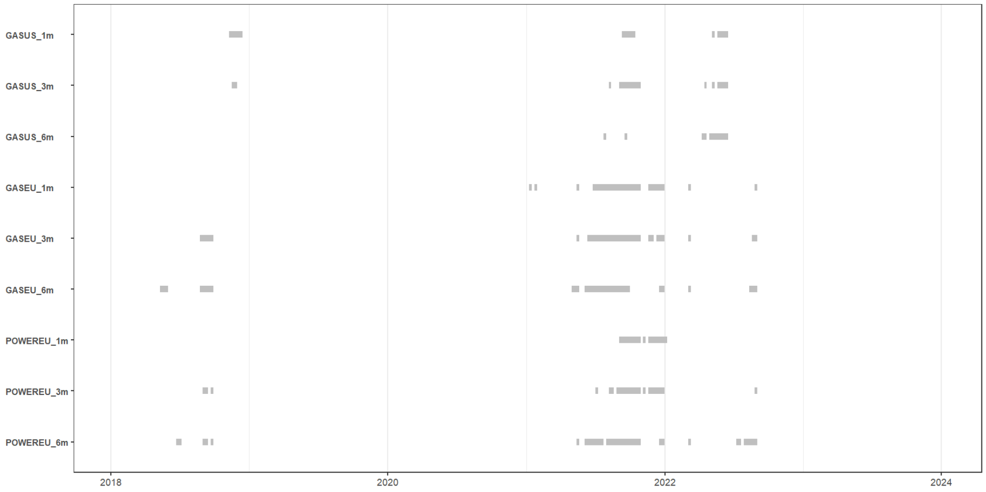

Figure 5: Date-stamping on weekly series using MC critical values 5% significance level

earlier explosive signal in April 2021. Shorter episodes are date stamped in March and August 2022 but none of them fulfill the minimum bubble condition. We report results for the 10% significance critical values in Table B.23 in the Appendix. Results show that there is long bubble for the six month case starting in April with a duration of 23 weeks. For this significance level the 6 month GASEU benchmark which shows longer explosive episodes in the summer of 2022 compared to the 1 month and 3 month prices. We can see that in this case the three gas price series declare bubbles in 2022.

Date stamping results for USGAS prices are reported in Table 6. The US gas series exhibit less pronounced explosive patterns than the EUGAS counterparts with a shorter 2021 bubble that is 8 week long for the 3m benchmark and a 5 week episode in the GASEU1m price. Interestingly, the only bubble identified for GASUS6m is in 2022 between April and June, after the initiation of the war in Ukraine. There is only a one week spike in the autumn of 2021 for this benchmark. The 3m and 1m benchmarks exhibit short explosive periods in 2022, predominantly during the second quarter. Results for the 10% significance level are reported in Table B.24 in the appendix. A ten week bubble is declared for the GASUS3m benchmark and from September to November 2021 which is only reflected as a spike in the GASUS6m and GASUS1m benchmarks. It is interesting to see how the GASUS6m benchmark exhibits a 10 week bubble in the spring 2022.

Bubble tests results for the European power markets are reported in table 7 for the 5% significance level. One bubble is date stamped in the fall of 2021 for the POWEREU1m price. A 9 week bubble episode is date stamped between August 2021 and October 2021 for the 3m benchmark. A longer period of 13 weeks starting in July 2021 is found for the POWEREU6m benchmark. Bubbles are also dated between November 2021 and January 2022 for the POWEREU1M. The POWEREU6m benchmark exhibits one episode just missing the bubble condition from July to September 2022. Note that this is around the time time in which gas flows from the North Stream I pipeline are definitively halted confirming that the gas and power price shocks were supply driven. Results for the 10% cv case reported in table B.25 in the appendix. They show that the summer 2022 episode detected in POWEREU6m fulfills the minimum bubble condition. Additional bubbles for all power price benchmarks are dated at this significance level during the last two quarters of 2021.

The time series evolution of BSADF statistics under MC critical values are illustrated in Fig 7. Shaded areas represent the date stamped bubble periods We can see that these are more preponderant in the three European gas series and in the European power series than in the US gas benchmarks.

We have analyzed the role of time changing volatility in Fig A.19 which illustrates the one year (52 weeks) rolling standard deviations for the given weekly series over the period analyzed. We can see that volatility series for the EU gas and power benchmarks exhibit two important periods of clustering covering the 2019-June2021, June2021-Sep2022 sub-periods. Volatility is maximized in the last sub-period covering gas price shock and reaches the most pronounced spike in August 2022 coinciding with the definitive closure of the North Stream I pipeline. This last episode is exhibited specially in the European and gas references. This Figure, thus, suggests that the documented bubble behaviour in the different price series may be volatility driven. This motivates us to perform the analysis under WP critical values.

We perform the same exercise for WB critical values. We report bubble test results uder the WB in Fig 8. We illustrate the time series evolution of BSADF statistics only for those series for which a bubble is identified at the

5% significance level. This requires that the GASADF statistic rejects the null hypothesis of no general bubble behaviour as reported in Table B.19 in the appendix. The Figure shows that only bubbles found in GASEU3m and POWEREU3m survive the wild bootstrap cvs.

As was the case for the MC cvs the most important episodes are seen during June 2021-October 2021 period. The same charts for the 10% cv case are provided in Figure A.21 in the appendix. Both series exhibit a larger number of bubbles in this case. However the 2021 summer-fall episode remains the most important. For space saving purposes we do not report detailed start and bubble end dates.

Results provided in this section suggest that the most important point of the energy crisis was initiated in June 2021, when the bubble behaviour is documented in all European gas benchmarks, in the GASUS3m price series as well as in the three European power series. Earlier signals were shown by GASEU6m for which the bubble starts in April 2024 when considering the 10% significance level. The GASUS6m benchmark shows a longer bubble in the aftermath of the war in Ukraine than other US and European (gas and power) benchmarks. The bubbles detected between June 2021 and October 2021 (and even earlier for GASEU6m) are consistent with the Quaterly Report of the European commission on gas markets (issue 2, Q2 2021) which states that the start of the energy crisis, dates back to the second quarter of 2021 documenting that wholesale gas prices in Europe exhibited a significant increase setting off from 19 €/MWh at the beginning of April, to 35 €/MWh at the end of June, finally reaching 48 €/MWh in mid August. The gas price continued to soar in the early autumn. The report acknowledges that such price increases were never seen since the beginning of trade on the European gas hubs. The same report states that in Q2 2021 and over the summer, Gazprom booked less than expected (and/or no additional) capacities, mainly through the Ukrainian and Yamal-Europe pipelines, as gas flows remained reversed eastward. [19]

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[19] See Reuter´s report ”Gazprom books no Q2 or Q3 Yamal gas pipeline capacity at auction”, February the 7th which states that the The section of the pipeline between Poland and Germany has been reversed eastward since December 21, helping drive up European gas prices.

Note that our findings are consistent with those reported in the literature. Segarra *et al.* (2024) analyze the existence and timing of a structural break in gas and power (spot and futures) volatility price dynamics in US and EU documenting a break between August and September 2021.[20] In this paper we focus on regime changes in the price level process and show that the first regime shift is documented in June 2021 for European gas and power series. Some evidence of an earlier start is reported for the GASEU6m benchmark in April 2021.

Cincinelli and Pellini(2025) examine wholesale day-ahead electricity markets of twelve European countries with different energy mixes and inter-connection settings. They find multiple periods of explosiveness in these markets documented since September 2021 adding to the scarce literature on electricity price determinants. We extend their findings by including the gas price benchmarks in the analysis as well as the green hydrogen and renewable PPA price signals. Our results are consistent with the work of Emiliozzi *et al.*(2025). They document the most important periods in the gas market during the European Energy Crisis highlighting how the EIA urged Russia to rump up gas supply to Europe on the 21st of September 2021. The authors also highlight that President Putin instructed Gazprom to prioritize filling Russia's domestic gas storage before supplying storage facilities in Europe.

Chuliá *et al.* (2024) address the dynamic and asymmetric connectedness between natural gas and electricity prices and find that there are strong spillovers between natural gas and electricity prices in scenarios of high and low returns highlighting periods of energy stress such as the Russian invasion of Ukraine. Specifically they find that spillovers are particularly pronounced for negative returns (quantiles below 20%) and positive returns (quantiles above 80%). Both Fabra (2023) and Segarra *et al.* (2024) discuss that the reduction of gas flows due to Gazpron´s actions in June 2021 would imply that the shock in energy prices took place much earlier than the start of the war in Ukraine on the 24th of February 2022. Such conclusions are also documented by Emiliozzi *et al.* (2025), which also addresses how the start of the war provoked the final interruption of the North Stream I. We find a

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[20] An F test for differences in standard deviations as the Kokoszka and Leipus (2000) change-point estimation for heteroskedastic time series is applied for this purpose.

number of short bubbles in the spring of 2022 for GASUS6m when Poland and Bulgaria are (the first European countries) to be cut of from Russian gas. A later bubble is documented in July-August 2022 in POWEREU6M prices.[21] Shorter spikes around the same period were seen in GASEU price benchmarks. In late July 2022 Gazpron announced indefinite shutdown of the North Stream I pipeline.

The June 2021 period does therefore constitute the start of the gas market shock which had direct consequences on electricity prices.These are highly dependent on gas due to the marginal pricing system. This is consistent with the literature that has highlighted that the dependence between electricity and natural gas prices is more pronounced during periods of stress in energy generation Uribe *et al.* (2022.)

The last price peak for all maturities in GASEU and GASUS6M prices as well as for the POWEREU3 and POWEREU6 benchmarks takes place in August 2022 when gas flows from the North Stream I where definitively suspended. [22]. Fig 6 shows the time series evolution of the North Stream daily nominations in Megawatts hours per day over the May 2017 to December 2023 period.[23] These are depicted with the front month TTF gas price. We can see that the daily nominations were temporary stopped every July for maintenance purposes but that the flows started to exhibit irregularities in June 2021 to significantly diminish on the first of June 2022. Flows are definitively suspended on the 30th of August 2022 when front month TTF prices reach maximum values.

