PERSISTENCE IN SILVER PRICES AND THE INFLUENCE OF SOLAR ENERGY

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Abstract

This paper deals with the analysis of silver prices and the influence of solar energy on its behaviour. For this purpose, the analysis uses long memory methods based on fractional integration and cointegration. The results indicate that the two variables are very persistent, though any long run equilibrium relationship between them is not observed. Nevertheless, the results illustrate some short-run negative effects from solar energy capacity on silver prices.

Keywords: Silver prices; solar energy production; persistence; fractional integration

JEL Classification: C22; E30; Q40

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1. Introduction

This paper deals with the analysis of the statistical properties of silver prices and the influence of solar energy on its behaviour. The demand for silver is becoming one of the driving forces of the photovoltaic energy sector. Silver's unique reflective and conductive properties make it a key component in capturing and generating electricity through sunlight. The fastest growing industrial segment for silver has been its use in photovoltaic panels for solar energy. This has led to an increase in the demand for solar energy usage becoming a key component in the silver market (Maxwell Gold, 2017).

According to the London Silver Fixing of London Bullion Market Association (May 2020), a 10-year return of 25.26% is expected in the silver market by mid of July 2020, while the percentage returns are 298.46% and 277.62% at a 20-year and 30-year return horizon, respectively. Following the International Energy Agency (IEA, May 2020), by 2050, renewables are expected to generate 85% of total energy, with photovoltaic energy being the one to provide the cleanest energy source.

The first applications of solar power, photovoltaic cells, date from the decade of the fifties in the twentieth century, during the space race. Nowadays, it is still one of the energies used in earth orbit satellites (Perlin, 1999). Aiming to bring down related costs, in the 60s, the US chemist Robert Berman managed, through the manipulation of silicon, to significantly reduce the manufacturing cost per watt from $100 to $20. Today, the cost of the production has fallen below one dollar/W (Fraunhofer ISE, 2015). Progress and cost reductions have made photovoltaic energy the most commonly used in many sectors, including telecommunications, home appliances, electric and hybrid engines. The largest producer in the world is China with an installed power of more than 170 GW in 2019 (Global Market Outlook, 2018). This growth is explained by the decrease of the manufacturing sector and the commitment of the Chinese government to ensuring that solar energy can replace other non-renewable energy sources (i.e., coal and gas) in the near future, while allowing for greater energy independence.

The fight against climate change is one of the priorities for most countries throughout the world. In 2015, the Paris agreement (Jäger-Waldau, 2017) was signed establishing a global plan of action that has put targets on global warming of below two degrees of Celsius. In 2019, within the framework of the World Economic Forum, building a sustainable society was marked as one of the main objectives, and the use of renewable energy as a crucial element for environmental sustainability was encouraged. In this context, Antonio Guterres (United Nations Climate Change, 2019), the ONU Secretary General said: *"that climate change is the biggest global systemic threat in relation to the global economy and that requires a unified response in the form of inclusive multilateralism that involves all parts of the society."*

In 2017, the investment in clean energy grew by 2%, with the bulk of this increase occurring in the solar energy sector, which attracted the largest number of investments: 161 billion dollars in 2016 and a growth rate of 18% in 2018. (BNEF, 2019). Implementing policies to prevent climate change from occurring is also a big concern for governments, especially since the Paris agreement. The option of renewables has led to an increase in the global demand for silver. Most of this demand comes from China, the US, and India. China is the country with the biggest demand for silver and the one which invests the most money into solar energy, seeking to reduce pollution while meeting the growing global demand for energy. According to data from Reuters GFMS, it is expected that this Asian giant's demand for silver will be around 50 million ounces in 2020. (Thomson Reuters, 2017). At the same time, silver prices are primarily determined by demand and supply conditions in the solar panel industry and as long as there is a lack of any technology that can replace silver as the main ingredient in solar panels the long-term trends in the demand for silver are expected to result in a strong price, given that the supply conditions will not be sufficient to satisfy demand (Gold, 2017).

The interest is not only due to environmental but also to economic reasons. Photovoltaic is relatively cheap energy. The International Renewable Energy Agency (IRENA) has estimated that in 2020, the price of energy production in large solar power plants could fall approximately three cents per kWh in many regions around the globe. Therefore, photovoltaic energy is clean and affordable. Furthermore, the industrial demand for silver increased from 79.3 million ounces in 2016 to 94.1 million ounces in 2017, which has led to an increase in prices by 9% since the beginning of 2016. According to Wood Mackenzie (2019), the capacity of energy photovoltaics will increase up to 116,3 gigawatts in 2023. There will undoubtedly be a strong increase in the demand for silver as each solar panel uses between 2/3 oz. to 7/8 ounce of it. Silver's reflective and conductive properties make it an essential component to obtain electricity from solar panels.

