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"Price Bubbles in Lithium Markets around the World"

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Abstract

The global energy transition to low-carbon technologies for transportation is heavily dependent on lithium. By leveraging the latest advances in time-series econometrics we show that lithium prices (carbonate and hydroxide) have recently experienced market bubbles, particularly from the end of 2015 to the end of 2018, although in the case of European hydroxide we also date a bubble as recently as September 2020. Bubbles are accompanied by market corrections and extreme uncertainty which, in the case of lithium, may put at risk the future continuous supply needed for manufacturing lithium-based batteries for the electric vehicle. Governments and private stakeholders could reduce uncertainty imposed by these speculative dynamics, for instance, by establishing public stabilization funds and setting up capital buffers that help to diversify operational and market risks induced by a bubble bursting. Such funds should be ideally located in portfolios, such as the global stock markets or other energy commodities, which exhibit idiosyncratic bubbles unsynchronized with the bubbles observed in lithium markets.

JEL classification: Q21, N70, Q41, Q42.

Keywords: Speculative processes, Electric vehicle, Li-ion batteries.

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1. Introduction

Lithium mineral is a keystone for the global energy transition to low-carbon transportation[1]. Monitoring lithium prices is, therefore, of upmost importance for both governments and private stakeholders around the world. Prices are the means for markets to send coordinating signals for making optimal decisions on supply and demand. In the case of lithium, prices provide, among other signals, information required by lithium producers to decide how much investment should be secured to guarantee future availability of the raw mineral for its multiple stationary and transportation applications in the energy sector, where lithium-ion (Li-ion) batteries for electric vehicles (EVs) are its principle focus but also consumer electronics and starting-lighting-ignition usages are currently gaining momentum[2–4]. The importance of Li-ion batteries is only expected to increase in the coming decades due to the intermittency of wind and solar electricity generation which call for efficient ways of storage and the expected exponential growth of the EVs' market size, especially in China, Europe and the United States. Analysts project annual mobility storage demands in 2030 of between 1.5 to 3.0 terawatt-hours (TWh)[2], roughly fourfold the current size, with the demand for light-duty EVs dominating short-term projections[4].

Market prices of lithium might be failing to fully deliver the information that is expected from them. This urgently calls for innovative courses of action from all market participants, including governments, raw material producers and manufacturers of batteries that depend on the mineral as an input. As with any other commodity or market asset, the prices of lithium are subject to price "bubbles". A bubble is a situation that manifests itself in prices temporarily diverging from market fundamentals. When markets experience a bubble, prices are too high (positive bubbles) or too low (negative bubble) compared to what they should be, according to the underlying forces of supply and demand. Bubbles are almost always accompanied by market corrections (crashes) and extreme uncertainty[5], following on from phases of overheating, intense trading activity and speculation[6]. This can endanger the operation of entire industries and sectors and even the whole economy of a region or a country, as occurred after the bursting of the mortgage market bubble in the United States in 2007 which led to the Global Financial Crisis from 2008 to 2009.

Despite bubbles being self-evident from a historical perspective[5,7], they were declared to be impossible a few decades ago by the mainstream economics profession and were relegated to a marginal position in the study of financial markets, mainly because they did not fit well with the efficient market hypothesis according to which prices rarely reflect something

different than market fundamentals[8]. In opposition, recent advances in economics do not only acknowledge that bubbles are possible but also that they are at the core of financial crises and all sorts of macroeconomic imbalances[9]. Bubbles can arise for many reasons but the main explanations for bubbles are behavioral, especially in light of recent strong evidence contrary to the so-called "rational bubbles"[10]. Trading activity is subject to overconfidence and excessive extrapolation of market trends[6,11] which, in the case of lithium markets, mainly comes from its predominant role in the battery manufacturing industry for EVs. Bubbles may also persist as a consequence of market incompleteness and lack of coordination, which makes it impossible for market participants to react in time to the mispricing observed in practice[12].

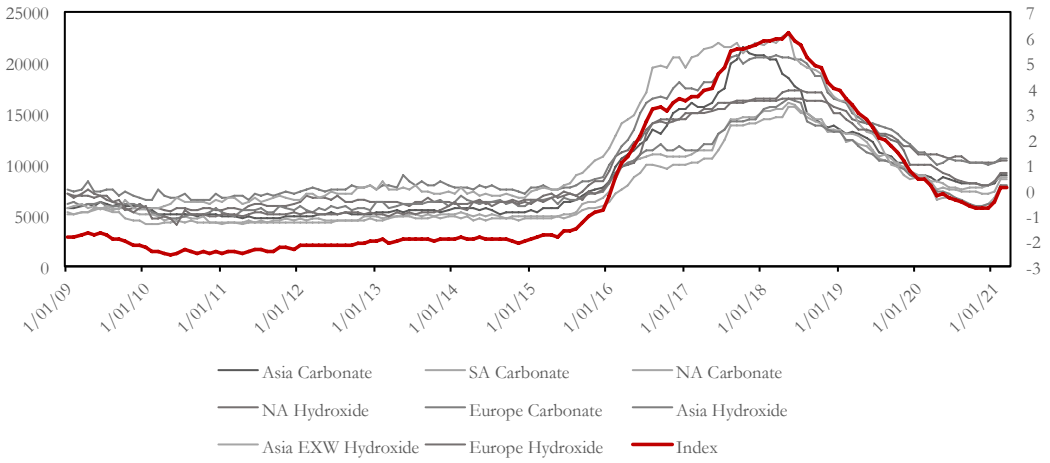
Acknowledgment of bubbles and, more importantly, of their ubiquitous presence in all kind of markets and asset classes has been accompanied by advances in time-series econometrics which have put forward empirical ways to monitor the origination and bursting of market bubbles in real time[13–17]. In what follows, by bringing in to play such recent advances in the energy field, we test the hypothesis that bubbles have been an important characteristic of lithium markets in recent years. Our results should be of interest to the numerous companies, municipalities and countries that are investing large resources in EV-charging infrastructure, product design and commercialization as well as European governments that have enacted strong policies to incentivize domestic manufacturing of Li-ion batteries, such as those relying on the two gigafactories planned to be located in Dourvin and Kaiserslautern in the near future[4]. Overall, our findings aim to significantly inform techno-economic analyses routinely carried out by the various stakeholders in the EV sector, bearing in mind that Li-ion cathode, anode and electrolyte materials account for 50%-70% of plug-in EV technologies battery costs[3].

Predicting the date for a bubble in real time is a challenge since, by definition, a good bubble indicator should balance observable dynamics of market prices and unobservable market fundamentals which include projections of future demand and supply, both of which are largely uncertain. Nevertheless, our modern understanding of bubbles implies that all bubbles (in all markets) share common features, the most evident being mildly explosive dynamics of the series of prices which is not totally supported by market fundamentals. Recent trends and future projections of the growing demand for lithium up to year 2030 explain the positive trend of lithium prices observed over recent years, but they do not explain the dramatic swings of lithium prices that have also been observed during the same

period (see Figure 1) with virtually no change in market fundamentals. For example, lithium has consistently gained importance over recent years, following the dominance of Li-ion batteries as the most representative and fastest-growing rechargeable battery segment, with global sales across all markets (stationary and transportation) that more than doubled between 2013 and 2018 and which are expected to increase by four- or five-fold by 2030[2,4].