The next step is to apply the PSY bubble test at panel level for the nine weekly series following the methodology proposed by Pavlidis *et al.* (2016). Results, reported in table 8, show that there is a common bubble with a

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[21] This episode just fails to meet the minimum bubble condition at the 5% level but declares a bubble at the 10% level

[22] Details of the interruptions of Russian gas flows to Europe during the gas squeeze can be found in the BBC news articles: "Nord Stream 1: Russia shuts major gas pipeline to Europe" September 1st 2022 (`https://www.bbc.com/news/world-europe-62249015`), "Nord Stream 1: How Russia is cutting gas supplies to Europe" September the 22d, 2022 (`https://www.bbc.com/news/world-europe-60131520`

[23] The data source for North Stream Daily Nominations is also Bloomberg

Table 5: PSY Multiple bubble test results for weekly EU gas future series (5% significance level)

	GASEU 1m		GASEU 3m		GASEU 6m	
	Bubble period	Duration (weeks)	Bubble period	Duration (weeks)	Bubble period	Duration (weeks)
	01/2021 - 01/2021	1	08/2018 - 09/2018	5	05/2018 - 06/2018	3
	01/2021 - 01/2021	1	05/2021 - 05/2021	1	08/2018 - 09/2018	5
	05/2021 - 05/2021	1	06/2021 - 10/2021	20	04/2021 - 05/2021	3
	06/2021 - 10/2021	18	11/2021 - 12/2021	2	06/2021 - 10/2021	17
	11/2021 - 12/2021	6	12/2021 - 12/2021	3	12/2021 - 12/2021	2
	03/2022 - 03/2022	1	03/2022 - 03/2022	1	03/2022 - 03/2022	1
	08/2022 - 09/2022	1	08/2022 - 09/2022	2	08/2022 - 09/2022	3
Number of bubbles		7 (2)		7 (1)		7 (1)
Average duration		4.14		4.86		4.86
Max. Duration		18.00		20.00		17.00

Table 6: PSY Multiple bubble test results for weekly US gas future series (5% significance level)

	GASUS 1m		GASUS 3m		GASUS 6m	
	Bubble period	Duration (weeks)	Bubble period	Duration (weeks)	Bubble period	Duration (weeks)
	11/2018 - 12/2018	5	11/2018 - 11/2018	2	07/2021 - 07/2021	1
	09/2021 - 10/2021	5	08/2021 - 08/2021	1	09/2021 - 09/2021	1
	05/2022 - 05/2022	1	09/2021 - 10/2021	8	04/2022 - 04/2022	2
	05/2022 - 06/2022	4	04/2022 - 04/2022	1	04/2022 - 06/2022	7
			05/2022 - 05/2022	1		
			05/2022 - 06/2022	4		
Number of bubbles		4 (0)		6 (1)		4 (1)
Average duration		3.75		2.83		2.75
Max. Duration		5.00		8.00		7.00

Table 7: PSY Multiple bubble test results for weekly EU Power future series (5% significance level)

	POWEREU 1m		POWEREU 3m		POWEREU 6m	
	Bubble period	Duration (weeks)	Bubble period	Duration (weeks)	Bubble period	Duration (weeks)
	09/2021 - 10/2021	8	08/2018 - 09/2018	2	06/2018 - 07/2018	2
	11/2021 - 11/2021	1	09/2018 - 09/2018	1	08/2018 - 09/2018	2
	11/2021 - 01/2022	7	07/2021 - 07/2021	1	09/2018 - 09/2018	1
			08/2021 - 08/2021	2	05/2021 - 05/2021	1
			08/2021 - 10/2021	9	06/2021 - 07/2021	7
			11/2021 - 11/2021	1	07/2021 - 10/2021	13
			11/2021 - 12/2021	6	12/2021 - 12/2021	2
			08/2022 - 09/2022	1	03/2022 - 03/2022	1
					07/2022 - 07/2022	2
					07/2022 - 09/2022	5
Number of bubbles		3 (2)		8 (2)		10 (2)
Average duration		5.33		2.88		3.63
Max. Duration		8.00		9.00		13.00

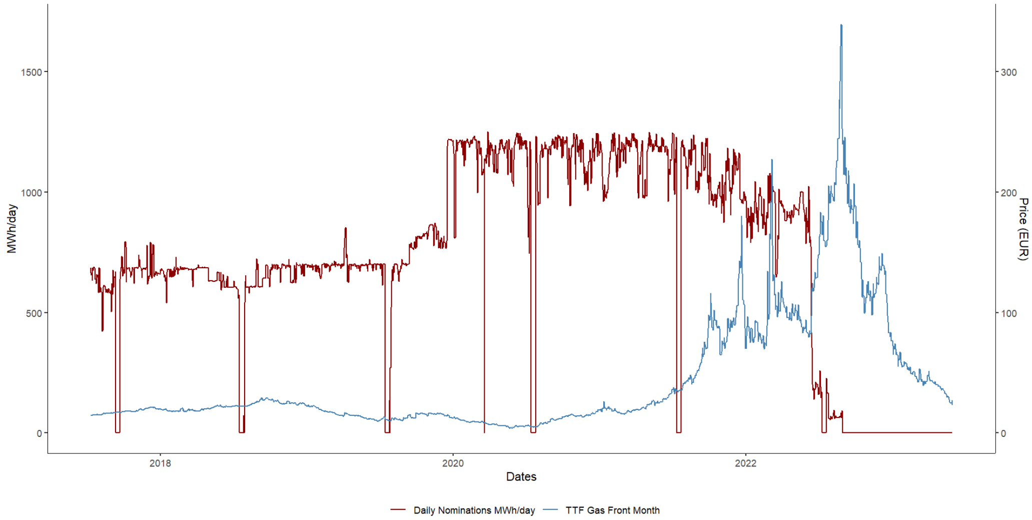

Figure 6: Evolution of North Stream 1 Daily Nominations in MWh per day

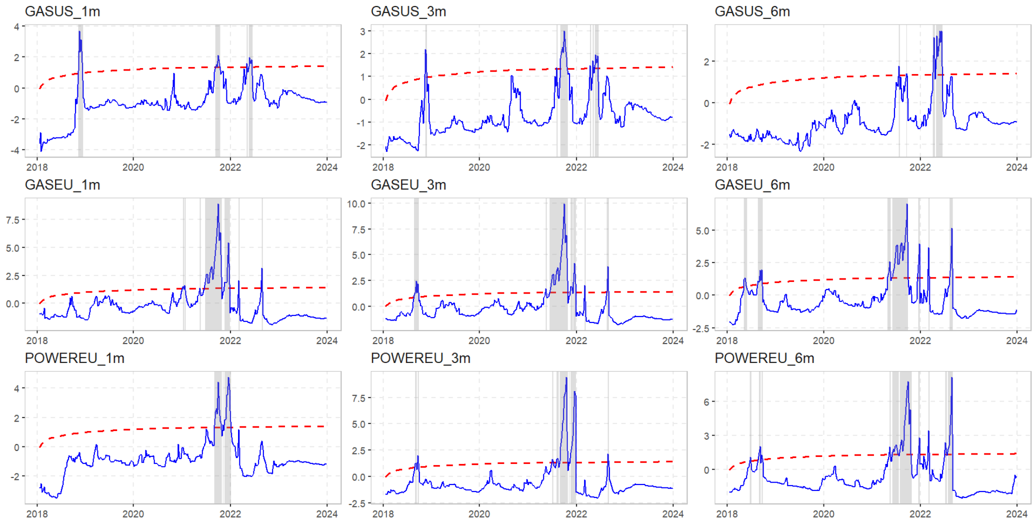

Figure 7: Datestamping on the basis of the BSADF statistic for all series considered under the MC critical values (5% significance level)

duration of 30 weeks that is date stamped between June 2021 and December 2021. Weekly panel results therefore confirm that the start of the energy crisis is date stamped in June 2021. Results show another important episode that just misses the minimum bubble condition between July and September

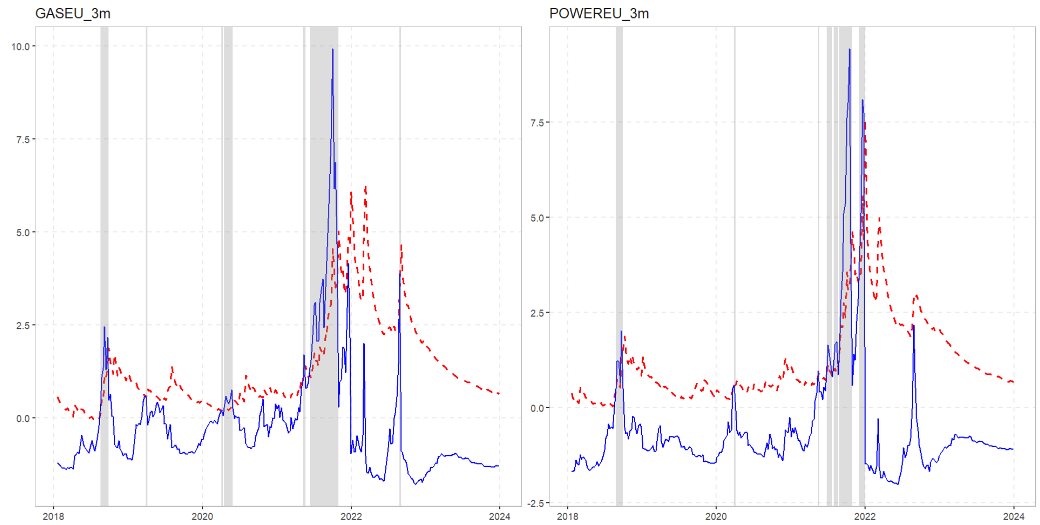

Figure 8: Datestamping on the basis of the BSADF statistic for all series that show general bubble behaviour (according to the GSADF) under the WB critical values (5% significance level)

of 2022, again highlighting the relevance of the definitive halt of glass flows from the North Stream I pipeline.

Table 8: PSY multiple bubble Test results for a Panel of weekly price series (5% significance level)

	Panel	
	Bubble period	Duration (weeks)
	09/2018 - 09/2018	1.00
	09/2018 - 09/2018	1.00
	11/2018 - 11/2018	1.00
	05/2021 - 05/2021	2.00
	06/2021 - 12/2021	30.00
	03/2022 - 03/2022	1.00
	07/2022 - 09/2022	5.00
Number of bubbles		7 (1)
Average duration		5.86
Max. Duration		30.00

5.2. *Mild explosivity for gas, electricity and Carbon Neutral daily prices*

Next, we apply the PSY test for all the daily price series for the sample available for carbon neutral (HUS and HEU) prices which ranges from January

2022 to December 2023. Results from estimated GSADF statistics, reported in table B.20 in the appendix show that there is general bubble behaviour in all series but in HUS and POWEREU1. Specifically the H_0 of no general bubble behaviour is rejected for the 5% significance level for all GASEU and GASUS benchmarks as well as for HEU and POWEREU3m and POWEREU6m. We therefore do not provide date stamping results for HUS and POWEREU1m. [24] The minimum bubble condition of Phillips *et al.* (2015b) is 6 consecutive days. All tables report within parenthesis, the number of explosive periods with duration higher than 6 days. These are introduced in the row labeled as "number of bubbles."

Tables 9, 10, 11 date stamp bubble periods for the different daily series analyzed. As was the case for the weekly series, bubble periods are documented when the BSADF statistic surpasses the MC critical value for a period longer than ln(T). Bubble duration results on the basis of the BSADF statistic. While the 5% significance level is applied as benchmark, the 10% significance level is used as means of robustness.