Given the above discussion, the goals of this paper are twofold. First, following the works by Gil-Alana et al. (2015), Cunado et al. (2019) and others on persistence in silver prices, it examines the statistical properties of the silver prices, for the time period 1990q1–2016q4, in order to know the level of persistence of the data. In doing so, we will be able to determine if shocks in the series have permanent or transitory effects. The analysis is carried out by fractional integration, which is very appropriate in the sense that it is more general than other standard methods based on integer differentiation. However, unlike these previous works, we focus exclusively on the level of persistence of the data, not looking at other features, like the cyclical patterns. Second, and following here the work by Apergis and Apergis (2019), it attempts to link any evidence of persistence to the role of solar production and capacity, given that the solar industry is the primary absorber of silver in international markets. For this second goal, we depart from Apergis and Apergis (2019) by using methods based on fractional cointegration, which are more general than those used by these authors and based on ARDL and combined cointegration. Allowing for fractional degrees of integration we permit a higher degree of flexibility in the dynamic specification of the data and the relationship between the variables. The results can be summarized as follows: all series examined are highly persistent, showing evidence of unit roots and even orders of integration higher than one in the case of solar energy production. Looking at the relationship between between silver prices and solar energy capacity we observe no evidence of long-run relationships between them, but a negative short-run effect was found of solar energy capacity on silver prices.

2. Literature review

The financial crisis that started at 2007 produced a global increase in the economic uncertainty all over the world, leading to investors to look for new ways for their investments, including energy products and precious metals. Among the latter, silver has become very popular and many papers have been produced in recent years studying their statistical properties as well as the relations with other products and macro variables.[1]

The strand of the literature that deals with the link between silver and energy explores the nexus between oil prices and the prices of precious metals, especially gold. Baffes (2007) provides solid evidence that precious metals exhibit a strong pass-through mechanism with oil prices, while Sari et al. (2010) document that oil has a small impact on precious metals prices, with oil and silver prices indicating a bidirectional relationship. McGuire (2013) highlights how silver could be the gold of the future in financial markets. Using data from silver prices over the period 1970 to 2011, he addresses the thirteen

[1] See, among others, the papers by Kilian and Park (2009), Batten et al. (2010), Baur and Lucey (2010), Baumeister and Peersman (2013), Apergis et al. (2014) and Gil-Alana et al. (2015a).

elements that are considered as drivers of the increase in the demand for this metal. Finally, Zhang and Tu (2016) explore the effect of global oil price shocks on the Chinese metal markets. They highlight that oil price shocks significantly affect Chinese metal markets.

Overall, the studies on silver have focused on its use as an instrument of investment in relation to gold, oil and stocks. Certain studies also emphasize the role of precious metals as an alternative investment vehicle, especially, in times of economic uncertainty and stress (Kilian and Park, 2009; Batten et al., 2010; Gil-Alana et al. 2015b). Kilian and Park (2009) emphasize the yields of U.S. actions in relation to the evolution of oil prices and relate them with gold and silver prices.

Studies on the relationship between the prices of gold and silver and their impact on other variables (such as, inflation, financial prices) are abundant (Booth et al., 1979; Solt et al., 1981; Escribano at al., 1988; Christie et al., 2000; Baur et al., 2014; Bampinas et al., 2015; among others). Chatrath et al. (2001) review the literature on the financial economy of silver, platinum and palladium. Their study covers a wide variety of topics related to these metals including, market efficiency, forecastability, behavioural findings, diversification benefits, volatility drivers, and macroeconomic determinants.

In another strand of the literature, several studies analyze the link between the price of silver and other precious metals. Gil-Alana et al. (2015a) using monthly data from 1972 to 2013, analyse the statistical properties of five major precious metal prices (i.e., gold, silver, rhodium, palladium, and platinum) based on a fractional integration modelling framework, while identifying structural breaks. Their findings provide solid evidence of an increase in the degree of persistence across time in the majority of the cases. Moreover, Gil-Alana et al. (2015b) propose an alternative modelling specification for the real prices of gold (1833-2013) and silver (1792-2013) which allows the long-run trend and cyclical behaviour to be modelled simultaneously by incorporating two differencing parameters in a fractional integration framework. They document that higher orders of integration are associated with the cyclical component of silver prices. Wthin the same framework, Cunado et al (2019) examine persistence characteristics in gold (1257-2016) and silver (1687-2016) prices using a similar methodology. As opposed to many previous papers in the literature, once the cyclical differencing parameter is taken into account, then mean reversion is detected in the long-run for both gold and silver prices.