Figure 1

Monthly prices in eight lithium markets around the world from February 2009 to March 2021



Note: Prices of eight lithium carbonate and hydroxide in Asia, Europe, North America and South America from February 2009 to March 2021. The red line is the first principal component of the original price series. Source: Own elaboration

We hypothesize that such extreme fluctuations are, in all probability, related to recurrent speculative dynamics and the ignition and bursting of bubbles in the lithium market. In what follows, by leveraging state-of-the-art techniques from time-series econometrics for identification and dating of bubbles, based on recursive supremum Dickey-Fuller statistics[13], we dynamically contrast the statistical hypothesis of a stochastic trend, describing eight different series of lithium prices against the alternative of explosiveness, the latter being archetypal of market bubbles. We find strong empirical evidence supporting our initial research hypothesis, i.e., there was a large bubble in the lithium market from late 2015 to the end of 2018 and in certain markets, such as European hydroxide, there were additional bubbles as recently as September 2020. Results here emphasize the need to closely monitor price dynamics in lithium markets. If bubbles emerged before, nothing prevents other

bubbles from emerging in the future. Our findings also call for innovative ways to promote market coordination, mainly seeking to isolate lithium production from the high degree of uncertainty induced by market bubbles and speculation. This can be achieved, for instance, by establishing a stabilization fund with public sources in regions, such as Europe, United States and China, that rely on lithium as a cornerstone for the decarbonisation of their economies and, in particular, of their transportation sector. Our results also emphasize the convenience of establishing capital buffers, similar to those conventionally found in the financial industry, to support mineral producers and consumers. Our methodology also allows establishing origination dates of bubbles in real time.

Public stabilization funds would help to reduce uncertainty on expected cash flows of lithium producers as lithium consumers would be able to (contractually) commit to minimum lithium prices, backed by public funds. These prices should cover investment expenditures in exploration and operation activities, essential for guaranteeing future availability of the mineral for its multiple transportation and consumer electronics applications. This is crucial because uncertainty significantly slows down firms' investment decisions and, in this case, it may put at risk the already tight timing for the energy transition of the transportation sector to low carbon technologies. The fund's financial resources should be ideally located in specific markets that do not tend to experience bubbles at the same time as the lithium market, thus helping to diversify the risk induced by the bubble bursting. Later, in section 4.2, we explore some alternatives in this respect. Finally, our results highlight the importance for governments and society to support fundamental and applied research on alternatives to Li-ion batteries (the so-called post-lithium technologies, such as sodium-ion batteries) even when such alternatives might seem, at first glance, too expensive or less than efficient, given the current dominance of the already mature infrastructure of the Li-ion battery's industry[18].

1.1. How do bubbles emerge and persist?

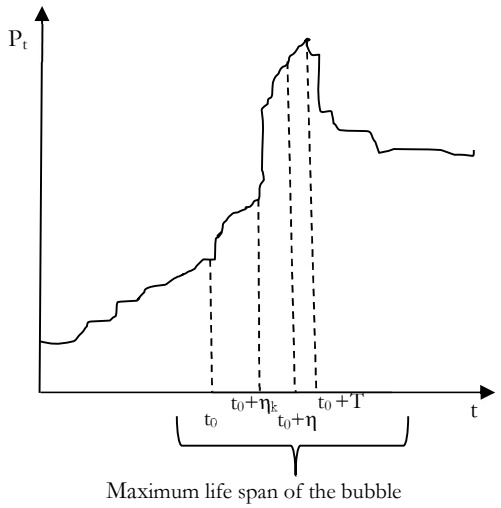
Recent theoretical contributions highlight the role of factors such as price extrapolation, overconfidence, market incompleteness and speculation for explaining market bubbles[6,7,11,12,19,20]. In particular, price extrapolation and speculation may play a major role, judging by the prominent characteristics of historical bubbles, especially those accompanied by excessively optimistic trading observed after the adoption of a new technology such as railroads or the Internet or, in our case, increasingly favorable expectations with respect to the massive adoption of the EV in the markets of Europe, US and China. Generally, after an economically beneficial innovation is seen accompanied by a sequence of positive news

related to fundamentals, traders overinflate their beliefs in the direction of the new state of the world, i.e., positive outcomes are overvalued in expectations while negative outcomes are neglected. This is followed by an increase in price growth which encourages buying which, in turn, leads to further price increments. In this way, prices reach levels substantially above fundamental values. Finally, the bubble collapses when good news becomes marginal and cannot sustain the overpricing any longer[6]. This results in a price crash provoked by the same extrapolative dynamics that contributed to forming the bubbles in the first place, generating dangerous negative bubbles before fundamental equilibrium is reached. One model that helps to articulate the elements outlined above in a slightly different way was proposed by ref.[12] who postulate that, in a market with rational agents, bubbles can emerge as a result of the interaction between behavioral agents and rational arbitrageurs. Behavioral agents base their portfolio decisions on fashions and sentiments, and show overconfidence in recent market trends. Rational arbitrageurs base their decisions only on fundamental information but this information is noisy and, even when rational traders believe the market will eventually collapse; they also want to ride the bubble for as long as it continues to grow and generate abnormally high returns. Rational arbitrageurs would prefer to exit the market before the crash but it is difficult to determine the perfect time to do so. The dispersion in exit strategies and lack of coordination are the causes underlying the bubble origination and persistence. The bubble finally bursts when a sufficiently high number of agents exit the market.

This process is depicted in Figure 4, where t_0 corresponds to a given random point at which the commodity price exceeds its fundamental value. From this point onwards, k arbitrageurs become sequentially aware that the price has surpassed its fundamentals until reaching the point $t_0+\eta_k$. However, some rational arbitrageurs do not know whether they have learned of this information before or after other rational arbitrageurs. Hence, information is not perfect. They face the decision of leaving the market or continuing to ride the explosive dynamics and gain abnormal returns. In this context, a coordination problem arises: the selling pressure only bursts the bubble (stopping the explosive dynamics) when a sufficiently large number of arbitrageurs decide to exit the market. Thus, a sharp change in the price is only possible if a sufficiently high number of agents (or some with a considerable market share) leave the market. At $t_0+\eta$, all market participants are aware that price dynamics are explosive. However, an exogenous event is necessary to stop the price surge, which is ended at $t_0+\tau$.

In the lithium market, we can date the first phase of the bubble as the end of 2015 when an increasing amount of good news about fundamentals, mainly regarding the massive and sooner-than-expected adoption of the EV in European markets, started to circulate in the press and in market reports. The second phase of speculative trading and learning about prices using extrapolative expectations likely took place from 2016 to 2017 and, finally, the bursting of the bubble is observed in all markets at the beginning of 2018, when the positive news was not enough to continue sustaining the price of lithium.

Figure 2. Formation and bursting of bubbles



Source: Own elaboration

2. Methodology

2.1. Bubble detection and dating

Ref[13,16,17] develop a Generalized Sup Augmented Dickey-Fuller (GSADF) method to test for the presence of multiple bubbles and a recursive backward regression technique to date the bubble origination and termination. GSADF tests rely on a recursive series of right-tailed ADF tests where, instead of fixing the starting point of the recursion on the first observation, the window of observations changes its sample size by changing the starting and the endpoints of the recursion on a feasible range of windows (see Figure 3).