Details with explosive dates reported in Table 9 show that under the 5% level GASEU1m just misses the minimum bubble condition while GASEU3m and GASEU6m exhibit a 7 day bubble in August 2022. Table 10 shows that the there is an earlier GASUS bubble reflected in GASUS3m and GASUS6m that takes place in April 2022. Table 11 shows that HEU exhibits an explosive episode of four weeks in August 2022 while POWEREU3m and POWEREU6m declare 6 day and 9 day bubbles over the same period.

A graphical representation of the recursive BSADF statistic is provided in Figure 9, under the MC cv. Shaded areas show the periods in which the explosive episodes are declared highlighting the relevance of the August 2022 period also documented in Emiliozzi *et al.* (2025). Figure 10 illustrates BSADF statistics when considering the 10% significance level. The HEU's explosive episode in August 2022 is then declared as a bubble as it fulfills the minimum bubble condition. When applying the test for WB critical values which is a

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[24] The failure to reject the null hypothesis of no general bubble behaviour for POWEREU1 prices is unexpected. It is worth noting that this is the case for our sample of 510 daily observations. The test fails to reject the null hypothesis for a sample of 400, 300, 200, and 100 observations

more restrictive version we only reject the null hypothesis of no mild explosivity for all the GASUS and GASEU series and for the POWER6m series at the 10% significance level as reported in table B.20. [25] Interestingly, bubble behaviour is more pronounced in the long term series signaling abnormal market conditions. [26]

Table 9: PSY Multiple bubble test results for daily EU gas future series (5% significance level)

	GASEU_1m		GASEU_3m		GASEU_6m	
	Bubble period	Duration (weeks)	Bubble period	Duration (days)	Bubble period	Duration (days)
	07/2022 - 07/2022	1	07/2022 - 07/2022	1	07/2022 - 07/2022	5
	08/2022 - 08/2022	5	07/2022 - 07/2022	2	08/2022 - 08/2022	7
			08/2022 - 08/2022	7		
Number of bubbles		2 (0)		3 (1)		2 (1)
Average duration		3.00		3.33		6.00
Max. Duration		5.00		7.00		7.00

Table 10: PSY Multiple bubble test results for daily US gas future series (5% significance level)

	GASUS_1m		GASUS_3m		GASUS_6m	
	Bubble period	Duration (weeks)	Bubble period	Duration (days)	Bubble period	Duration (days)
	04/2022 - 04/2022	1	04/2022 - 04/2022	8	04/2022 - 04/2022	7
	04/2022 - 04/2022	5	05/2022 - 05/2022	2	05/2022 - 05/2022	2
	05/2022 - 05/2022	2	12/2023 - 12/2023	1		
Number of bubbles		3 (0)		3 (1)		2 (1)
Average duration		2.67		3.67		4.50
Max. Duration		5.00		8.00		7.00

We can state that the bubble periods are highly related to the gas supply reduction through the North Stream I pipeline. We can also establish that the gas and the power price are closely linked to the carbon neutral hydrogen prices. In fact, as was stated earlier, electricity prices are the most important cost component of hydrogen cost based valuations. For instance a close analysis of the the leveled Cost of Hydrogen (LCOH) calculator provided by the European Hydrogen Observatory shows that the most significant cost

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[25] Detailed bubbled dates can be reported upon requests

[26] Under normal conditions we would expect higher volatility in the short term maturities due to the well known Samuelson effect Samuelson(1965)

Table 11: PSY Multiple bubble test results for daily EU Power future and EU Hydrogen series (5% significance level)

	HEU		POWEREU_3m		POWEREU_6m	
	Bubble period	Duration (weeks)	Bubble period	Duration (days)	Bubble period	Duration (days)
	07/2022 - 07/2022	2	07/2022 - 07/2022	2	07/2022 - 07/2022	3
	08/2022 - 08/2022	1	08/2022 - 08/2022	6	08/2022 - 08/2022	9
	08/2022 - 08/2022	4	09/2022 - 09/2022	1		
Number of bubbles		3 (0)		3 (1)		2 (1)
Average duration		2.33		3.00		6.00
Max. Duration		4.00		6.00		9.00

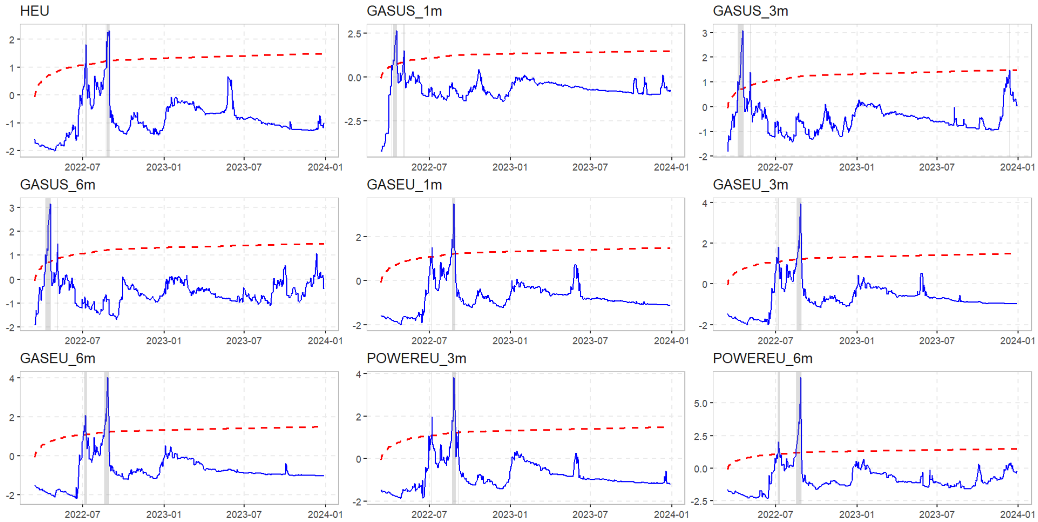

Figure 9: Datestamping on the basis of the BSADF statistic for all daily series considered under the MC critical values (5% significance level)

for producing renewable hydrogen is the electricity cost, which represents between 50% and 70% of the final LCOH[27].

Given that electricity wholesale prices are driven by the marginal producer, it can be expected that the gas price to be the main determinant of electricity

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[27] This calculator provides estimates of hydrogen production costs via low temperature water electrolysis in the different EU27 countries, Norway and the UK.Details can be obtained in (https://observatory.clean-hydrogen.europa.eu/tools-reports/levelised-cost-hydrogen-calculator]

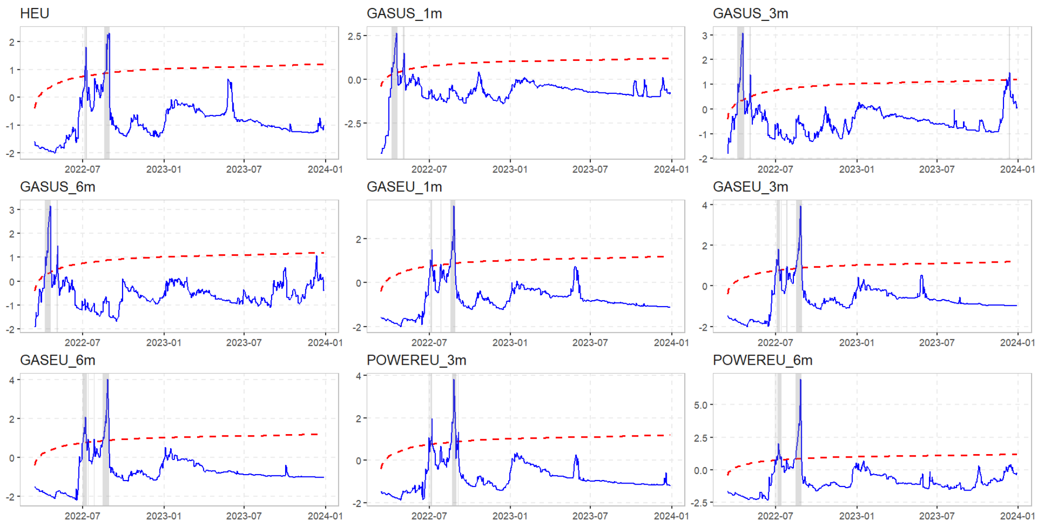

Figure 10: Datestamping on the basis of the BSADF statistic for all daily series considered under the MC critical values (10% significance level)

prices and therefore carbon neutral hydrogen prices. The result is that the explosive episode date stamped in HEU at the 5% significance level (which is declared as a bubble at the 10% significance level) coincides with the bubbles documented in GASEU3m and GASUEU6m as well as POWEREU3m and POWEREU6m. We can therefore establish that the exuberance detected in HEU price benchmarks arises due to exuberance seen in the gas and electricity price series.[28]

Results related to the S&P global carbon neutral hydrogen price assessments should be interpreted with caution. While these are the only carbon neutral hydrogen price benchmarks with a relatively long history of data, they are mainly price assessments based on the production cost or "ask" side of the value chain. These assessments do not reflect signals from the consumer or "bid" side. This implies that further efforts are required for the introduction of hydrogen price benchmarks that provide signals from the producer and consumer side and that are consistent with the generation capacity of

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[28] Note that explosive episodes fulfill the bubble condition only when 3m and 6m maturities are considered. Under abnormal market conditions prices for longer maturities capture regime shifts due to expectation of future bubble conditions

renewable energy.

The PSY methodology has been applied for daily price series by Etienne *et al.* (2015) and Etienne *et al.* (2014) for agricultural spot and futures prices over a sample that focuses on the global financial crisis. This literature has considered as minimum bubble condition the h number of days where h is set to be 3 or 5 days. This is less stringent approach than the one applied here. We follow the ln(T) rule to avoid choosing a too short minimum bubble criterion that may generate bubble type phenomena in the form of 'froth' that, while is of concern to market participants, will be of limited policy interest (see Figuerola-Ferretti *et al.* (2015).

Note that the use of daily data facilitates testing for potentially relevant, shorter periods of mild explosivity than weekly or monthly data would permit. This sampling frequency may be more appropriate for assessing behavioural trends. However lower frequency data permits the complementary analysis based on some of the more traditional fundamentals and avoids documenting bubble episodes that represent microstructure noise (Brooks *et al.* (2015) or "froth".

Results reported in Tables 9, 10 and 11 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 12 are consistent with the figures reported in Tables 9, 10, 11 and show that there is a common 10 day bubble in August 2022. Shorter episodes are date-stamped in July. As previously discussed, the collapse of this later bubble coincides with the definite halt of the Russian gas supplies to Europe through the North Stream I. As previously discussed The common episode date stamped with daily data can be explained by Fig 6 which shows the daily time series evolution of European gas prices (measured as the TTF front month future) and the NELPIF index which measures the gas flows from Russia to Europe from the North Stream I obtained from Bloomberg. A closer look at the figure shows that cuts in gas flows were first seen in late June 2021 and were definitively halted on the 30th of August 2022 [29]. Reported results are therefore suggesting a close link of the bubble behaviour to the supply side fundamental proxied by the North Stream I gas flows. The existence of tight fundamentals may have also attracted speculative players to the markets. We test this proposition in section 5.4.