Lucey et al. (2006) using a recursive cointegration model for a 25-year period, examine the results of Ciner (2001) who claims that a historically stable relationship between gold and silver broke in the 1990s. The findings support that while there are periods when the relationship is weak, a stable relationship generally prevails. Arouri et al (2013) using an ARFIMA-FIGARCH model, explore the potential of structural changes and long memory properties in the returns and volatility of gold, silver, platinum and palladium. Their evidence highlights that the conditional volatility of precious metals is better explained by long memory than by structural ruptures.

When it comes to studies that link silver prices and energy, the literature focuses on the connection between the evolution of oil prices and that of gold prices, followed by silver. Sari, Hammoudeh and Soytas (2010) analyze the variations of the prices of four precious metals (i.e., gold, silver, platinum and palladium), the price of oil and the dollar/euro exchange rate. They document a weak balance long-term relationship, but a strong feedback in the short run. Apergis and Apergis (2019) discuss the impact that the development of photovoltaic energy has on silver prices. They conclude that the increase in silver prices can have negative effects on the solar energy sector. This paper is in fact very much related to the one presented here in the sense that we also attempt to look at the relationship between silver production and solar production; however, a completely different modelling and estimation method is followed here, which is based on fractional integration and cointegration methods.

Bearing these considerations in mind, we strongly believe that this work could be of considerable interest to certain stakeholders in the renewable energy market (i.e., suppliers of silver, manufacturers of solar panels, photovoltaic energy demanders, investors, and regulators).

3. Methodology

Fractional integration means that the number of differences required in a series to become I(0) stationary may be a fractional value. In this context, a process $\{x_t, t = 0, \pm 1, \ldots\}$ is said to be integrated of order d, and denoted as $x_t \approx I(d)$, if it can be expressed as:

$$(1 - B)^d x_t = u_t, \qquad t = 1, 2, \ldots, \tag{1}$$

where B is the lag operator (i.e., $Bx_t = x_{t-1}$) and u_t is I(0). The I(0) or short memory processes are characterized because the spectrum is bounded and positive at all frequencies, and though it may be a simple white noise process, it also allows for weak autocorrelation of the ARMA form. However, a stronger degree of autocorrelation is permitted if we allow for positive values of d in (1). In such a case, the process x_t is said to be long memory since the spectrum displays a singularity or pole at the zero frequency.

The fact that d in (1) can be any real value, and thus including fractional numbers opens a wide range of modelling alternatives, including stationary long memory models (if $0 < d < 0.5$) and nonstationary mean reverting processes ($0.5 \leq d < 1$) among other alternatives. Note that the polynomial in B in (1) can be expressed in terms of a Binomial expansion, such that for all real d,

$$(1 - B)^d = \sum_{j=0}^{\infty} \binom{d}{j} (-1)^j B^j = 1 - d\,B + \frac{d\,(d-1)}{2} B^2 - \ldots,$$

and thus, x_t in (1) depends on all its past history if d is a fractional value. Moreover, and based on the above equation, higher the value of d is, higher the dependence between the observations is, and thus, d can be considered as an indicator of the degree of persistence in the data.

The estimation of the differencing parameter will be conducted based on parametric models that use the Whittle function in the frequency domain along with a testing procedure developed by Robinson (1994), which is very appropriate when dealing with nonstationary data.[2]

For the multivariate setting, the analysis uses fractional cointegration, as initially proposed by Engle and Granger (1987), i.e., testing, in the first step, the order of integration of the individual series, and then, testing for cointegration by looking at the degree of integration of the estimated residuals of the regression of one variable against the other (see, e.g., Cheung and Lai, 1993; Gil-Alana, 2003).[3] The multivariate fractional CVAR (FCVAR) approach of Johansen (2008) and Johansen and Nielsen (2010, 2012) will also be implemented in the paper. This is basically a generalization of the Cointegrated Vector Autoregressive model (Johansen, 1996), named CVAR, and it allows for series which are integrated of order d and that cointegrate with order d - b, with b > 0 and both, d and b, potentially fractional values.

4. Data and empirical results

We use data on quarterly silver prices (measured as the spot London Bullion Market silver fix-dealer market), installed solar energy capacity (measured in GWs) and solar gross

[2] See Gil-Alana and Robinson (1997) for details of the version of the tests used in this application

[3] Note that Engle and Granger's (1987) methodology was originally presented for any real values d and b, with d referring to the order of integration of the individual series and d-b to the order of integration of the cointegrating errors. However, most of the empirical applications conducted since then have focussed on integer values, with d = 1 and b = 1. Among the few papers dealing with fractional values, see Cheung and Lai (1993) and Gil-Alana (2003).

electricity production (measured in TWHs), spanning the period 1990 to 2016. We work with both the original data and the log-transformed values. Data on installed solar capacity are obtained from the International Energy Agency (IEA), while the remaining data comes from Datastream. Installed solar energy capacity and solar electricity production are considered as two alternative measures of total electricity consumption coming from solar sources. The installed capacity definition is wider than the production definition since it contains off-grid solar systems (where there is no connection to the electrical grid) (Borenstein, 2008; Chesser et al., 2018). Table 1 displays some descriptive statistics about the three series of interest.