Let us consider the following asset pricing equation:

$$P_t = \sum_{i=0}^{\infty} \left(\frac{1}{1+r_f}\right)^i E(U_{t+i}) + B_t, \quad (1)$$

where P_t is the price of the asset, r_f is the risk-free interest rate, U_t represents the unobservable market fundamental factors, and B_t is the bubble element. Since we are considering a commodity (lithium) price instead of equity prices, we have excluded the dividend term that is commonly encountered in Equation (1). $P_t^f = P_t - B_t$ is called the market fundamental, and B_t satisfies the following property:

$$E_t(B_{t+1}) = (1 + r_f)B_t. \quad (2)$$

When B_t presents the dynamics described in (2), the asset price is said to be explosive. When the observable fundamentals are at most I(1), empirical evidence of explosive behavior in asset prices may be used in order to infer the existence of financial exuberance or price bubbles. Naturally, model specification is important for estimation. It has potential impacts on the test critical values, whether intercepts, deterministic trends, or trend breaks are included (or not) in the alternative hypothesis. Other authors include a martingale null with a negligible drift[15], which is empirically realistic over long time periods. A model of this type can be written as:

$$P_t = dT^{-\eta} + \theta P_{t-1} + \varepsilon_t,\ \varepsilon_t \sim iid(0, \sigma^2),\ \theta = 1\,, \quad (3)$$

where d is a constant, T is the sample size, and the parameter η regulates the magnitude of the intercept and drift as $T \to \infty$. Solving for P_t in (3) leads to:

$$P_t = d\frac{t}{T^{\eta}} + \sum_{j=1}^{t} \varepsilon_j + P_0, \quad (4)$$

where dt/T^{η} corresponds to a deterministic drift. When $\eta > 0$, the drift is small relative to a linear trend; when $\eta > 1/2$, it is relatively small with respect to the martingale element of P_t. When $\eta < 1/2$, $T^{-1/2}P_t$ behaves asymptotically like a Brownian motion with drift. Specifically, for the test used in this study, we consider the case of $\eta > 1/2$, in which the order of magnitude of P_t is the same as that of a pure random walk.

The model specification in (4) is usually complemented with temporary dynamics in order to test for exuberance, as in standard ADF unit root testing for stationarity. The recursive approach involves a rolling window ADF style regression. Specifically, the rolling window regression sample starts from the r_1^{th} fraction of the sample (T) and ends at the r_2^{th} fraction of the sample, where $r_2 = r_1 + r_w$, and $r_w > 0$ is the window size in relative terms.

The empirical regression model takes the following form:

$$\Delta P_t = \hat{\alpha}_{r1.r2} + \hat{\beta}_{r1.r2} P_{t-1} + \sum_{i=1}^{k} \hat{\psi}_{r1.r2}^{i} \Delta P_{t-i} + \hat{\varepsilon}_t, \quad (5)$$

where k is the (temporary) lag order. The sample size in the regressions is $T_w = \lfloor T r_w \rfloor$, where $\lfloor . \rfloor$ is the floor function. The ADF statistic based on this regression is denoted by ADF_{r1}^{r2}. Basically, the GSADF consists of a repeated set of ADF regressions as in (5), conducted on subsamples of the data in a recursive fashion. This test allows the starting point in (5) to change within a feasible range from $r_2 - r_0$. [16] and defines the GSADF statistic as the largest ADF statistic in a double recursion over all possible ranges from r_1 and r_2:

$$GSADF(r_0) = \sup_{\substack{r_2 \in [r_0, 1] \\ r_1 \in [0, r_2 - r_0]}} \{ADF_{r_1}^{r_2}\}. \quad (6)$$

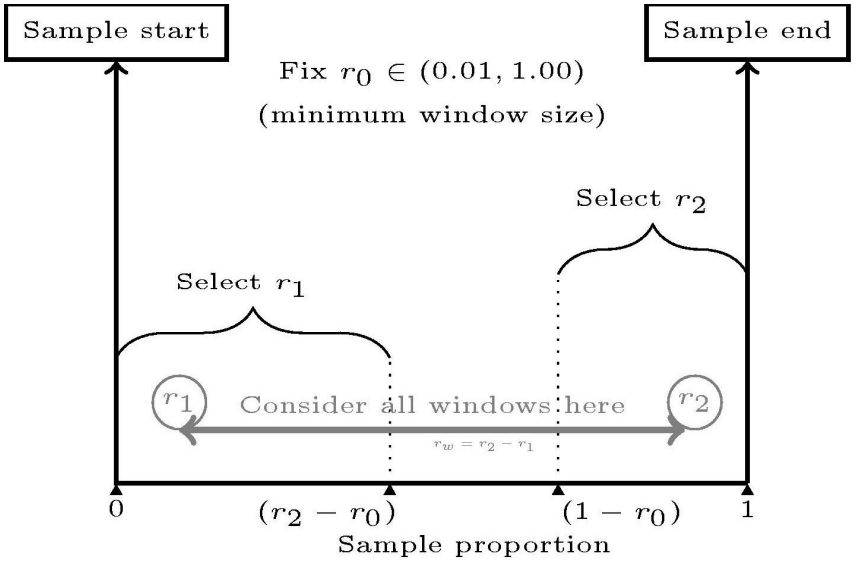
Based on extensive simulations, ref[16,17] recommend a rule for choosing r_0 that is based on a lower bound of 1% of the full sample $r_0 = 0.01 + 1.8/\sqrt{T}$.

The bubble detection test is based on a double recursive test procedure, called backward sup ADF (BSADF) test, which is designed to enhance the identification accuracy of the original statistic. Specifically, the BSADF test performs a sup ADF test on a backward expanding sequence in which the endpoint of each sample is fixed at r_2 and the start point varies from 0 to $r_2 - r_0$, as shown in Figure 3. The corresponding ADF statistic sequence is $\{ADF_{r_1}^{r_2}\}_{r1 \epsilon [0, r_2 - r_0]}$. The backward SADF statistic is written as:

$$BSADF_{r_2}(r_0) = \sup_{r_1 \epsilon [0, r_2 - r_0]} \{ADF_{r_1}^{r_2}\}. \quad (7)$$

The bubble origination date ($\lfloor T \hat{r}_e \rfloor$) is established as the first observation whose BSADF statistic is higher than the critical value[16].of the test. The ending of a bubble is dated as the first observation after $\lfloor T \hat{r}_e \rfloor + \delta \log(T)$ whose BSADF statistic falls under the critical value. For an exuberance episode to be considered as a bubble, its duration should exceed a minimal period represented by $\delta \log(T)$, where δ is a predetermined parameter that refers to the minimal duration of the bubble.

Figure 3. Sample sequences and window widths of the GSADF test



Source: Own elaboration

Formally, the origination and the ending points of a bubble are estimated according to the following formulae:

$$\hat{r}_e = \inf_{r_2 \epsilon [r_0, 1]} \left\{ r_2 : BSADF_{r_2}(r_0) > scv_{r_2}^{\beta_T} \right\} \tag{8}$$

$$\hat{r}_f = \inf_{r_2 \epsilon \left[\hat{r}_e + \frac{\delta \log(T)}{T}, 1 \right]} \left\{ r_2 : BSADF_{r_2}(r_0 < scv_{r_2}^{\beta_T} \right\}, \tag{9}$$

where $scv_{r_2}^{\beta_T}$ is the $100(1-\beta_T)\%$ critical value of the sup ADF measure based on $\lfloor T_{r_2} \rfloor$ observations. The GSADF procedure employs the backward sup ADF test for each $r_2 \epsilon [r_0, 1]$ and its inferences are based on the sup value of the backward sup ADF sequence $\{BSADF_{r_2}(r_0)\}_{r_2 \epsilon [r_0, 1]}$. Therefore, the GSADF statistics can be written as:

$$GSADF(r_0) = \sup_{r_2 \epsilon [r_0, 1]} \{ BSADF_{r_2}(r_0) \}. \tag{10}$$

2.2. Synchronization of bubbles

Novel to the literature, we propose to measure the level of synchronization between different lithium market price' bubbles and potentially between any other pair of commodities or

assets, by means of the following concordance statistic and assuming there is at least one bubble period:

$$\hat{I} = \sum_{t=1}^{T} S_{xt} S_{yt} / \sum_{t=1}^{T} S_{xt} \, . \quad (11)$$

For $\sum_{t=1}^{T} S_{xt} > 0$, where x_t and y_t are the series of prices of two market assets, and S_{xt} and S_{yt} are binary indicators that take the value of 1 and 0 depending on whether the market is in a bubble phase or not, respectively. The concordance index reads as the proportion of time that the two series were in a bubble phase, relative to the number of periods the first asset, x_t , was in a bubble phase. A value of one indicates that every period the first market was in a bubble, the second market was in a bubble too.