Table 12: Multiple bubble test results for panel of daily energy price series (5% significance level)

	Panel	
	Bubble period	Duration (days)
	06/2022 - 07/2022	1
	07/2022 - 07/2022	5
	08/2022 - 08/2022	10
Number of bubbles		3 (1)
Average duration		5,33
Max. Duration		10,00

5.3. *Mild explosivity for daily PPA prices*

Power Purchase Agreements (PPAs) are long-term bilateral contracts—typically ranging from 10 to 15 years—between electricity generators and corporate off-takers, structured outside of wholesale spot markets. They play a crucial role in financing and stabilizing renewable energy projects by securing predictable revenue streams for producers and shielding buyers from electricity price volatility Ghiassi-Farrokhfal *et al.*2021), Bruck and Sandborn (2021). Given their growing importance in green energy financing, our study contributes by applying bubble detection techniques to RE PPA price series, offering new evidence on the stability and price dynamics of this alternative market segment.

We perform the PSY bubble test to all PPA prices considered at univariate and panel level. The later is performed using the Pavlidis *et al.*2016 methodology. Results are reported for MC and WB critical values in Table B.22. We find that we can reject the null hypothesis of no mild explosivity

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[29] See FT article available " Russia switches off Europe's main gas pipeline until sanctions are lifted." September 5th 2022. `https://www.ft.com/content/2624cc0f-57b9-4142-8bc1-4141833a73dd`

for all series under MC cv for 1% significance level. When we apply WB methodology, we fail to find bubbles in three time series: Germany, Italy and the Netherlands. In fact, we can see that only PEXA EURO COMPOSITE, PEXA EURO WIND OFFSHORE, PEXA EURO WIND ONSHORE, PEXA Great Britain, PEXA Nordics and PEXA Portugal survive the WB at the 5% significance level (see also Fig A.25 in the Appendix).

The PSY test is applied for all the PPA series for the 2019-2023 period for which they are all available. Tables 13 and 14 date stamp periods of bubble behaviour under the MC critical values for a sample of the series. Reported results are summarized in Fig. 11. They show that there is bubble preponderance around the fall of 2021, in the spring of 2022 and in the summer of 2022. As it is the case with the previous analysis, bubble end dates in that period coincide with the definitive halt of gas flows from the North Stream I into Europe. Long bubble periods (greater than 21 days) are documented for the PEXA EURO COMPOSITE, PEXA EURO Wind Onshore, PEXA EURO SOLAR, PEXA GERMANY,and PEXA Nordics. Interestingly we see that PEXA Portugal and PEXA Spain only show bubble episodes in the fall of 2021 manifesting the effects of cap in gas prices introduced by the central governments. The Iberian market was protected by policy measures capping gas prices. Similar results can be extracted from Fig A.24 in the Appendix that applies 10% significance critical values.

The time series evolution of the BSADF for each of the PPA series analyzed is illustrated in Fig. 12. A close look at this figure confirms that bubble syncronicity starts in the spring 2021 and ends in September 2022. An earlier bubble episode is observed during the 2020 COVID crisis for PEXA Europe Composite, PEXA wind and PEXA Poland. Long bubbles are date stamped in the fall of 2021 and the spring of 2022. The time series of the BSADF statistics with corresponding WB critical values are illustrated in Fig 13 which shows that the PEXA Euro PPAS exhibit higher mild explosivity than the individual country PPA implying that energy shocks are not diversified across European countries. Reported results also suggest that shocks are also common across the different energy commodities.

We report for space saving purposes date stamping for PEXA EURO COMPSITE, PEXA EUROWIND ONSHORE, PEXA EURO Solar in Table A.25. Bubble dates for PEXA GERMANY, PEXA NORDICS and PEXA Spain

Table 13: PSY Multiple bubble test results for daily PPA series by Technology (5% significance level)

	EURO COMPOSITE		EURO WIND ONSHORE		EURO SOLAR	
	Bubble period	Duration (weeks)	Bubble period	Duration (days)	Bubble period	Duration (days)
	02/2020 - 02/2020	1	03/2020 - 03/2020	10	01/2020 - 02/2020	3
	03/2020 - 04/2020	11	05/2021 - 05/2021	1	03/2020 - 03/2020	2
	05/2021 - 05/2021	1	09/2021 - 09/2021	7	03/2020 - 03/2020	1
	05/2021 - 05/2021	2	09/2021 - 10/2021	17	01/2021 - 01/2021	1
	09/2021 - 10/2021	34	10/2021 - 10/2021	4	05/2021 - 05/2021	1
	10/2021 - 10/2021	2	11/2021 - 01/2022	27	05/2021 - 05/2021	2
	11/2021 - 01/2022	38	01/2022 - 01/2022	6	09/2021 - 09/2021	14
	01/2022 - 01/2022	1	01/2022 - 03/2022	37	09/2021 - 10/2021	8
	01/2022 - 03/2022	37	03/2022 - 06/2022	58	10/2021 - 10/2021	1
	03/2022 - 06/2022	57	07/2022 - 07/2022	8	12/2021 - 12/2021	16
	07/2022 - 07/2022	7	07/2022 - 07/2022	2	01/2022 - 02/2022	2
	07/2022 - 07/2022	2	07/2022 - 07/2022	3	02/2022 - 02/2022	17
	07/2022 - 07/2022	3	08/2022 - 08/2022	22	03/2022 - 03/2022	7
	08/2022 - 08/2022	22			04/2022 - 05/2022	31
					05/2022 - 06/2022	5
					06/2022 - 06/2022	2
					08/2022 - 08/2022	15
Number of bubbles		14 (6)		13 (7)		17 (6)
Average duration		15.57		15.54		7.53
Max. Duration		57.00		58.00		31.00

Table 14: PSY Multiple bubble test results for daily PPA series by Technology (5% significance level)

	GERMANY		NORDICS		SPAIN	
	Bubble period	Duration (weeks)	Bubble period	Duration (days)	Bubble period	Duration (days)
	07/2019 - 07/2019	1	01/2020 - 02/2020	3	03/2020 - 03/2020	2
	03/2020 - 03/2020	6	01/2021 - 01/2021	1	03/2020 - 04/2020	3
	05/2021 - 05/2021	5	09/2021 - 09/2021	5	09/2021 - 10/2021	8
	09/2021 - 09/2021	6	09/2021 - 09/2021	6	08/2022 - 08/2022	2
	09/2021 - 09/2021	1	09/2021 - 09/2021	2		
	09/2021 - 09/2021	2	10/2021 - 10/2021	3		
	09/2021 - 10/2021	8	12/2021 - 12/2021	1		
	11/2021 - 12/2021	25	12/2021 - 12/2021	2		
	01/2022 - 01/2022	7	12/2021 - 12/2021	1		
	01/2022 - 02/2022	24	12/2021 - 12/2021	1		
	03/2022 - 03/2022	2	04/2022 - 05/2022	13		
	03/2022 - 03/2022	7	05/2022 - 05/2022	3		
	03/2022 - 06/2022	55	06/2022 - 06/2022	4		
	07/2022 - 07/2022	9	06/2022 - 09/2022	56		
	08/2022 - 08/2022	13	09/2022 - 09/2022	1		
			03/2020 - 04/2020	3		
			09/2021 - 10/2021	8		
			08/2022 - 08/2022	2		
Number of bubbles		15 (6)		18 (3)		4 (1)
Average duration		11.40		6.39		3.75
Max. Duration		55.00		56.00		8.00

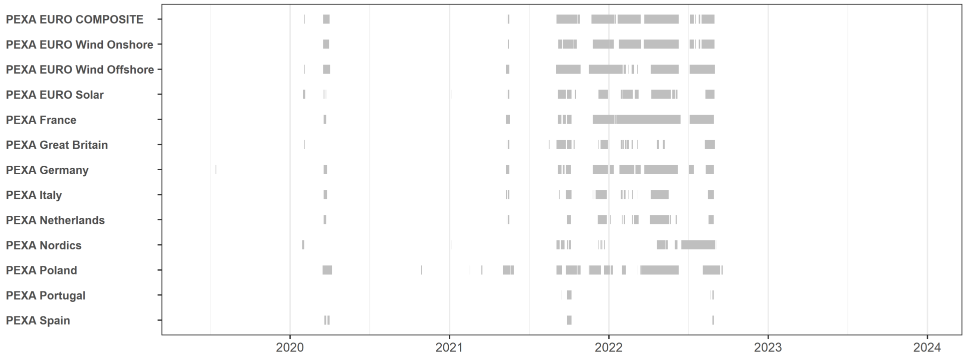

Figure 11: Datestamping on the basis of the BSADF statistic for all daily PPA series considered under the MC critical values (5% significance level)

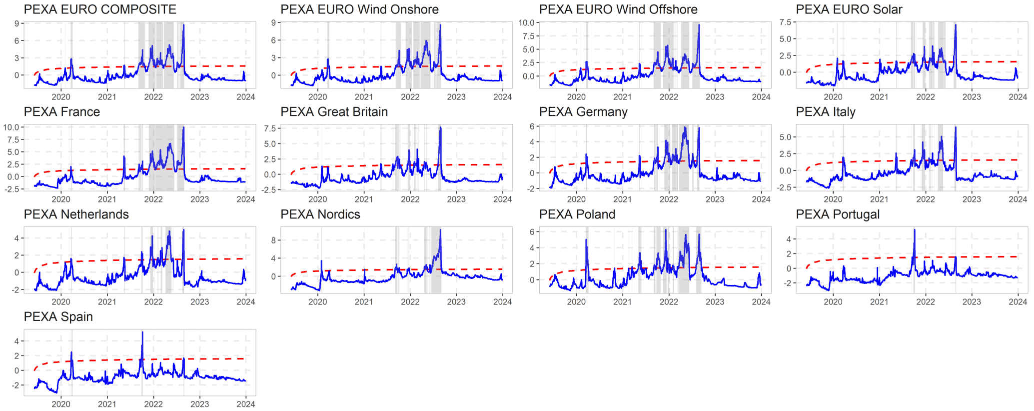

Figure 12: Datestamping on the basis of the BSADF statistic for all daily PPA series considered under the MC critical values (5% significance level)

are provided in Table 13 [30]. The finding of long explosive periods in PEXA Wind Onshore is consistent with Cincinelli and Pellini2025, which highlights the role of wind speed in determining bubbles in electricity markets.