[Insert Figure 1 and Table 1 about here]

The statistics in Table 1 clearly indicate a greater dispersion in the solar gross electricity compared with the series of silver prices and installed solar energy capacity. This could be due to the great variety of the transformation technology of the energy capacity in energy production.

The analysis first examines the following model:

$$y_t = \beta_0 + \beta_1 t + x_t; \qquad (1-L)^d x_t = u_t, \qquad t = 0, 1, \ldots, \qquad (2)$$

where y_t refers to each of the observed time series (silver prices and the two solar energy variables); β_0 and β_1 are unknown coefficients referring, respectively, to an intercept and a linear time trend, while x_t is supposed to be I(d), where d can be any real value; finally, u_t is I(0), expressed in terms of both uncorrelated and autocorrelated (Bloomfield) errors.[4]

We start in Table 2 with the case of uncorrelated errors. The table illustrates the estimated values of d (along with the 95% confidence bands of the non-rejection values

[4] This is a non-parametric approach to model the I(0) error term. It is non-parametric in the sense that the model is only implicitly determined in terms of its spectral density function, producing autocorrelations that decay exponentially fast as in the AR case. See Gil-Alana (2004) for the accommodation of this model in the context of fractional integration.

of d using Robinson's (1994) tests), under the three standard cases: i) no deterministic terms (i.e., $\beta_0 = \beta_1 = 0$ in (2)), ii) an intercept ($\beta_1 = 0$ in (2)), and iii) an intercept with a linear time trend (β_0 and β_1 unknown). We have marked in bold in the table the selected model for each series, based on the t-values of the estimated coefficients on the d-differenced series.

Starting with the original data, we can highlight that a time trend is required in the case of energy capacity; however, for the logged data, the time trend is required only for energy production. Focussing on the estimated values of d, we observe that the I(1) hypothesis (i.e., d = 1) cannot be rejected for the case of silver prices in either of the two series (original and log-values); neither can this hypothesis be rejected for the logs of solar capacity. In the remaining cases, this hypothesis is rejected in favour of higher degrees of integration, i.e., d > 1, with a substantially large value in the cases of the solar production series, i.e. 1.56 with original data and 1.45 with the log-transformed data.

[Insert Tables 2 and 3 about here]

Table 3 displays the results under the assumption of autocorrelated errors. We can observe that the time trend is only required in the case of the solar series expressed in logarithms. Moreover, the I(1) hypothesis cannot be rejected for the case of silver prices (both original and logged values), or for the solar capacity series in logarithms.

Next, the analysis explores the relationship between the two types of variables, i.e., silver prices and energy (production/capacity). In order to look at a potential long-run equilibrium relationship, the analysis makes use of the cointegration methodological approach. However, a mathematical requirement in a bivariate context is that the two variables must display the same degree of integration. In our case, the above results indicate that silver prices are clearly I(1). However, for energy, this hypothesis is only satisfied in the case of the logged energy capacity (both in the case of uncorrelated and autocorrelated errors). Thus, in what follows, the analysis focuses on the log of silver prices, as well as on the log of energy capacity. A plot of the two series is displayed in Figure 2.

[Insert Figure 2 about here]

This part of the analysis implements the approach developed by Gil-Alana (2003), which is basically an extension of the two-step strategy recommended by Engle and Granger (1987) to the fractional case. Given that in the first step the two parent series are found to be I(1), the next part of the analysis conducts regression estimates based on one variable against the other, i.e.,

$$sp_t = \beta_0 + \beta_1 ec_t + v_t, \qquad t = 0, 1, ..., \qquad (3)$$

where "*sp*" is logged silver prices and "*ec*" denotes installed solar capacity, testing the order of integration of the estimated errors, once more with the version of the tests of Robinson (1994) used above, while using the critical values derived by Gil-Alana (2003). More specifically, it tests the following null hypothesis:

$$H_o : b = 0 \qquad (4)$$

versus the alternative hypothesis:

$$H_a : b > 0 \qquad (5)$$

in the model given by:

$$(1 - L)^{d-b} v_t = \varepsilon_t, \qquad t = 1, 2, ... , \qquad (6)$$

with v_t given by the errors in equation (3). Thus, the rejection of the null hypothesis (4) against the alternative hypothesis (5) will provide evidence of cointegration, and, thus, fractional cointegration will be applied if the estimated parameter b is found to be fractional.