When $\sum_{t=1}^{T} S_{xt} = 0, \hat{I} \equiv 0$. Thus, a value of zero of the concordance statistic indicates that the two markets were never in a bubble at the same time.

3. Data and Results

3.1. Data and software

We use lithium contract prices for geographic regions retrieved by Benchmark Metals Inc., available at Bloomberg. Such contracts include negotiation prices of lithium carbonate and lithium hydroxide, selected according to their current and future relevance for the electric vehicle (VE). We consider: Asian lithium carbonate, hydroxide -Cost, Insurance and Freight (CIF) Swaps- and hydroxide -Ex Works (EXW) Swap-; European lithium carbonate and lithium hydroxide CIF swaps, North American lithium carbonate and lithium hydroxide CIF swaps, and South America lithium carbonate -Free on Board (FOB) Swap-. Our sample spans February 2009 to March 2021 and consists of monthly observations of the contract prices (147 observations). Table 1 shows lithium price descriptive statistics.

All the results were obtained using statistical software R, using the psymonitor package developed by ref. [13,14]

Table 1. Lithium swap contracts descriptive statistics (February 2009 - March 2021)

	Asia Carbonate	Asia Hydroxide	Asia EXW Hydroxide	Europe Carbonate
Max	21500.00	20750.00	23000.00	16500.00
Min	4725.00	6475.00	5600.00	4700.00
Mean	8816.16	10837.59	10608.42	8172.87
Median	6050.00	8050.00	7750.00	6375.00
Mode	4775.00	7450.00	6700.00	11500.00
Standard deviation	4729.99	4616.73	5542.78	3270.04
Kurtosis	0.25	-0.49	-0.38	-0.21
Observations	147	147	147	147
	Europe Hydroxide	**North America Carbonate**	**North America Hydroxide**	**South America Carbonate**
Max	16500.00	16000.00	17250.00	15750.00
Min	4050.00	4300.00	5400.00	4150.00
Mean	8850.51	7642.01	9488.10	7209.18
Median	6950.00	5400.00	6950.00	5250.00
Mode	5200.00	4850.00	5700.00	4250.00
Standard deviation	4126.67	3597.01	3996.44	3539.09
Kurtosis	-0.98	-0.56	-1.11	-0.32
Observations	147	147	147	147

Note: The table shows summary statistics for Asian lithium carbonate, hydroxide CIF Swaps and hydroxide EXW Swap, European lithium carbonate and lithium hydroxide CIF swaps, North American lithium carbonate and lithium hydroxide CIF swaps, and the South America lithium carbonate FOB Swap. The sample spans February 2009 to March 2021 and has a monthly frequency. Cost, Insurance and Freight (CIF) represent the delivered price going in to a particular region/country. Ex Works (EXW) is used to represent a domestically traded price with minimal shipping or transportation costs. Free on board (FOB) is used to represent the price out of an originating region/country.

3.2. Lithium Price Bubbles

Our results suggest that the spectacular price surge observed from 2015 to 2018 in all lithium markets is associated with speculative dynamics and bubbles. Duration and persistence of such bubbles differ across geographic locations and according to whether the market is for hydroxide or carbonate (see Figure 3).

On the left of Figure 3, the GSADF statistic estimated as in Equation (11) is plotted. Alongside the statistic, we present the critical values at 90%, 95%, and 99% of confidence (dotted lines). Every month that the GSADF statistic exceeds the critical value, lithium is said to exhibit a price bubble, i.e., to follow mildly explosive dynamics. The right column of Figure 2 shows the lithium contract price path and grey areas correspond to bubble phases at 99% level of confidence.

In the Asian market, the three contracts in our sample exhibited explosive dynamics simultaneously; such explosive dynamics are mostly concentrated between 2016 and 2018. For instance, the lithium carbonate price shows an explosive behavior from November 2015 to April 2018 with a total duration of 30 months. In the case of lithium hydroxide, the explosive dynamics took place from February 2016 to March 2018, lasting 27 months.

Analysis of the price dynamics of the Asia lithium hydroxide EXW reveals two periods of explosiveness during the sample. The first period extends from December 2015 to September 2017 and lasts 22 months. The second period spans September and November 2019. Note that the explosive performance in Asian lithium prices is more pronounced in 2016 and starts fading from 2017 onwards.

In the European lithium market, both lithium carbonate and lithium hydroxide prices exhibit explosive dynamics, albeit with a different duration. For instance, the lithium carbonate price follows an explosive path from February 2016 to September 2016 and resumes in July 2017, extending to July 2018. The two bubbles last 8 months and 13 months, respectively. However, lithium hydroxide prices display several periods of explosiveness. For instance, the first and longest period extends from March 2016 to December 2017 and lasts 22 months. Three shorter periods of explosive behavior take place from April 2019 to July 2019, from November 2019 to January 2020, and from June 2020 to September 2020.

Lithium carbonate and lithium hydroxide prices also exhibit explosive paths in the North American market. For lithium carbonate, a bubble lasting 31 months was observed between January 2016 and July 2018. The lithium hydroxide price showed explosive behavior for 33 consecutive months, from January 2016 to September 2018, and during a shorter period spanning November 2019 to January 2020.

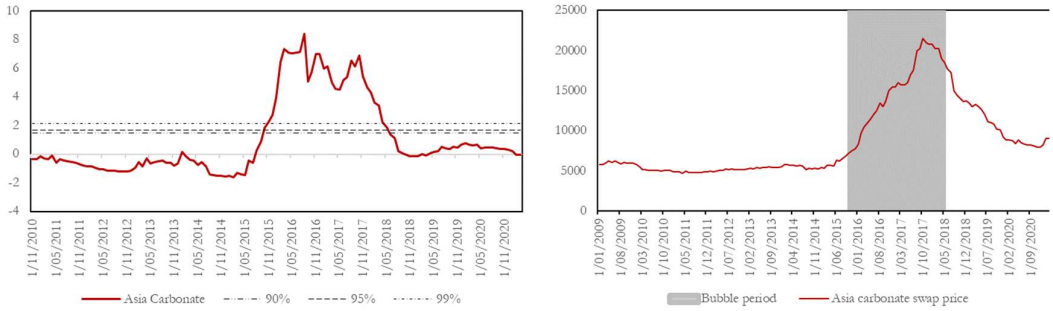
With respect to the South American lithium market, we analyze the dynamics of lithium carbonate using the information available. This price exhibits two bubble periods; the first period extends from January 2016 to October 2018, lasting 34 consecutive months, and the second period of explosive behavior takes place during April 2020.

In general, lithium prices in all the markets studied exhibit a sustained explosive pattern from the beginning of 2016 (or even late 2015) until the start of 2018. However, the persistence of explosive dynamics varies between markets and within types of lithium. The longest duration of a lithium bubble was recorded in the South American market (34 months for lithium carbonate). In the European market, the explosive processes took place during several periods; the longest periods being between 2016 and 2017, and the shortest at the end of the sample (2020).