Results for the the panel bubble test at PPA level are reported in Fig 14. This figure suggest that there is a short bubble episode in 2020 at the beginning of the COVID crisis and bubble preponderance during the 2021-2022 period.

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[30] Detailed bubble dates for remaining PPAs can be provided upon request

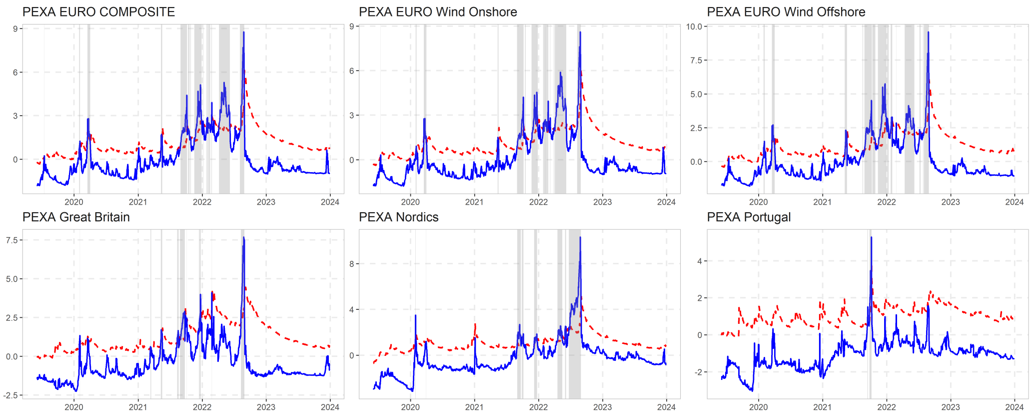
PEXA EURO COMPOSITE
PEXA EURO Wind Onshore
PEXA EURO Wind Offshore
PEXA Great Britain
PEXA Nordics
PEXA Portugal

Figure 13: Datestamping on the basis of the BSADF statistic for PPA series considered under the MC critical values (5% significance level)

Exact bubble dates are reported in Table 15 which dates a long common bubble of 269 days from August 2021 to September 2022. Reported results show clear commonality with those reported for the gas, power and green hydrogen markets suggesting that energy shocks are not diversified across the different (green and brown) energy sources.

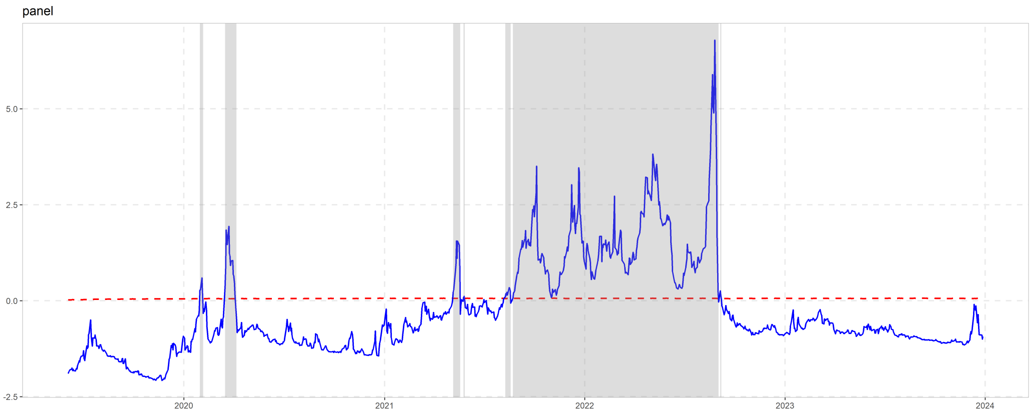
panel

Figure 14: Datestamping on the basis of the BSADF statistic for a Panel of PPA series considered under Sieve bootstrap critical values (5% significance level)

Table 15: Multiple bubble test results for Panel of daily PPA price series (5% significance level)

	Panel	
	Bubble period	Duration (days)
	01/2020 - 02/2020	4
	03/2020 - 04/2020	15
	05/2021 - 05/2021	9
	05/2021 - 05/2021	2
	08/2021 - 08/2021	8
	08/2021 - 09/2022	269
	09/2022 - 09/2022	2
Number of bubbles		7 (4)
Average duration		44,14
Max. Duration		269,00

5.4. Mild explosivity for weekly differences of future spot and forward prices

Following Pavlidis *et al.* (2017a), we perform the analysis of fundamentals by analyzing the difference between spot and future electricity and gas prices. The analysis of daily data shows that episodes of exuberance in the gas market extended to the power and low carbon hydrogen markets. It is therefore important to determine whether there was speculative behaviour in the gas and electricity markets. We pursue this analysis at weekly level.

Pavlidis *et al.* (2017a) suggest that bubbles can be tested by running the recursive unit root tests against the alternative of explosiveness on $spot_{t+n} - f_{t,n}$ as this difference is defined to be linear function of a bubble process (see Equation 6). Fundamentals are captured in this framework by the term structure of futures prices so the test has the advantage of not requiring identification of model dependent fundamentals.[31] This method applies the PSY test to the differences between the spot prices at time t and the 3 month futures prices (defined as $Diff_1 = s_{t+3} - f_{t,3}$) as well as the difference between the spot price in t and the six month futures price (defined as $Diff_2 = s_{t+6} - f_{t,6}$). We use the front month future as a proxy for the spot. We follow Pavlidis *et al.* (2017a) and do not consider longer horizons to avoid issues related to low liquidity. GSADF estimation results are reported in table B.21 which shows that the null hypothesis of random walk is rejected

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[31] Note that because we do not have a term structure of EUH2 or USH2 this test cannot be applied to low carbon hydrogen prices.

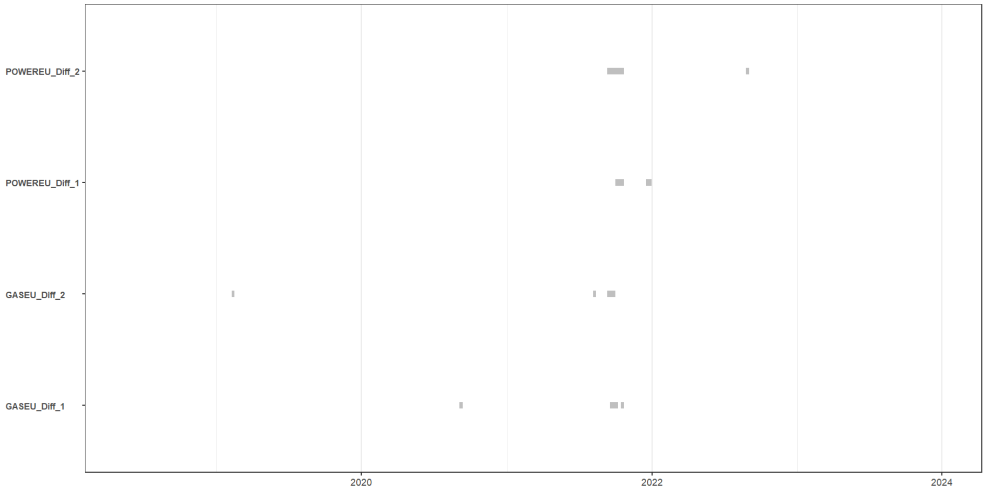

Figure 15: Date-stamping on gas futures using MC critical values 5% significance level

for the differences $(s_{t+n} - f_{t,n})$ in European gas and power series at the 1% significance level when using MC cv. We therefore conclude that there is general price bubble behaviour in the difference series during the sample period. We however fail to reject the null hypothesis for the US difference series.

Using the PSY methodology to datestamp potential bubbles in spot and futures price differences (that can also be defined as the futures basis), we see that all series exhibit explosive behaviour in the third quarter of 2021. However the minimum window of 6 weeks in $s_{t+3} - f_{t,3}$ is only fulfilled for the POWEREU-DIFF2 benchmark. The time series evolution of BSADF statistic for the three different bubbles is illustrated in Figure 16 for MC cvs. While the GASEU differential for different maturities does not fulfill the minimum bubble condition we find that there is a 3 week spike from September to October 2021 at the 5% significance level in the two difference benchmarks providing some weak evidence of speculation in the gas market. The speculative activity is extended and amplified in the power market as can be seen in the results provided for the one month and six month price differential. A bubble is declared in the POWEREU-DIFF2 suggesting that there was stronger speculative behaviour in the European power markets than in the European gas markets. As shown in Table B.21, these bubbles

Table 16: Multiple bubble test results for differences between future spot and future GASEU and POWEREU prices (5% significance level)

	GASEU_Diff_1		GASEU_Diff_2	
	Bubble period	Duration (days)	Bubble period	Duration (days)
	09/2020 - 09/2020	1	02/2019 - 02/2019	1
	09/2021 - 10/2021	3	08/2021 - 08/2021	1
	10/2021 - 10/2021	1	09/2021 - 10/2021	3
Number of bubbles		3 (0)		3 (0)
Average duration		1.67		1.67
Max. Duration		3.00		3.00
	POWEREU_Diff_1		POWEREU_Diff_2	
	Bubble period	Duration (days)	Bubble period	Duration (days)
	10/2021 - 10/2021	3	09/2021 - 10/2021	6
	12/2021 - 12/2021	2	08/2022 - 09/2022	1
Number of bubbles		2 (0)		2 (1)
Average duration		2.50		3.50
Max. Duration		3.00		6.00

do not survive the wild bootstrapped critical values suggesting that they were volatility driven. Reported results provide evidence suggesting that speculative behavior by market participants played a contributing role in the onset of the energy crisis. The speculative signal possibly arose under the expectation of future supply shortages and was transmitted to the six month maturity electricity markets as shown by the power front month and six month differential.

We formally test for common speculative bubble behaviour by using the panel bubble detection methodology. Estimation results are reported in Table 17.They confirm that there is a common 6-week bubble ranging from September to October 2021 suggesting that speculative positions in the gas and power markets contributed to the energy shock initiated in June 2021. They extend former evidence of market inefficiencies in the gas market during the Russian-Ukraine conflict (Belhoula *et al.*2024).