[Insert Table 4 about here]

Table 4 displays the results of the cointegrated model. We observe that the null hypothesis of no cointegration cannot be rejected in any of the two cases presented based on both uncorrelated and autocorrelated (Bloomfield) errors, with the value d-b being very close to 1 in both cases. This lack of cointegration implies that the OLS regression of "*sp*" on "*ec*" would produce spurious results and suggests the use of alternative methods.[5]

Still in the context of fractional cointegration, the FCVAR methodology of Johansen (2008) and Johansen and Nielsen (2010, 2012) is also implemented in the two series. The model is a generalization of Johansen´s (1996) Cointegrated Vector AutoRegressive (CVAR) model which allows for fractional processes of order d that cointegrate to order d-b.[6] In fact, the results using this method indicate an order of integration for the individual series of about 1.02, consistent with the univariate results reported in Tables 2 and 3, and an estimate of b equal to 0.03, rejecting the hypothesis of cointegration of any degree, and thus, no finding any long run equilibrium relationship between the variables.

The next strategy the analysis recommends is to consider a regression of "*sp* " on the previous values of "*ec*", taking into account that the later variable can be considered as weakly exogenous or deterministic in the analysis of silver prices. This indicates that as silver, out of all metals, is characterised by the highest electrical and thermal conductivity, making it perfect for solar panel production, any potential cost production mitigating trends are expected to be highly associated with a significant impact on silver

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[5] Alternatively, we could also have looked at the ratio between the two series. However, in doing so, we impose a more restrictive model than the one presented in equation (3) since it then imposes $\beta_0 = 0$ and $\beta_1 = 1$ in the cointegrating relation.

[6] Empirical applications using this approach include, among others, Jones et al. (2014), Dolatabadi et al. (2015) and Goodness et al. (2017).

prices (Apergis and Apergis, 2019). Thus, we estimate the parameters in the following model:

$$\mathrm{sp}_t = \gamma_0 + \gamma_1 ec_{t-k} + v_t, \quad (1-L)^b v_t = \varepsilon_t, \quad t = 0, 1, \ldots, \tag{7}$$

and based on the weakly exogenous nature of the regressors, we can still apply the methodology proposed by Robinson (1994). The results for k = 1, 2, 3 and 4 are displayed in Table 5.

[Insert Table 5 about here]

We can see that the unit root null hypothesis cannot be rejected in any single case, implying once more a large degree of persistence in the data; moreover, the γ_1-coefficient is only found to be statistically significant for k = 1 and 2, implying a degree of short-run association between the two variables. The slowdown of the Chinese economy, the strengthening of the dollar, low interest rates, the lack of attention to raw materials as elements for investment and the stocks of silver increases could potentially explain the relationship between silver prices and solar energy capacity. The link between interest rates and silver prices is justified on certain theoretical mechanisms. For instance, Ajayi and Mougoue (1996) and Cheung and Ng (1998) argue that inflation expectations affect interest rates which can be linked to portfolio substitution, thus affecting precious metals prices, i.e. silver prices. However, lower interest rates may induce higher silver prices due to portfolio substitution effects, or lower silver prices due to higher demand for alternative assets, such as stocks. The slowdown of the Chinese economy seems to have detrimental effects on both China's newly installed solar capacity, as well as on its exports, resulting in negative spillovers to the demand for silver and lower silver prices. Moreover, slower growth prospects in the Chinese economy have mitigated R&D expenses in the solar industry funded by the public sector (Ming et al., 2019), while increasing market uncertainties, such as cost, demand and infrastructure (Zhao et al., 2019). Finally, US dollar and silver prices move in opposite positions (Hillier et al., 2006), therefore, the strengthening of the dollar is expecting to lead to lower silver prices.

The negative correlation between the dollar and silver prices is justified on the grounds that the appreciation of the dollar favoured a short-term trend to the decrease in silver prices. By contrast, the economic slowdown in China directly affects the silver market. After growing at an average rate somewhat more than 10% over the period 1991 to 2014, in 2015, for the first time in 25 years, a rate of GDP growth less than 7% was recorded (World Economic Outlook, 2016). To increase the competitiveness of the Chinese economy, the Chinese Central Bank devalued the yuan by 2%, a move that strengthened the dollar more, while negatively affecting silver prices. Moreover, the presence of a surplus in the inventories of silver, potentially due to the recovery in the mining sector (the reserves of silver in 2018 were 560 thousand tons-U.S. Geological Survey 2019, p. 151), could also potentially explain the recorded relationship.

4. Concluding comments

In this paper the relationship between silver prices and solar energy has been examined by using updated time series methods based on the concepts of fractional integration and cointegration. The analysis used quarterly data on silver prices, installed solar energy capacity and solar production, spanning the time period 1990q1–2016q4.

