**PERSISTENCE IN SILVER PRICES AND THE INFLUENCE OF SOLAR ENERGY**

**Nicholas Apergis,** *University of Piraeus, Piraeus, Greece,* *napergis@unipi.gr*

 *University of Derby, Derby, UK,* *n.apergis@derby.ac.uk*

**Nieves Carmona-González,** *University Francisco de Vitoria, Madrid, Spain*

**Luis A. Gil-Alana,** *University of Navarra, Pamplona, Spain*

**Corresponding author:** Prof. Luis A. Gil-Alana

 University of Navarra

 Faculty of Economics and ICS

 E-31080 Pamplona

Spain

 email: alana@unav.es

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**Abstract**

This paper deals with the analysis of silver prices and the influence of solar energy production 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

**1. Introduction**

This paper deals with the analysis of the statistical properties of silver prices and the influence of solar energy production 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 (2019), a 10-year return of 28.74% is expected in the silver market in 2019; 353.60% at a 20-year return, and at a 30-year, a return of 314.50% is also expected. Following the International Energy Agency (IEA, 2017), by 2040, renewables are expected to generate 40% of total energy, with photovoltaic energy being the one to provide the most clean 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 goal of this paper is to detect whether the silver market contains a ‘price bubble’; if the explosive price decouples from its fundamental values, or whether this bubble could be called ‘speculative price bubble’ (or alternatively ‘rational bubble’) if the demand for silver pushes its price beyond the intrinsic value given that buyers anticipate rising silver prices. Hence, a rational price bubble could not exist without investors speculating on rising prices. The novelties of the paper are twofold. First, the analysis examines the persistence of silver prices. The analysis is carried out by the fractional integration method, which is very appropriate in the sense that it is more general than other standard methods based on integer differentiation. Second, 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, fractionally cointegrated methods are employed.

**2. Literature review**

Following the 2008 global financial crisis and the rising economic uncertainty, investors were encouraged to turn into safer investment instruments, such as energy and precious metals contracts, as hedging vehicles (Hammoudeh and Araújo-Santos, 2012). The literature offers certain studies that emphasize the role of precious metals as safe-haven instruments against overall economic uncertainty (Batten et al., 2010; Baur and Lucey, 2010; Gil-Alana et al., 2015). Research has also paid more interest to silver as a commodity, along with its interactions with equity prices and other commodities, primarily oil (Kilian and Park, 2009; Baumeister and Peersman, 2013). Apergis et al. (2014) highlight strong spillovers between gold and silver, stock markets and certain macroeconomic variables in the G7 countries.

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 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. 2015). 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.

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, 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**

As earlier mentioned in the paper, the analysis focuses on fractional integration, which is a fairly general method in the sense that it allows us to consider the standard cases of stationarity I(0) and nonstationarity I(1) as particular cases of interest. A process {xt, t = 0, ±1, …} is considered to be integrated of order d, and denoted as xt ≈ I(d), if it requires d differences to render it stationarity I(0), i.e.,

 (1)

where L is the lag operator (i.e., Lxt = xt-1) and ut is I(0).[[1]](#footnote-1)1 In most cases in the empirical literature, this number, referring to the number of differences, i.e., d, is an integer value (usually 1), though this may not necessarily that be the case, and d can be any real value, including a fractional one constrained between 0 and 1, or even above 1. These processes were introduced in the early 80s by Granger (1980, 1981), Granger and Joyeux (1980), and Hosking (1981) in the context of aggregated data, and they have been widely employed in the literature during the last twenty years when modelling macroeconomic and financial time series data (see, Baillie, 1996; Gil-Alana and Robinson, 1997; Michelacci and Zaffaroni, 2000; Mayoral, 2006; Christensen et al., 2010; Martins and Rodrigues, 2012; Gil-Alana and Moreno, 2012; Hassler et al., 2014; Cavaliere et al., 2015; Abbritti et al., 2016; among others).

 Allowing for fractional integration will permit us to consider alternative specifications, such as stationarity I(0) (if d = 0); stationary with long memory (0 < d < 0.5); nonstationary though mean reverting processes (0.5 ≤ d < 1); unit roots or I(1) (if d = 1) or even explosive processes (d > 1). The estimation of d is conducted by using the Whittle function in the frequency domain (Dahlhaus, 1989), by employing a version of a procedure developed by Robinson (1994), which is very convenient in the context of the present work. Thus, for example, this method remains valid even in nonstationary contexts (d ≥ 1) as is the case with the series examined here; it follows a standard Normal null limit distribution and this behaviour holds independently of the inclusion of deterministic terms and of the assumptions made on the I(0) error term.[[2]](#footnote-2)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]](#footnote-3)3 The multivariate fractional CVAR (FCVAR) approach of Johansen (2008) and Johansen and Nielsen (2010, 2012) will also be implemented in the paper.