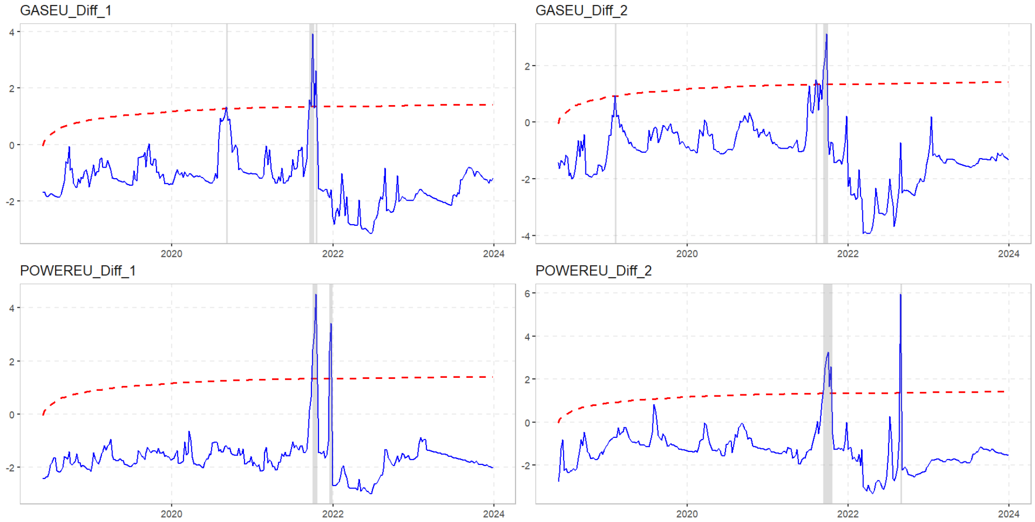

Figure 16: Datestamping bubble behaviour in daily spot and future difference price series with MC critical values (5% significance level)

Table 17: Multiple bubble test results for panel of differences between future spot and forwards

	Panel	
	Bubble period	Duration (days)
	09/2020 - 09/2020	1
	09/2021 - 10/2021	6
	12/2021 - 12/2021	1
	08/2022 - 09/2022	1
Number of bubbles		4 (1)
Average duration		2,25
Max. Duration		6,00

6. Conclusion

The triggering of Russia's invasion of Ukraine lead to global boom-and-bust cycles in energy markets. Natural gas markets worldwide have been tightening since June 2021. Russia's decision to suspend gas deliveries to EU member states created important disruptions that further intensified the need to foster local supply of energy.

Given that Russia has cut its gas exports to the EU by around 90% since the invasion, many European countries had to redesign their energy strategy accelerating the adoption of green alternatives such as renewable energy and low carbon hydrogen.

This paper offers novel insights into the dynamics of European and US energy markets during the recent energy crisis by applying bubble detection techniques based on the PSY test. Reported results show that the gas supply shock had spillover effects on both renewable and fossil fuel electricity markets, driven by the role of natural gas as a marginal generator and a key driver of electricity price formation. This arises due to the auction mechanism set for the final electricity price.

The recent geopolitical disruptions, within a gas-dependent power price market design, triggered synchronized price bubbles well before the outbreak of the war in Ukraine. These common bubble episodes began in the summer of 2021, lasting approximately 30 weeks in the weekly benchmark data and 269 days in the daily renewable PPA series. To our knowledge, this is the first paper that uses renewable PPA and carbon neutral hydrogen benchmarks to address the development of the energy transition. By extending the PSY methodology to green hydrogen prices and renewable PPA trends, we uncover pricing behavior that raises concerns about the alignment of current market signals with long-term energy transition objectives. Furthermore, our results provide evidence of speculative dynamics contributing to these price distortions. Reported findings therefore enhance the ongoing debate on speculation versus fundamentals driven bubbles (Kang *et al.*2023, Figuerola-Ferretti *et al.*2020, Kruse and Wegener2020).

Speculative-driven market bubbles in the gas and power sector can distort resource allocation, leading to suboptimal outcomes for producers, consumers, and society as a whole. Addressing these distortions is crucial to promote efficient allocation and uphold market stability and social welfare.

Our results also demonstrate reduced-form empirical approach applied complements existing literature and offers a robust framework for identifying periods of instability across both fossil fuel and renewable energy markets.

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Appendix A. Figures

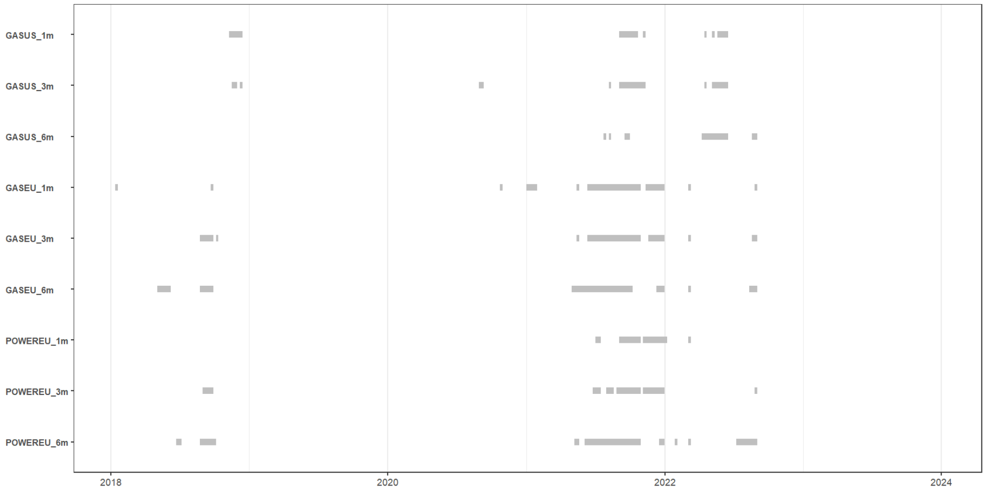

Figure A.17: Date-stamping on weekly series using MC critical values 10% significance level

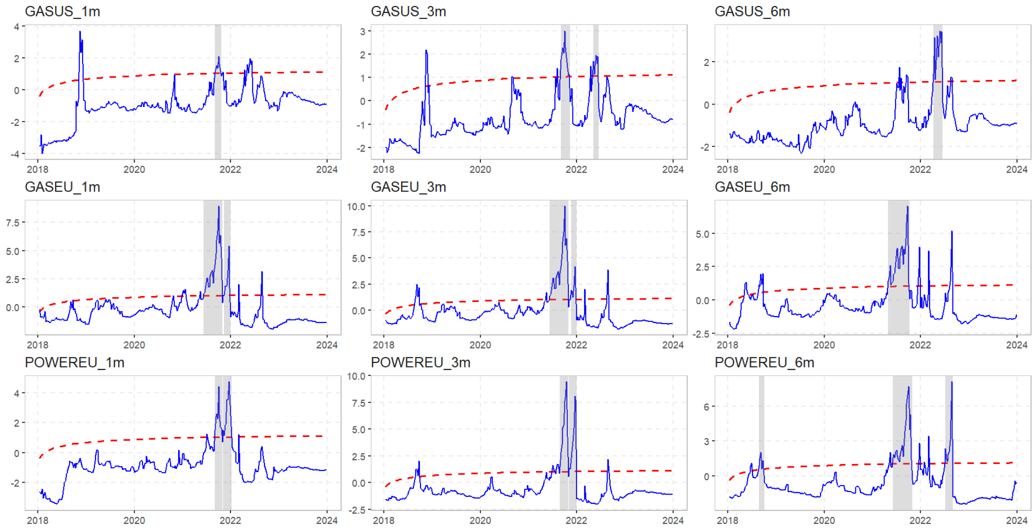

Figure A.18: Datestamping on the basis of the BSADF statistic for all series considered under the MC critical values (10% significance level)

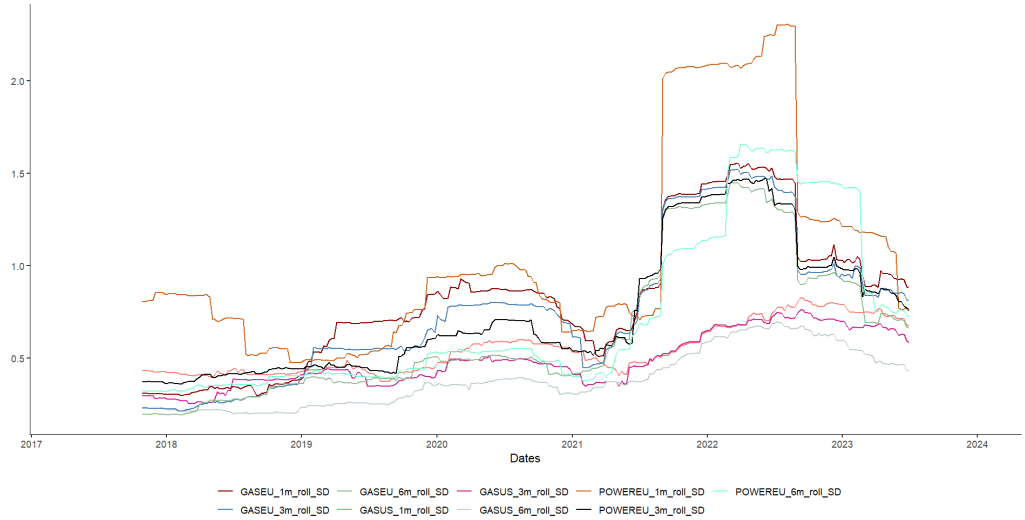

Figure A.19: Rolling 52 week volatility for weekly time series

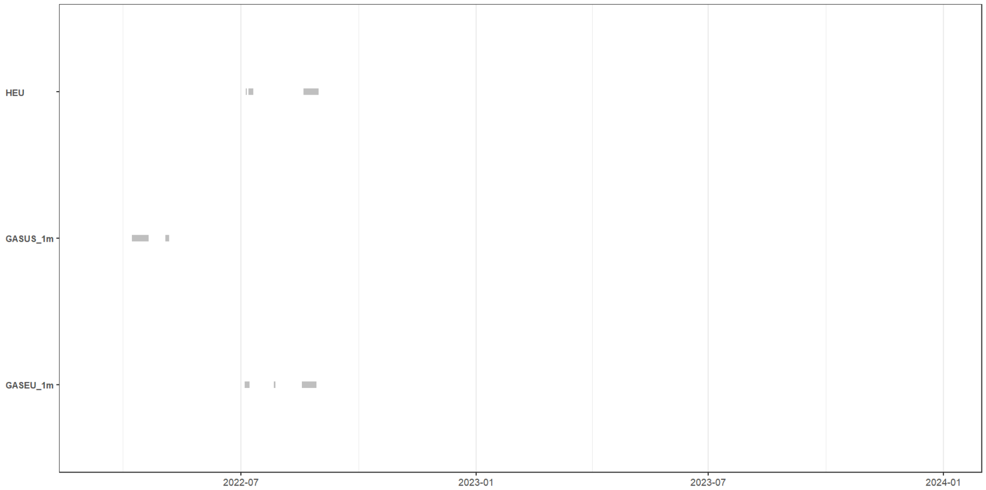

Figure A.20: Date-stamping on the basis of the BSADF statistic on daily series using MC critical values 10% significance level