The univariate results provided evidence of the presence of unit roots in the cases of silver prices and solar capacity, but an order of integration higher than 1 was found in the case of the solar energy production series. Thus, the results indicate strong degrees of persistence in the three series examined with shocks having permanent effects, and thus requiring strong policy measures to recover their original trends. The presence of persistence signifies potential bubble formation cases, since bubbles are associated with peaks in the series of persistence (Abreu and Brunnermeier, 2003; Gomez-Gonzalez et al., 2017). The identification of bubbles for silver prices is highly useful for all market participants. How to approach the bubble after identification so that it does not have damaging effects to the real economy is also even more important. If portfolios are highly leveraged in the boom period, the probability of an asset crash becomes very high. Upon realization of a bubble, the strength of credit and financial markets should be the first concern. If these parties are able to lower the leverage in their portfolios upon the realization of a bubble, the effect of the implosion on the real economy will be minimized. Nevertheless, there will still be a loss of wealth for the holders of the bubble asset, but the overall economy will still be able to operate in an effective way. Moreover, the presence of bubbles in silver prices clearly illustrates that this precious metal market is not subject to regulations and imperfections comparatively to other markets, while transaction costs seem to be lower than other standardised financial markets. Finally, although silver is highly traded on electronic platforms at a very high frequency, it seems that arbitrage opportunities are not quickly closed, thus violating the efficient market hypothesis. In the bivariate work, we look at the relationship between silver prices and solar energy capacity. The results indicated no evidence of long-run cointegrating relationships between them, but short-run effects were found with a significant negative effect of solar energy capacity on silver prices.

According to the obtained results and in spite of the increase of solar energy capacity recorded in the time period under study, the growth of solar installations cannot be considered as a push factor for the demand for silver. Moreover, the lack of a cointegrating relationship between solar capacity and silver prices leads us to conclude that the increase of solar energy capacity does not influence these prices. The explanation could probably be found in the productive process of photovoltaic energy. The amount of silver needed as input proves to be small in relation to the energy capacity obtained as output. In other words, the volume of solar energy capacity is a poor indicator of the evolution of silver prices and in that sense cannot have any predictive capacity. The presence of bubbles with respect to solar production and capacity signifies explosive trends in solar development opportunities and investments, while it has negative influences on the process of optimizing energy structure, mitigating energy crisis and improving environmental quality (Xu and Lin, 2018). Moreover, such bubbles phenomena are expected to bring a negative impact on economic activities, such as firm bankrupt and investment volatility (Narayan and Doytch, 2017), while having detrimental effects on unemployment rates and fiscal revenues (Zeng et al., 2018). Finally, the bubble process in solar energy industries would affect energy structure optimization strategies, reduce economic growth speed and quality and further influence a country's sustainable development (Xu and Lin, 2019).

The growth observed in silver prices could be attributed to certain factors. Some of them could be related to the supply of silver, to the cycles of the mining production, to the evolution of real exchange rates in both producer and consumer countries, and, finally, to the return of silver as a refuge value in stressful periods, i.e. crisis events. This is something that will be investigated in future papers.

Finally, this paper can be extended in several other directions. First, noting that in the new generation of solar panels we might need to use less silver than in the old generation of panels, we could use alternative data (if available) based on normalizing the installed capacity of solar energy with respect to the amount of silver that is needed to produce a unit of electricity. The potential presence of structural breaks in the data is another issue that deserve special attention, taking into account the fact that several authors argue that fractional integration may be an artificial artefact generated by the presence of breaks in the data that have not been taken into account. In fact, many authors have demonstrated that the two issues (fractional integration and structural breaks) are very much related (see, e.g., Diebold and Inoue, 2001; Granger and Hyung, 2004; Sibbertsen, 2004; Cappelli and Di Iorio, 2007; Li, 2014; etc.). This and other issues like the presence of non-linearities and cyclical patterns will be examined in future papers.

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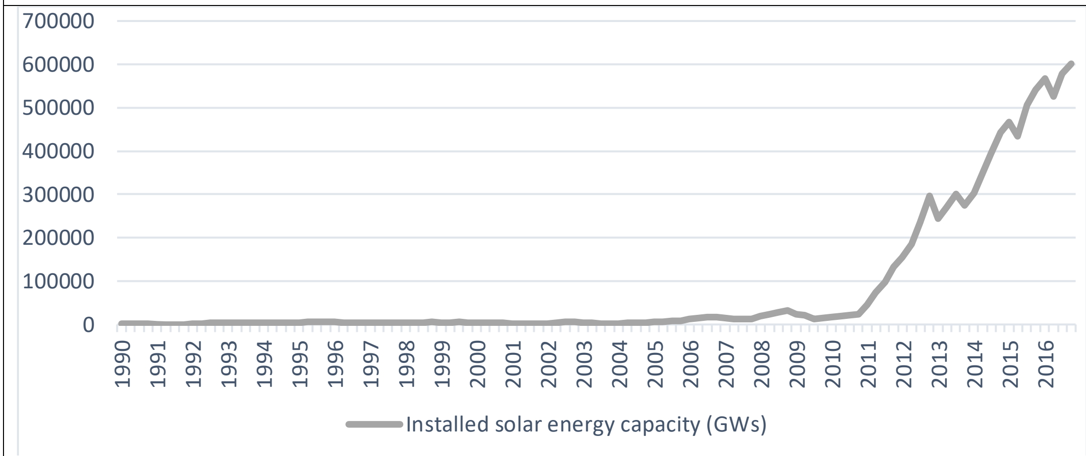
Fig. 1: Original time series plots