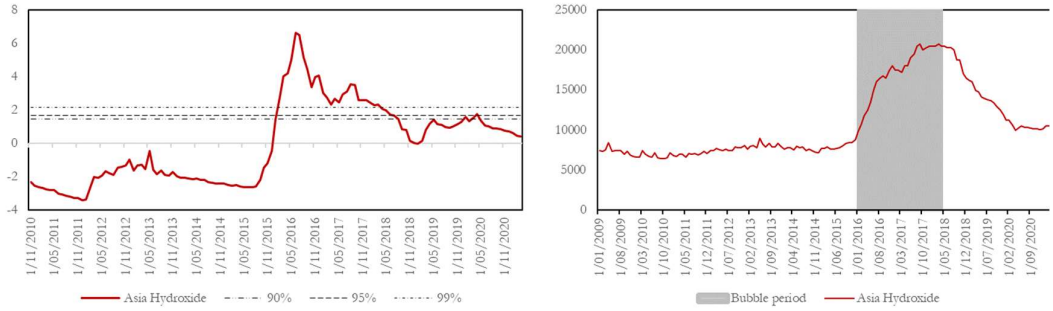
Figure 3. GSADF Statistics, Lithium price and explosive periods

Asia

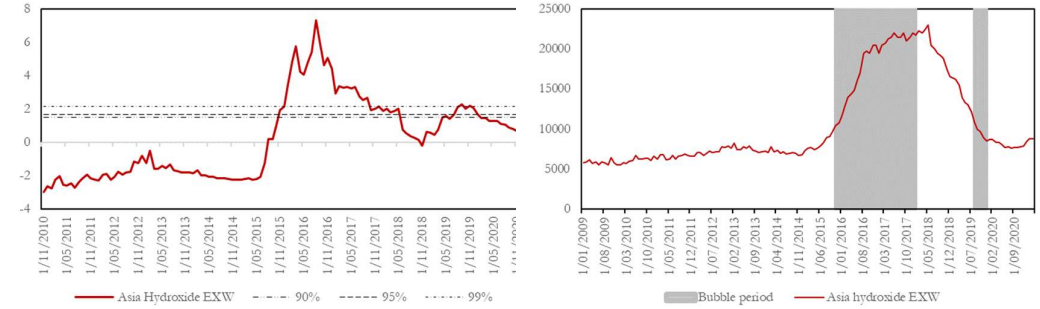
Carbonate



Hydroxide

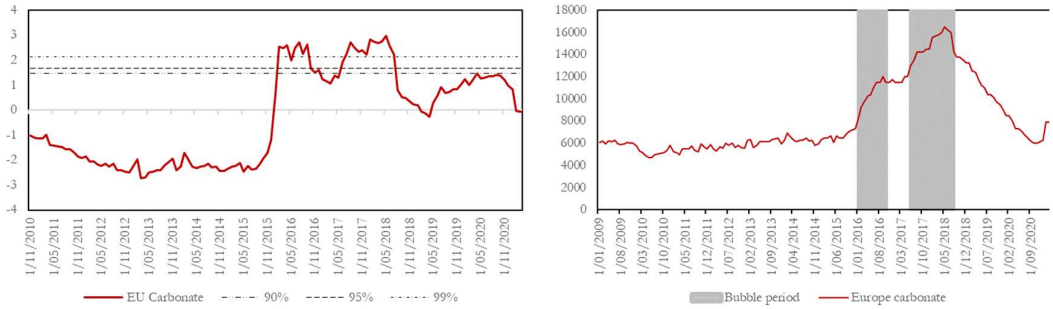


Hydroxide EXW

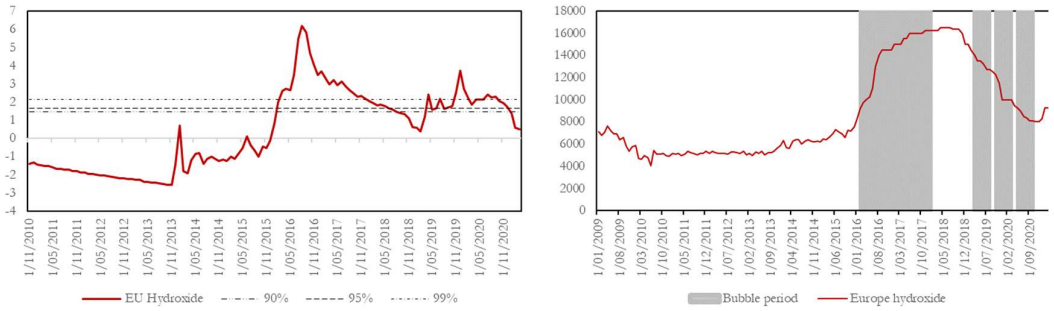


Europe

Carbonate

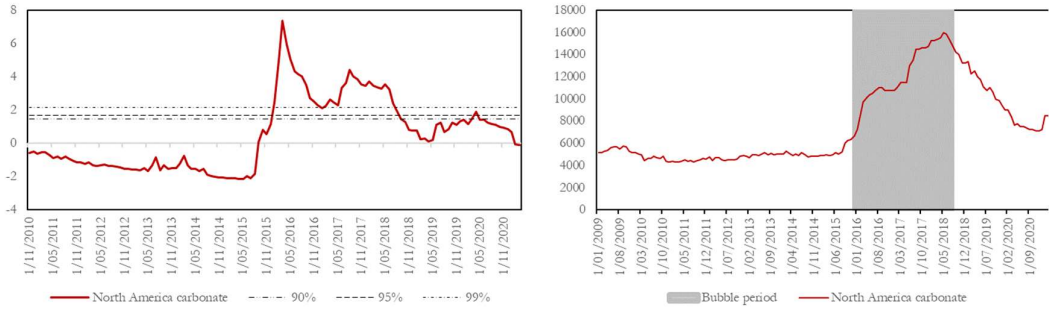


Hydroxide

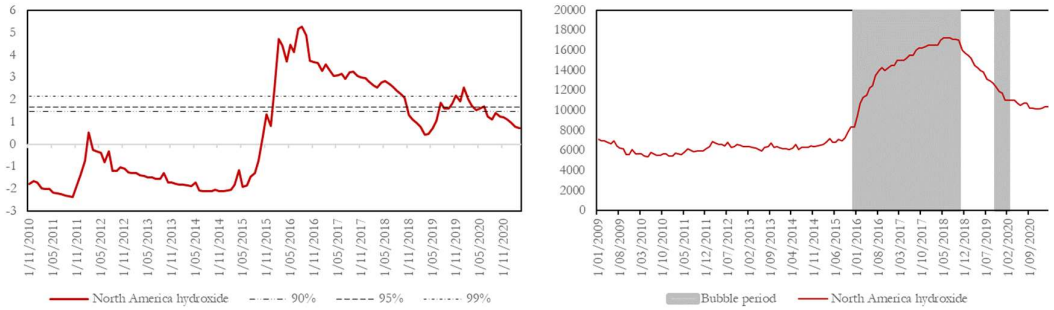


North America

Carbonate

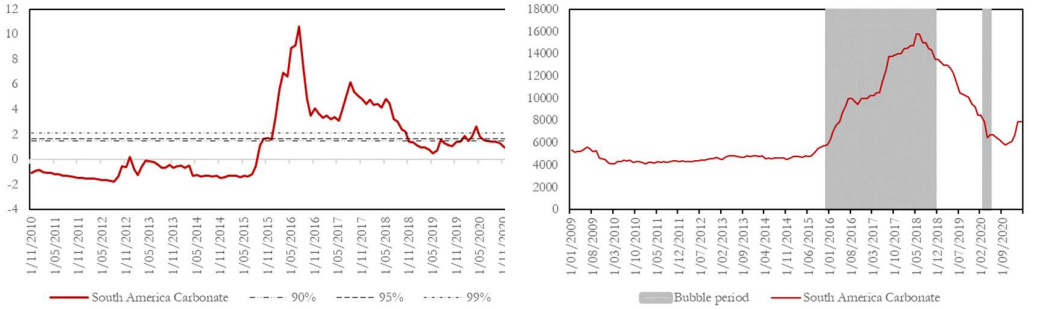


Hydroxide



South America

Carbonate



Note: On the left of the figure are plotted the GSADF statistics estimated according to Equation (11), and the test's critical values at 90%, 95%, and 99% of confidence. When the value of the statistic is greater than the value of the associated critical value, the lithium price is said to experience a bubble phase. Right column: the line corresponds to the lithium contract prices. The grey area corresponds to the period in which, according to the GSADF statistic (left column), the lithium price presented explosive dynamics at 99% confidence level.