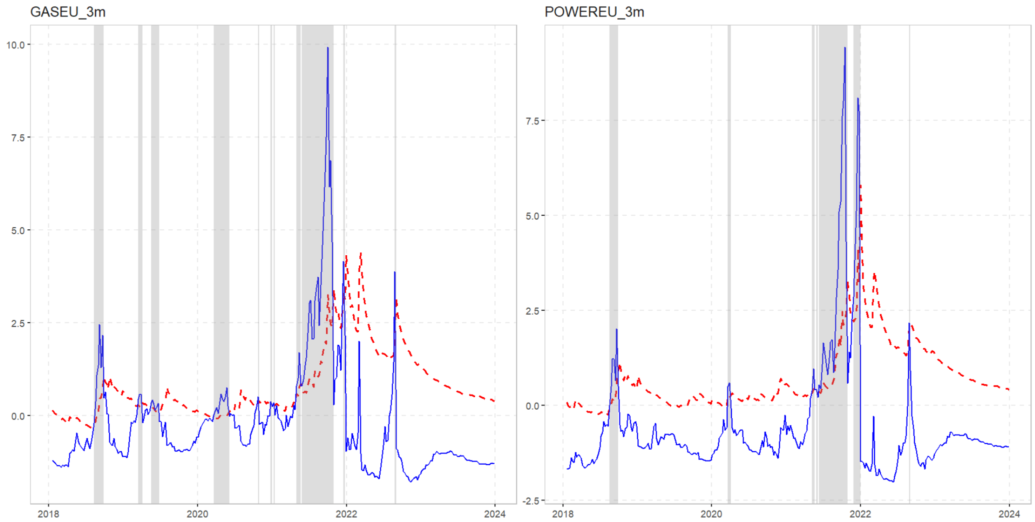

Figure A.21: Datestamping on the basis of the BSADF statistic for all series considered under the WB critical values (10% significance level)

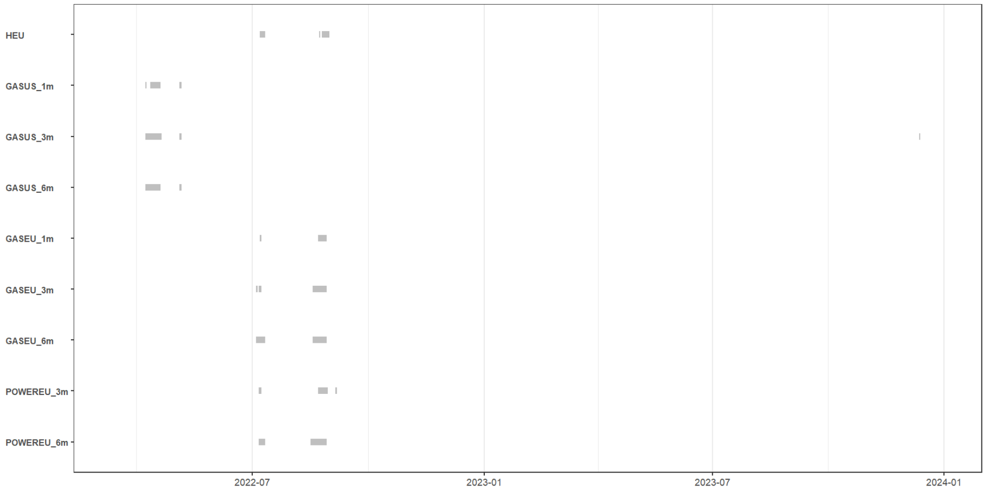

Figure A.22: Date-stamping on daily series using MC critical values 5% significance level

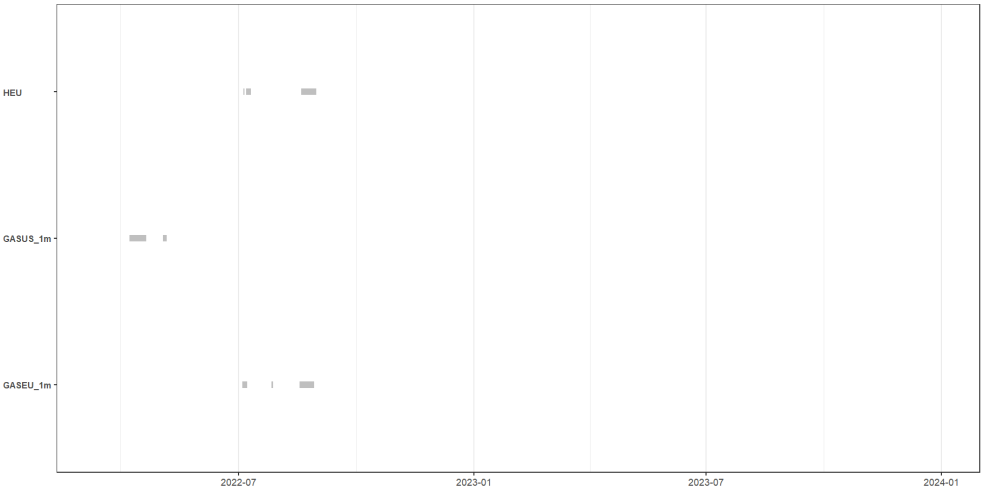

Figure A.23: Date-stamping on the basis of the BSADF statistic for daily series using MC critical values 10% significance level

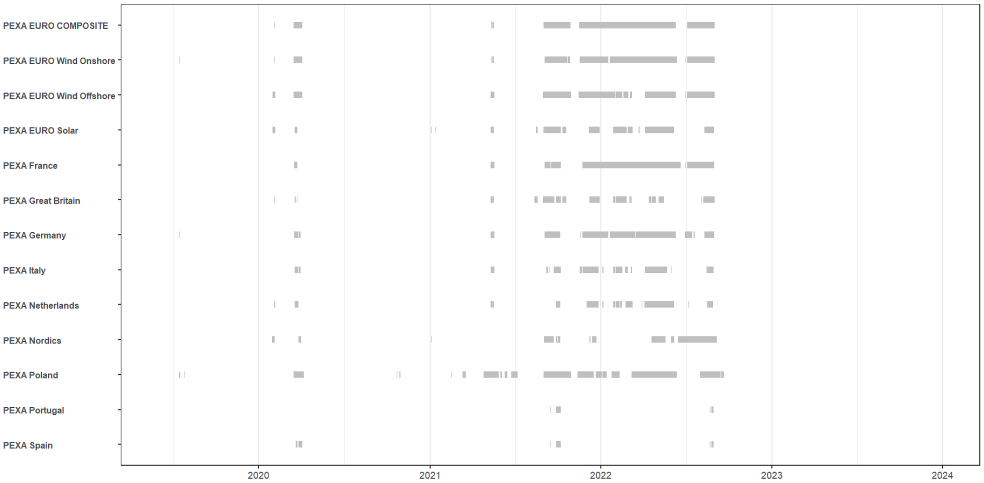

Figure A.24: Datestamping on the basis of the BSADF statistic for all daily PPA series considered under the MC critical values (10% significance level)

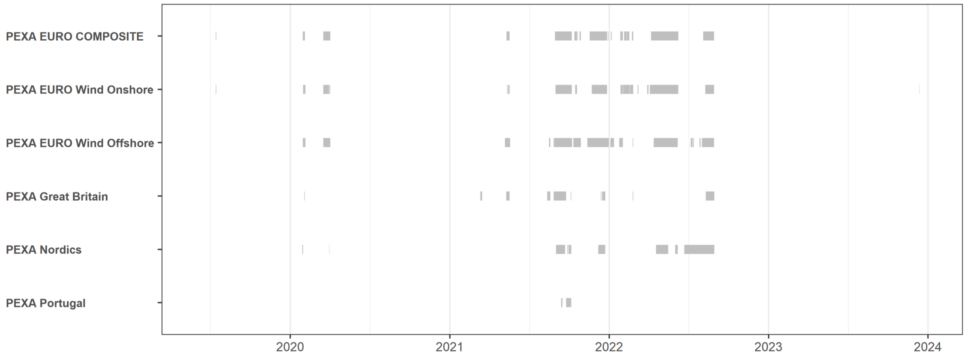

Figure A.25: Datestamping on the basis of the BSADF statistic for PPA series considered under the MC critical values (5% significance level)

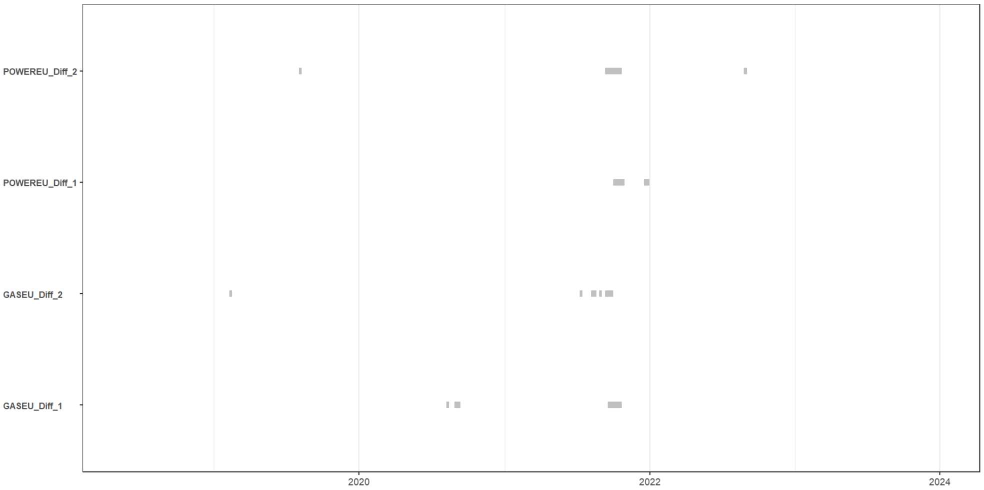

Figure A.26: Date-stamping mild explosivity in power differences using MC critical values 10% significance level

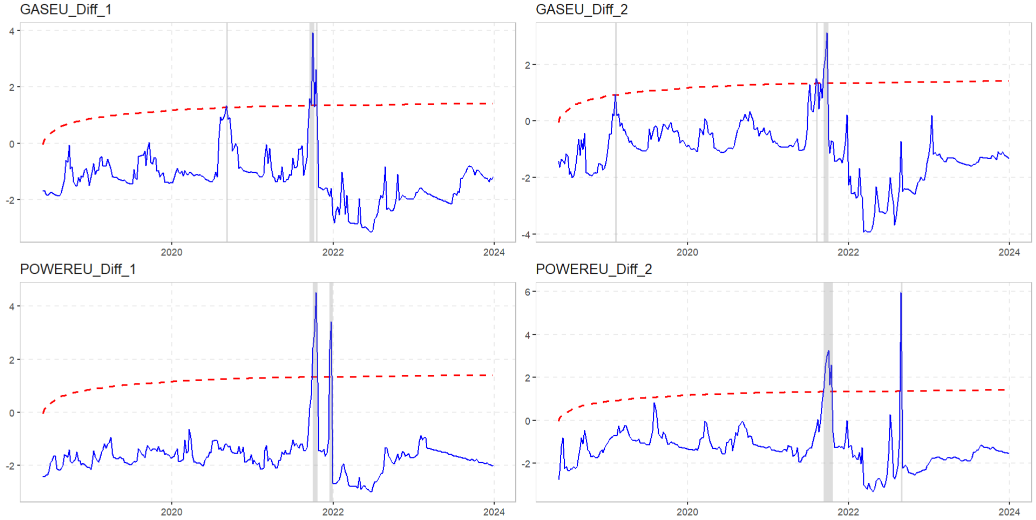

Figure A.27: Datestamping bubble behaviour in daily spot and futures price differentials with MC critical values (10% significance level)