Silver prices (measured as the spot London Bullion Market silver fix-dealer market)

Installed solar energy capacity (measured in GWs)



Solar gross electricity production (measured in TWHs)

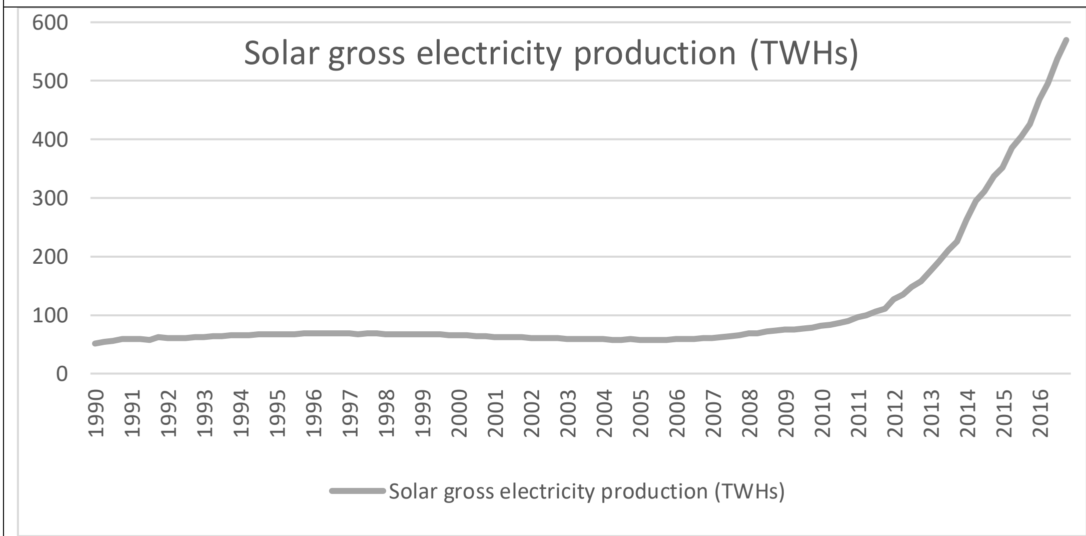


Fig. 2: Silver prices and solar gross electricity production

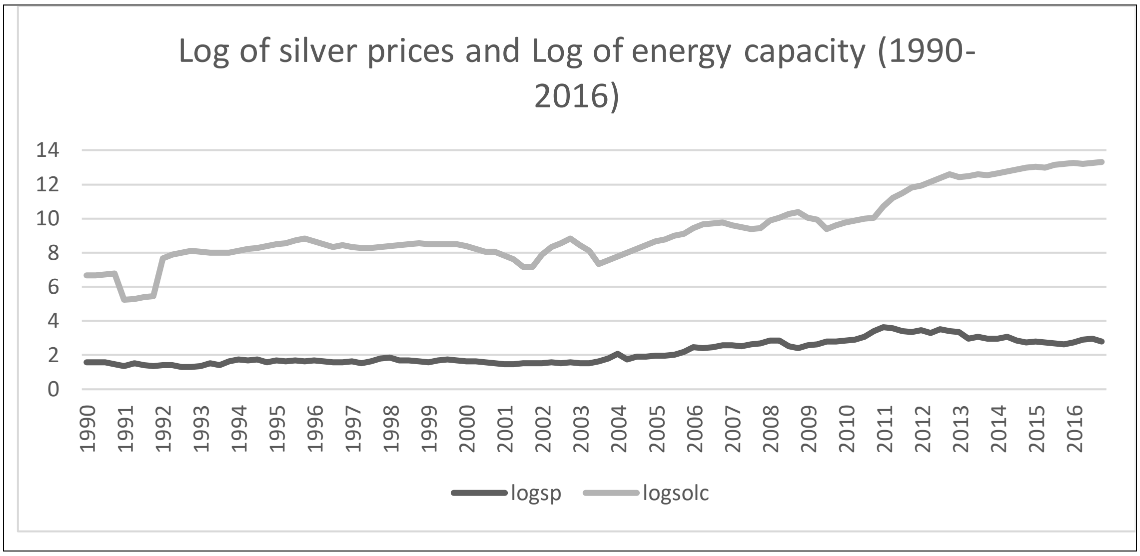


Table 1: Descriptive statistics

Annual Total

Series	***Minimum***	***Maximum***	***Mean***	***Std. Deviation***
Silver prices	15.64	130.72	43.9970	33.6133
Installed solar energy capacity	219.57	2071.83	447.2752	454.4378
Solar gross electricity prod.	841.67	2272840.75	319744.5430	636507.3956