3.3. Synchronization of bubbles

In Table 2, we present the concordance statistic between the bubbles of the 8 lithium markets in our sample. As can be seen, the bubbles identified in all 8 markets exhibit a high level of synchronization. There are several pairs for which the concordance statistic reaches 1, meaning that the bubbles identified for the market indicated in the first column of Table 2 occurred at the same time as the bubbles identified in other markets indicated in the first row of the table. For instance, Asia hydroxide bubble occurred at the same time, for 100% of the time, as the Asia carbonate bubble. However, the table is not symmetric. Using the same example, we note that the Asia carbonate bubble only intercepts with the Asian Hydroxide bubble for 87% of the months. This occurs because the bubbles do not have the same duration in months. The minimum value in the table is 57%, which corresponds to the percentage of time that the Asia carbonate's bubble overlaps with the EU carbonate bubble.

Table 2. Concordance statistics between the bubbles identified in the eight lithium markets

	Asia Carbonate	Asia H. Exw	Asia Hydroxide	EU Carbonate	EU Hydroxide	NA Carbonate	NA hydroxide	SA Carbonate
Asia Carbonate	1.00	0.77	0.87	0.57	0.73	0.90	0.93	0.93
Asia Hydroxide exw	0.92	1.00	0.84	0.44	0.84	0.84	0.92	0.88
Asia Hydroxide	1.00	0.81	1.00	0.62	0.85	0.96	1.00	1.00
EU Carbonate	0.85	0.55	0.80	1.00	0.60	1.00	1.00	1.00
EU Hydroxide	0.69	0.66	0.69	0.38	1.00	0.66	0.75	0.69
NA Carbonate	0.90	0.70	0.83	0.67	0.70	1.00	1.00	1.00
NA hydroxide	0.80	0.66	0.74	0.57	0.69	0.86	1.00	0.94
SA Carbonate	0.80	0.63	0.74	0.57	0.63	0.86	0.94	1.00

3.4. Other markets and alternative investments for lithium stabilization funds

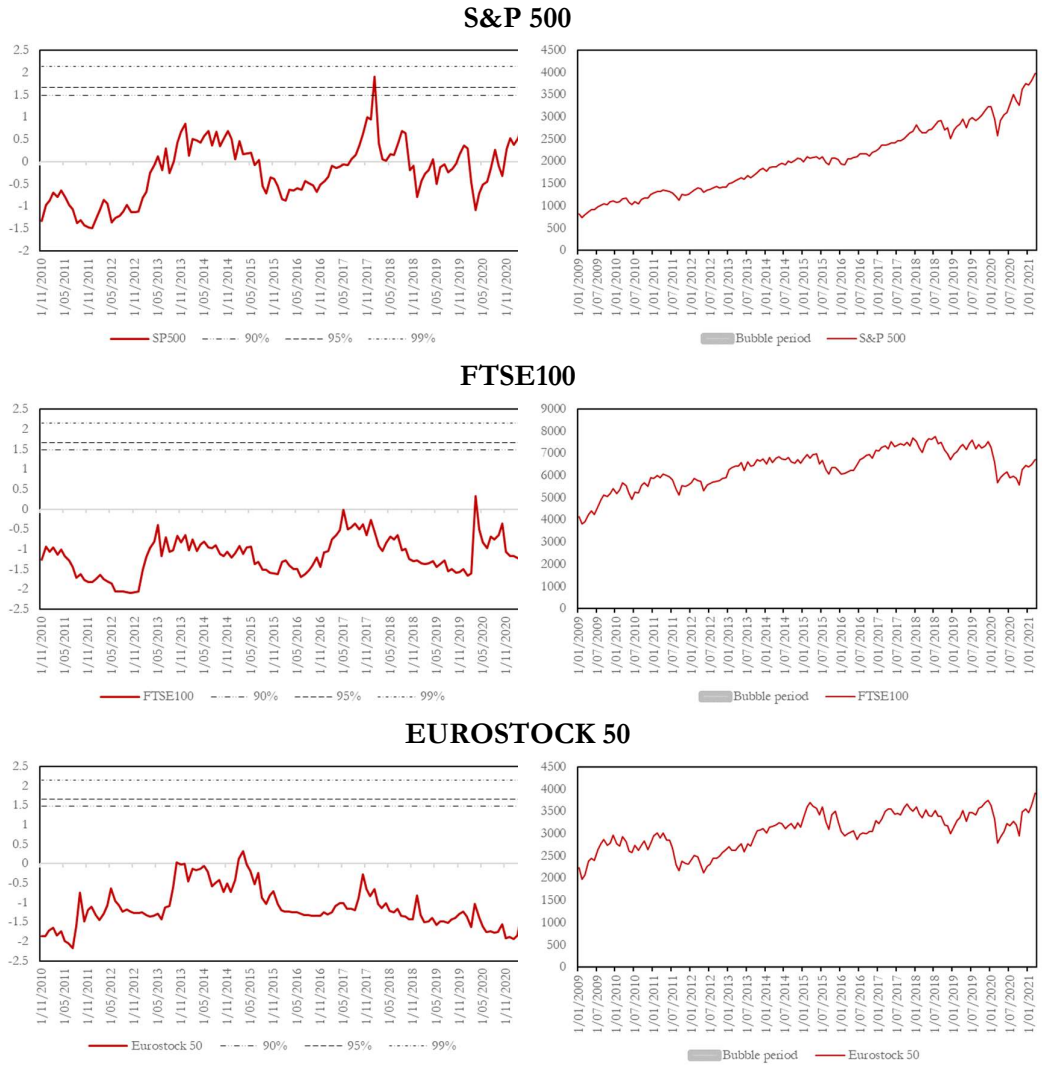
We test for the presence of bubbles in some global stocks and commodities markets that could serve as investment alternatives in the event that a stabilization fund for the lithium price is established. The analysis is carried out for the same sample period as before. For stock markets, we examine the price dynamics of the American, European and Asian stock markets through the following reference price indices: S&P 500 index, FTSE100 and Eurostock 50 indices, and the Asian Nikkei 225, Hong Kong Hang Seng, and TOPIX indices. In the commodity markets, we analyze exuberant price dynamics of benchmark oil prices, namely the West Texas Intermediate (WTI) and the Brent blend. We also test for explosiveness of gold and silver spot prices under the assumption that such metals can serve as value reserve in a portfolio.