Appendix B. Tables

Table B.18: Descriptive statistics for different PPAs

Variable	Mean	Median	Max	Min	Std.Dev	Skew	Kurt
PEXA EURO COMPOSITE	92.11	70.04	391.52	34.70	54.62	1.51	5.36
PEXA EURO Wind Onshore	86.44	64.82	361.60	34.17	50.15	1.58	5.50
PEXA EURO Wind Offshore	92.51	69.59	390.49	33.88	53.63	1.38	5.17
PEXA EURO Solar	99.12	78.21	472.28	27.35	66.94	1.57	5.82
PEXA France	99.39	66.23	591.12	34.28	76.00	2.00	7.59
PEXA Great Britain	114.59	81.09	608.65	29.58	85.91	1.91	7.74
PEXA Germany	101.48	76.55	392.31	34.29	61.12	1.25	3.88
PEXA Italy	85.36	61.86	349.27	32.04	48.71	1.23	4.75
PEXA Netherlands	85.52	62.95	403.09	30.74	53.61	1.69	5.79
PEXA Nordics	90.68	62.42	312.42	33.10	54.01	0.98	3.04
PEXA Poland	94.79	76.40	399.60	30.99	66.16	1.96	6.63
PEXA Portugal	54.15	51.82	109.46	28.92	14.23	1.06	4.59
PEXA Spain	50.94	47.90	104.53	26.48	14.00	1.00	4.31

[1] All metrics calculated from data in EUR

Table B.19: GSADF Statistic and significance levels for weekly series

		MC - cv level			WB - cv level		
Series	Gsadf stat.	90%	95%	99%	90%	95%	99%
GASUS_3m	3.005	1.891	2.137	2.618	3.922	4.524	5.883
GASUS_6m	3.471	1.891	2.137	2.618	4.067	4.901	6.595
GASEU_1m	8.926	1.891	2.137	2.618	7.687	8.954	11.913
GASEU_3m	9.961	1.891	2.137	2.618	7.726	8.772	11.311
GASEU_6m	7.029	1.891	2.137	2.618	7.93	9.341	12.097
POWEREU_1m	4.764	1.891	2.137	2.618	5.391	6.355	8.359
POWEREU_3m	9.442	1.891	2.137	2.618	7.487	8.766	11.556
POWEREU_6m	8.119	1.891	2.137	2.618	8.641	10.325	14.8

Table B.20: GSADF Statistic and significance levels for daily series

		MC - cv level			WB - cv level		
Series	Gsadf stat.	90%	95%	99%	90%	95%	99%
HUS	1.449	1.994	2.25	2.74	5.827	6.783	9.122
HEU	2.328	1.994	2.25	2.74	3.461	4.09	5.521
GASUS_1m	2.657	1.994	2.25	2.74	2.536	2.99	4.127
GASUS_3m	3.088	1.994	2.25	2.74	2.57	3.019	4.184
GASUS_6m	3.149	1.994	2.25	2.74	2.578	3.016	4.092
GASEU_1m	3.485	1.994	2.25	2.74	3.109	3.688	4.826
GASEU_3m	3.933	1.994	2.25	2.74	3.246	3.937	5.291
GASEU_6m	4.028	1.994	2.25	2.74	3.32	4.055	5.803
POWEREU_1m	1.965	1.994	2.25	2.74	2.787	3.241	4.288
POWEREU_3m	3.83	1.994	2.25	2.74	3.836	4.729	6.991
POWEREU_6m	6.969	1.994	2.25	2.74	5.697	7.147	10.34

Table B.21: GSADF Statistic and significance levels for differences series

		MC - cv level			WB - cv level		
Series	GSADF stat.	90%	95%	99%	90%	95%	99%
GASUS_Diff_1	0.625	1.896	2.142	2.623	3.847	4.402	5.586
GASUS_Diff_2	2.0159	1.896	2.142	2.623	3.447	4.038	5.106
GASEU_Diff_1	3.919	1.896	2.142	2.623	7.503	8.617	11.681
GASEU_Diff_2	3.1199	1.896	2.142	2.623	7.646	8.948	11.636
POWEREU_Diff_1	4.519	1.896	2.142	2.623	6.749	7.99	10.696
POWEREU_Diff_2	5.9719	1.896	2.142	2.623	8.169	9.941	13.667

Table B.22: GSADF Statistic and significance levels for PPAs series

		MC - cv level			WB - cv level		
Series	GSADF stat.	90%	95%	99%	90%	95%	99%
PEXA EURO COMPOSITE	8.772259	2.162016	2.381525	2.830428	6.653854	8.303277	12.26811
PEXA EURO Wind Onshore	8.610137	2.162016	2.381525	2.830428	6.530001	8.000117	11.42734
PEXA EURO Wind Offshore	9.587152	2.162016	2.381525	2.830428	6.713615	8.257983	11.87969
PEXA EURO Solar	7.091736	2.162016	2.381525	2.830428	6.172324	7.404254	10.58225
PEXA France	9.986478	2.162016	2.381525	2.830428	7.987268	10.05951	14.1011
PEXA Great Britain	7.694958	2.162016	2.381525	2.830428	6.313095	7.375723	9.647188
PEXA Germany	5.87008	2.162016	2.381525	2.830428	6.106207	7.502088	10.66209
PEXA Italy	6.465611	2.162016	2.381525	2.830428	7.277089	9.280255	14.20079
PEXA Netherlands	4.99622	2.162016	2.381525	2.830428	6.815918	8.316011	12.50927
PEXA Nordics	10.32348	2.162016	2.381525	2.830428	5.228373	6.535493	9.360744
PEXA Poland	6.258201	2.162016	2.381525	2.830428	6.218391	7.186884	9.327799
PEXA Portugal	5.293749	2.162016	2.381525	2.830428	4.481697	5.256278	7.410596
PEXA Spain	5.207379	2.162016	2.381525	2.830428	4.691444	5.493284	7.55546

Table B.23: PSY Multiple bubble test results for weekly EU gas future series (10% significance level)

	GASEU 1m		GASEU 3m		GASEU 6m	
	Bubble period	Duration (weeks)	Bubble period	Duration (weeks)	Bubble period	Duration (weeks)
	01/2018 - 01/2018	1	08/2018 - 09/2018	5	05/2018 - 06/2018	5
	09/2018 - 09/2018	1	10/2018 - 10/2018	1	08/2018 - 09/2018	5
	10/2020 - 10/2020	1	05/2021 - 05/2021	1	04/2021 - 10/2021	23
	01/2021 - 01/2021	4	06/2021 - 10/2021	20	12/2021 - 12/2021	3
	05/2021 - 05/2021	1	11/2021 - 12/2021	6	03/2022 - 03/2022	1
	06/2021 - 10/2021	20	03/2022 - 03/2022	1	08/2022 - 09/2022	3
	11/2021 - 12/2021	7	08/2022 - 09/2022	2		
	03/2022 - 03/2022	1				
	08/2022 - 09/2022	1				
Number of bubbles		9 (2)		7 (2)		6 (1)
Average duration		4.11		5.14		6.67
Max. Duration		20.00		20.00		23.00

Table B.24: PSY Multiple bubble test results for weekly US gas future series (10% significance level)

	GASUS 1m		GASUS 3m		GASUS 6m	
	Bubble period	Duration (weeks)	Bubble period	Duration (weeks)	Bubble period	Duration (weeks)
	11/2018 - 12/2018	5	11/2018 - 11/2018	2	07/2021 - 07/2021	1
	09/2021 - 10/2021	7	12/2018 - 12/2018	1	08/2021 - 08/2021	1
	11/2021 - 11/2021	1	08/2020 - 09/2020	2	09/2021 - 10/2021	2
	04/2022 - 04/2022	1	08/2021 - 08/2021	1	04/2022 - 06/2022	10
	05/2022 - 05/2022	1	09/2021 - 11/2021	10	08/2022 - 09/2022	2
	05/2022 - 06/2022	4	04/2022 - 04/2022	1		
			05/2022 - 06/2022	6		
Number of bubbles		6 (1)		7 (2)		5 (1)
Average duration		3.17		3.29		3.20
Max. Duration		7.00		10.00		10.00

Table B.25: PSY Multiple bubble test results for weekly EU Power future series (10% significance level)

	POWEREU 1m		POWEREU 3m		POWEREU 6m	
	Bubble period	Duration (weeks)	Bubble period	Duration (weeks)	Bubble period	Duration (weeks)
	07/2021 - 07/2021	2	08/2018 - 09/2018	4	06/2018 - 07/2018	2
	09/2021 - 10/2021	8	06/2021 - 07/2021	3	08/2018 - 10/2018	6
	11/2021 - 01/2022	9	07/2021 - 08/2021	3	05/2021 - 05/2021	2
	03/2022 - 03/2022	1	08/2021 - 10/2021	9	06/2021 - 10/2021	21
			11/2021 - 12/2021	8	12/2021 - 12/2021	2
			08/2022 - 09/2022	1	01/2022 - 02/2022	1
					03/2022 - 03/2022	1
					07/2022 - 09/2022	8
Number of bubbles		4 (2)		6 (2)		8 (3)
Average duration		5.00		4.67		5.38
Max. Duration		9.00		9.00		21.00

Table B.26: Multiple bubble test results for differences between future spot and future prices (10% significance level)

	GASEU_Diff_1		GASEU_Diff_2	
	Bubble period	Duration (days)	Bubble period	Duration (days)
	08/2020 - 08/2020	1	02/2019 - 02/2019	1
	08/2020 - 09/2020	2	07/2021 - 07/2021	1
	09/2021 - 10/2021	5	08/2021 - 08/2021	2
			08/2021 - 09/2021	1
			09/2021 - 10/2021	3
Number of bubbles		3 (0)		5 (0)
Average duration		2.67		1.60
Max. Duration		5.00		3.00
	POWEREU_Diff_1		POWEREU_Diff_2	
	Bubble period	Duration (days)	Bubble period	Duration (days)
	10/2021 - 10/2021	4	08/2019 - 08/2019	1
	12/2021 - 12/2021	2	09/2021 - 10/2021	6
			08/2022 - 09/2022	1
Number of bubbles		2 (0)		3 (1)
Average duration		3.00		2.67
Max. Duration		4.00		6.00