Table 2: Estimates of d based on a model with no autocorrelation

i) Original data			
	No regressors	An intercept	A linear time trend
Silver prices	0.95 (0.83, 1.12)	**0.98** **(0.86, 1.16)**	0.98 (0.84, 1.16)
Installed solar energy capacity	1.14 (1.08, 1.24)	1.14 (1.08, 1.24)	**1.15** **(1.08, 1.25)**
Solar gross electricity production	1.48 (1.41, 1.54)	**1.56** **(1.50, 1.63)**	1.56 (1.51, 1.63)
ii) Logged transformed data			
	No regressors	An intercept	A linear time trend
Silver prices	0.87 (0.75, 1.04)	**0.97** **(0.87, 1.12)**	0.97 (0.86, 1.12)
Installed solar energy capacity	0.97 (0.84, 1.15)	**1.11** **(0.94, 1.35)**	1.11 (0.94, 1.35)
Solar gross electricity production	1.01 (0.90, 1.16)	1.43 (1.37, 1.50)	**1.45** **(1.39, 1.52)**

In bold, the most appropriate model for each series according to the deterministic terms. In parenthesis, the 95% confidence band for the values of d.

Table 3: Estimates of d based on a model with autocorrelation

i) Original data			
	No regressors	An intercept	A linear time trend
Silver prices	0.88 (0.69, 1.18)	**0.90** **(0.71, 1.16)**	0.90 (0.70, 1.16)
Installed solar energy capacity	1.30 (1.17, 1.45)	**1.30** **(1.18, 1.45)**	1.31 (1.18, 1.47)
Solar gross electricity production	1.83 (1.69, 2.03)	**2.01** **(1.88, 2.17)**	1.99 (1.87, 2.17)
ii) Logged transformed data			
	No regressors	An intercept	A linear time trend
Silver prices	0.81 (0.60, 1.16)	**0.97** **(0.81, 1.21)**	0.97 (0.79, 1.21)
Installed solar energy capacity	0.85 (0.67, 1.11)	0.79 (0.62, 1.11)	**0.77** **(0.57, 1.14)**
Solar gross electricity production	1.01 (0.82, 1.25)	1.82 (1.69, 2.03)	**1.97** **(1.80, 2.24)**

In bold, the most appropriate model for each series according to the deterministic terms. In parenthesis, the 95% confidence band for the values of d.

Table 4: Estimated coefficients in a fractional cointegration framework

	d-b (95% c. band)	β_0 (constant)	β_1 (slope)
No autocorrelation	0.97 (0.86, 1.12)	1.451 (5.50)	0.023 (0.65)
Autocorrelation	0.96 (0.77, 1.19)	1.445 (5.52)	0.024 (0.68)

The value d-b in the second column refers to the estimate of the differencing parameter in the potentially cointegrated relationship in eq. (3)

Table 5: Estimated coefficients in a model with lagged energy capacity

	No autocorrelation			Autocorrelation		
K	b (95% band)	γ_0 (constant)	γ_1 (slope)	d (95% band)	γ_0 (constant)	γ_1 (slope)
t - 1	0.98 (0.87, 1.12)	**1.843* (7.08)**	**-0.047* (-1.96)**	1.01 (0.82, 1.27)	**1.857* (7.21)**	**-0.048** (-1.74)**
t - 2	0.98 (0.87, 1.14)	**1.961* (7.42)**	**-0.059** (-1.66)**	1.01 (0.82, 1.25)	**1.989* (7.58)**	**-0.062** (-1.75)**
t - 3	0.97 (0.86, 1.13)	**1.252* (4.89)**	0.033 (0.77)	0.94 (0.77, 1.19)	**1.235* (4.73)**	0.032 (0.63)
t - 4	0.95 (0.84, 1.11)	**1.287* (4.71)**	0.018 (0.41)	0.94 (0.78, 1.17)	**1254* (4.77)**	0.015 (0.44)

In parenthesis in the 2nd and 5th columns, the 95% confidence bands for the values of b; in the rest of the columns they are t-values. In bold, significant coefficients at the 5% level (*) and 1% level (**) .