Our estimates presented in Figure 3 indicate that during 2009 and March 2021 the stock markets indices included in our sample did not experience bubbles, contrary to lithium price dynamics described in the previous section. In terms of commodities, we document

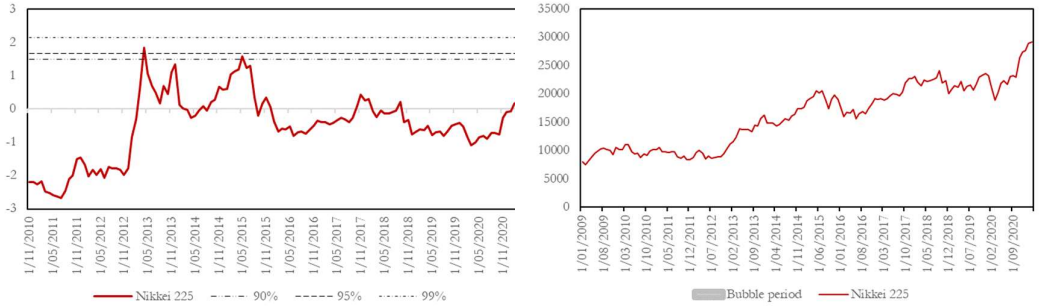
exuberant price behavior for short periods which do not coincide with explosive price dynamics in any of the lithium markets analyzed before. For instance, the WTI presents a bubble period between December 2014 and January 2015, the BRENT oil price from November 2014 to January 2015, the gold spot price exhibits explosive behavior from July 2020 to August 2020, and the silver spot price in April 2011.

Only in the case of European hydroxide, which experienced an overlapping bubble with the short bubble identified in gold (2 months), was the concordance statistic different to zero (0.0625). In all other cases, the synchronization of bubbles from the perspective of lithium markets was estimated at zero.

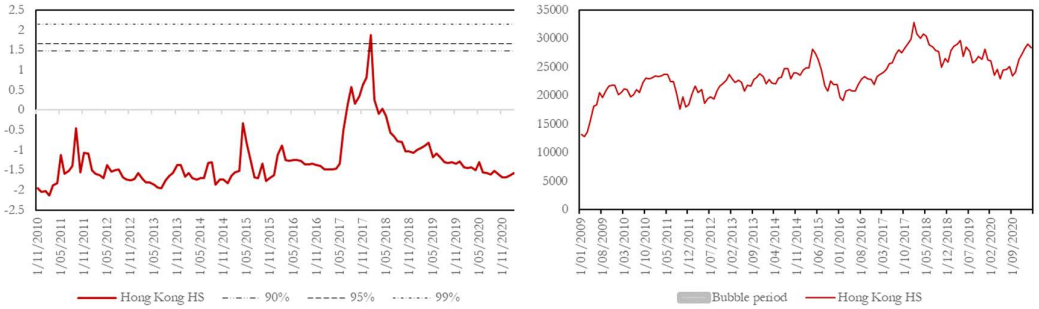
Figure 3. GSADF Statistics, Lithium Price Stabilization



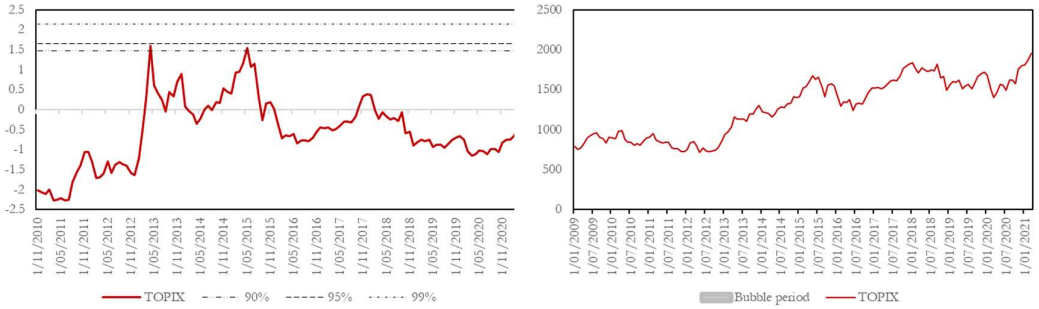
Nikkei 225



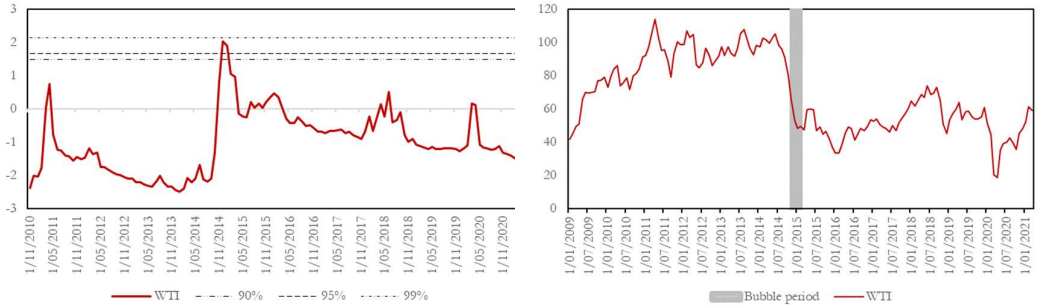
Hong Kong Hang Seng

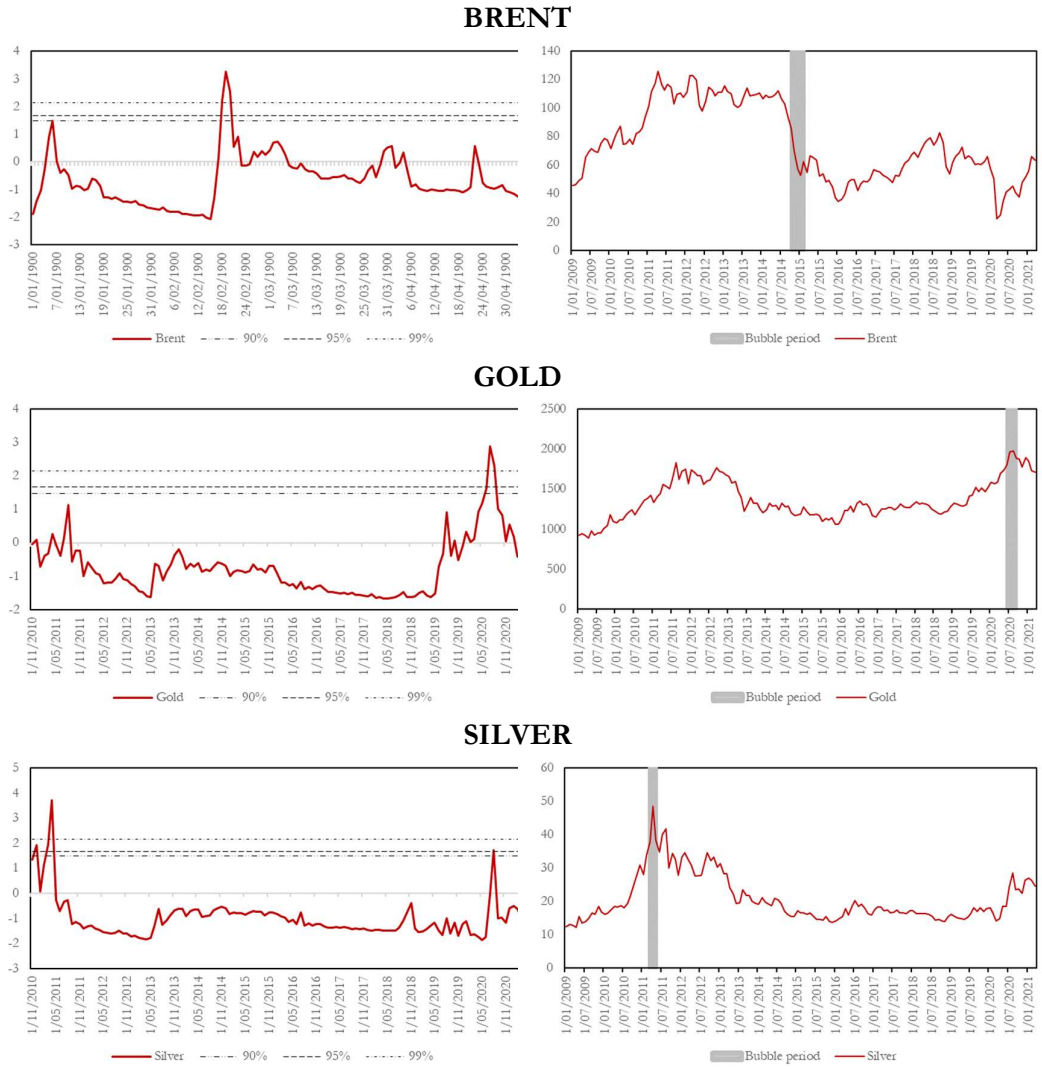


TOPIX



Commodities
WTI





Note: On the left of the figure are plotted the GSADF statistics estimated according to Equation (11), and the test's critical values at 90%, 95%, and 99% of confidence. When the value of the statistic is greater than the value of the associated critical value, the lithium price is said to experience a bubble phase. Right column: the line corresponds to the lithium contract prices. The grey area corresponds to the period in which, according to the GSADF statistic (left column), the lithium price presented explosive dynamics at 99% confidence level.