**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 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 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:

  (2)

where yt refers to each of the observed time series (silver prices and the two solar energy variables); β0 and β1 are unknown coefficients referring, respectively, to an intercept and a linear time trend, while xt is supposed to be I(d), where d can be any real value; finally, ut is I(0), expressed in terms of both uncorrelated and autocorrelated (Bloomfield) errors.[[4]](#footnote-4)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 of d using Robinson’s (1994) tests), under the three standard cases: i) no deterministic terms (i.e., β0 = β1 = 0 in (2)), ii) an intercept (β1 = 0 in (2)), and iii) an intercept with a linear time trend (β0 and β1 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 clearly highlight that a time trend is required in the case of energy capacity; however, for the case of logged data and energy production, the time trend is required. 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 1.

**[Insert Figure 1 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.,

  (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:

  (4)

versus the alternative hypothesis:

  (5)

in the model given by:

 (6)

in (3). Thus, the rejection of the null hypothesis (4) against the alternative hypothesis (5) will provide strong 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 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.

The first 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. That is, we estimate the parameters in the following model:

  (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 γ1-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 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.

As a final approach, 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 b.[[5]](#footnote-5)5 The results, based on this approach, not reported here, though available under request, indicate no evidence of cointegration, which is consistent with the previous results, not finding any long run equilibrium relationship between the variables.

**4. Concluding comments**

In this paper the relationship between silver prices and solar energy production 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. In the bivariate work, we look at the relationship between silver prices and solar energy capacity. The results indicated no evidence of long-run 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 weak 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 of this weak relationship 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 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.

**References**

Abbritti, M., L.A. Gil-Alana, Y. Lovcha and A. Moreno, (2016), Term Structure Persistence, Journal of Financial Econometrics 14, 2, 331-352.

Apergis, N., I. Apergis, (2019), Silver prices and solar energy production, Environmental Science and Pollution Research, forthcoming.

Apergis, N., C. Christou and J.E. Payne, (2014), Precious Metal Markets, Stock Markets and the Macroeconomic Environment: A FAVAR Model Approach, Applied Financial Economics 24, 691-703.

Baffes, J., (2007), Oil Spills on Other Commodities. Resources Policy 32, 126-134.

Baillie, R.T., (1996), Long memory processes and fractional integration in econometrics, Journal of Econometrics 73, 5-59.

Batten, J.A., C. Ciner and B.M. Lucey, (2010), The Macroeconomic Determinants of volatility in precious metals markets, Resources Policy 35, 65-71.

Baumeister, C., and G. Peersman, (2013), The Role of Time-Varying Price Elasticities in Accounting for Volatility Changes in the Crude Oil Market. Journal of Applied Econometrics 28, 1087-1109.

Baur, D.G. and B.M. Lucey, (2010), Is Gold a Hedge or a Safe Haven? An Analysis of Stocks, Bonds and Gold. Financial Review 45, 217-229.

BNEF (2019), Bloomberg New Energy Finance, 2019.

Borenstein, S., (2008), The Market Value and Cost of Solar Photovoltaic Electricity Production. Working Paper, No.176, Center for the Study of Energy Markets, California.

Cavaliere, G., M.O. Nielsen and A.M.R. Taylor, (2015), Boostrap score tests for fractional integration in heteroskedastic ARFIMA models, with an application to price dynamics in commodity spot and future markets, Journal of Econometrics 187, 557-579.

Chesser, M., J. Hanly, D. Cassells and N. Apergis, (2018), The Positive Feedback Cycle in the Electricity Market: Residential Solar PV Adoption, Electricity Demand and Prices. Energy Policy 122, 36-44.

Cheung, Y.W. and K.S. Lai, (1993), A fractional cointegration analysis of purchasing power parity. Journal of Business and Economic Statistics, 11, 103-112.

Christensen, B.J., M.O. Nielsen and J. Zhu, (2010), Long memory in stock market volatility and the volatility in mean effect: the FIEGARCH-M model, Journal of Empirical Finance 17, 460-470.

Cunado, J., L.A. Gil-Alana and R. Gupta (2019), Persistence in trends and cycles of gold and silver prices. Evidence from historical data, Physica A 514, 345-354.

Dahlhaus, R., (1989), Efficient parameter estimation for self-similar process. Annals of Statistics. 17, 1749-1766.

Dolatabadi, S., P.K. Narayan, M.Ø. Nielsen and K. Xu, (2018), Economic significance of commodity return forecasts from the fractionally cointegrated VAR model, Journal of Futures Markets 38, 2, 219-242.

Engle, R. and C.W.J. Granger, (1987), Cointegration and error correction. Representation, estimation and testing, Econometrica 55, 2, 251-276.

Fraunhofer ISE (February 2015), Current and Future Cost of Photovoltaics Long-term Scenarios for Market Development, System Prices and LCOE of Utility Scale PV Systems.