4. Discussion

Bering in mind the recent literature in which speculation and extrapolative expectations are proposed as the main factors behind bubble formation, in subsection 4.1, we examine the debate in the field regarding the existence of bubbles in the market of lithium. Our results clearly favor the hypothesis of a bubble (indeed, several for some lithium prices). Finally, we close this section by offering policy advice and risk management recommendations based on the synchronization results presented at the end of section 3.

4.1. Bubbles and lithium markets

Our contribution is related to a debate that took place a few years ago in the energy field, and which has been revived in recent years following the significant decline in lithium prices observed from 2018 onwards (see Figure 1). On the one hand, a branch of studies attributed a lithium price surge in the mid-2010s to lithium shortages, supply-demand imbalances, and production delays. On the other hand, speculative investors and the appearance of market bubbles have also been blamed for lithium's price booms. Within the former set of advocates, several questions have been raised about lithium reserves and availability. Such questions involve the possibility of a global lithium shortage, with a supply unable to match a growing demand. The more popular reasons claimed by analysts to explain the rapid price increase include a supply squeeze of the lithium exported to China, growing long-term demand from start-up and established EV manufacturers, and a growing market for portable electronic devices [21–24]. In the same vein, it has also been stated that this price surge was due to a consumption – production imbalance [25], following a rapid consumption growth of lithium battery applications.

However, the possibility of a lithium shortage has been ruled out by other authors[26]. According to this view, lithium is readily available on Earth and, furthermore, the world could triple its production from current levels and still have 135 years of supply available using solely known reserves. An alternative explanation suggests the reporting role of the financial press[27–29], which named lithium as the hottest commodity and documented that its demand was rising spectacularly as well as the demand for lithium-related securities, offering higher than average returns to investors.

4.2. Policy and risk-management in the face of bubbles

Results in section 4 show that there were bubbles in the 8 lithium prices considered here. Moreover, these bubbles were synchronized with each other, meaning that bubbles across various lithium markets tend to emerge (and burst) simultaneously. This is very inconvenient from a risk management perspective because risk is poorly diversified when simultaneous bubbles originate and collapse in multiple assets or inputs at the same time. Unfortunately, the economics profession has little to say about risk-management when dealing with market bubbles, and even less if such bubbles are highly synchronized with each other. The few advances of the discipline in this direction have focused on trading and on generating models for prediction of market corrections and crashes[20], but have said little about how to hedge against the risk of bubble inflation and bursting. The literature has traditionally, and consistently, relegated policy action in the face of bubbles to "wait until the market corrects

itself'. This was clearly the case after the dot.com bubble of technological firms that ended in 2002 in the US NASDAQ market. However, the Global Financial Crisis, and the dramatic bursting of the mortgage market bubble that preceded the crisis, pointed to the greater dangers of the "cleaning up the mess" approach only after a bubble has burst. Following the financial crisis, there have been some attempts to provide the means to understand and manage financial bubbles when they appear, mostly from a macroeconomic perspective. More in line with the scope of our study, one of the few studies that has examined those characteristics which make a firm more resilient in the presence of bubbles[9] focuses on financial institutions. It seems that larger banks, a stronger maturity mismatch and higher loan growth tend to make financial institutions, and hence the financial system, more vulnerable to systemic risk as a consequence of market bubbles. Unfortunately, such attributes do not extrapolate to lithium producers and consumers, who belong to a different industry which is considerably less cyclical than banking.

Our approach is different. We stress that the main issue regarding the presence of bubbles in lithium markets is related to the high degree of uncertainty that accompanies their inflation and bursting. Uncertainty is known to reduce investment[30]. When in an uncertain environment, firms optimally decide to delay investment until after uncertainty has passed. In the case of lithium, such a strategy is suboptimal from a societal perspective, given the large implications that a lithium shortage would have for the transition of the transportation sector to a low-carbon technology, especially in Europe, China and the United States. One way to reduce the uncertainty related to lithium prices and future cash flows of lithium producers is by setting minimum prices in advanced for buying lithium, by means of derivative contracts (e.g. options). These minimum prices should be high enough to cover investment expenditures by lithium producers, which are needed to guarantee an increasing supply of lithium in the forthcoming decades. Moreover, in countries relying on Li-ion batteries for their energy transition, stabilization funds could be established that would be used in case spot prices ended up being lower than prices projected by lithium producers. These funds could, in such an event, pay the market differential between the observed spot price at the time of delivery and the contracted price of lithium set at the time of investment in exploration and extraction.

The important question remains as to where these funds should be located. In this case, instead of resorting to a traditional portfolio optimization perspective to solve the problem of capital allocation, we explore some traditional investments, which have historically

depicted low synchronization with bubbles in the lithium markets. The general idea is to reduce the presence of simultaneous bubbles in the portfolio (treating lithium as an asset), given the inherent difficulty in forecasting in real time when a bubble will end[20]. In this case, our results highlight the lowest synchronization of bubbles in lithium markets with all traditional portfolios, including stocks, precious metals and oil. The kind of analysis conducted here does not aim to be comprehensive; indeed, other market assets may (and must) be explored. Ideally, where public funds and capital buffers are to be located depends on the specific stakeholder's asset-liability structure. Our aim is to provide a way of conducting this crucial part of techno-economic analyses which has so far been overlooked.

5. Conclusion

Using recent advances in time-series econometrics, we test for the hypothesis of explosiveness related to the origination and collapse of bubbles in several lithium markets over recent decades. Our results provide evidence of the existence of bubbles in all markets analyzed, albeit with different durations. Our results are of importance for governments and numerous private stakeholders who rely on the electric vehicle as an alternative to current transportation modes based on fossil fuels. The presence of speculative dynamics in the lithium market that we document here could limit access to the mineral for energy developers, jeopardize the popularization of the electric vehicle and the improvement of storability of electricity, which is key for the development of low-carbon societies. Thus, our results call for closer monitoring of lithium prices which, along with limitations of short-selling positions in the market, an increase in market transparency practices, and an improvement in communication platforms, could benefit from the setting up of stabilization funds backed by public sources to reduce uncertainty in cash flows for lithium producers. These public policy strategies need to be complemented by private counterparts with greater use of derivative contracts in the sector, and the establishment of capital buffers to avoid insolvency or illiquidity by lithium producers. These funds should be ideally invested in traditional assets, such as stock indexes, which do not tend to experience market bubbles at the same time as lithium does, thus helping to diversify the risk of bubbles bursting. Overall, findings here call for policy measures able to safeguard the global transition to low-carbon energy transportation which, currently, is heavily dependent on lithium.

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