Gil-Alana, L.A., (2003), Testing of fractional cointegration in macroeconomic time series, Oxford Bulletin of Economics and Statistics, 65, 4,

Gil-Alana, L. A., (2004) The use of the Bloomfield (1973) model as an approximation to ARMA processes in the context of fractional integration, Mathematical and Computer Modelling, 39: 429-436.

Gil-Alana, L.A., S.Chang, M. Balcilar, G.C. Aye and R. Gupta, (2015), Persistence of precious metal prices: a fractional integration approach with structural breaks. Resources Policy 44, 57-64.

# Gil-Alana, L.A. and A. Moreno, (2012), Uncovering the US term premium: An alternative route, Journal of Banking and Finance 36, 4, 1181-1193.

Gil-Alana, L.A. and P.M. Robinson (1997), Testing of unit roots and other nonstationary hypotheses in macroeconomic time series. Journal Econometrics80, 241-268.

Global Market Outlook, (2018).

Gold, M, (2017), Solar Remains a Bright Spot for Silver Demand. Investment Report, ETF Securities, New York.

Goodness, C.A., H. Carcel, L.A. Gil-Alana and R. Gupta, (2017), Does gold act as a hedge against inflation in the UK? Evidence from a fractional cointegration approach over 1257 to 2016, Resources Policy 54, 53-57.

Granger, C.W.J., (1980), Long memory relationships and the aggregation of dynamic models, Journal of Econometrics, vol.14, pp.227-238.

Granger, C.W.J., (1981), Some properties of time series data and their use in econometric model specification, Journal of Econometrics*,* vol.16, pp.121−130.

Granger, C.W.J., and R. Joyeux, (1980), An introduction to long memory time series models and fractional differencing, Journal of Time Series Analysis*,* vol.1, pp.15−39.

Hammoudeh, S., and P. Araújo-Santos, (2012), Downside Risk Management and VaR-Based Optimal Portfolios for Precious Metals, Oil and Stocks. North American Journal of Economics and Finance 25, 18-34.

Hassler, U., P.M.M. Rodrigues and A. Rubia, (2014), Persistence in the banking industry: Fractional integration and breaks in memory, Journal of Empirical Finance 29, 95-112.

Hosking, J.R.M., (1981), Fractional differencing, Biometrika, vol. 68, pp. 165-176.

IAE (2017), World Energy Outlook.

IRENA, 2018, Renewable Power Generation Cost in 2017, International Renowable Energy Agency, Abu Dhabi.

Jäger-Waldau, A., (2017), European Commision, PV Status Report.

Johansen, S., (1996), Likelihood based inference in cointegrated vector autoregressive models, Oxford University Press.

Johansen, S., (2008), A representation theory for a class of Vector Autoregressive Models for fractional models, Econometric Theory 24(3), 651-676.

Johansen, S. and M.Ø. Nielsen, (2010), Likelihood inference for a nonstationary fractional autoregressive model, Journal of Econometrics 158, 51-66.

Johansen, S. and M.Ø. Nielsen, (2012), Likelihood inference for a Fractionally Cointegrated Vector Autoregressive Model, Econometrica 80(6), 2667-2732.

Jones, M.E.C., M.Ø. Nielsen and M.K. Popiel, (2014), A fractionally cointegrated VAR analysis of economic voting and political support, Canadian Journal of Economics 47, 4, 1078-1130.

Kilian, L. and C. Park, (2009), The Impact of Oil Price Shocks on the U.S. Market. International Economic Review50, 1267-1287.

London Silver Fixing of London Bullion Market Association, 2019, available at <http://www.lbma.org.uk/lbma-silver-price>

# Martins, L.F. and P.M.M. Rodrigues, (2012), Testing for persistence change in fractionally integrated models. An application to world inflation rates Computational Statistics and Data Analysis76, 502-522.

Maxwell Gold (2017), ETF Securities, 2017.

Mayoral, L., (2006), Further evidence on the statistical properties of real GNP. Oxford Bulletin of Economics and Statistics 68, 901-920.

McGuire, S., (2013), The Silver Bull Market Investing in the Other Gold, Wiley

Michelacci, C. and P. Zaffaroni, (2000), (Fractional) Beta convergence. Journal of Monetary Economics 45(1),129-153.

Perlin, J., (1999), From Space to Earth: The Story of Solar Electricity, Harvard University Press.

Robinson, P.M., (1994), Efficient tests of nonstationary hypotheses, Journal of the American Statistical Association 89, 1420-1437.

Sari, R, S. Hammoudeh,. and U. Soytas, (2010), Dynamics of oil Price, precious metal prices and exchange rates. Energy Economics 32, 351-362.

Thomson Reuters (2017), GFMS Platinum Group Metals Survey.

United Nations Climate Change (25 January 2019), https://unfccc.int/news/antonio-guterres-climate-change-is-biggest-threat-to-global-economy

U.S. Geological Survey, Mineral Commodity, (February 2019).

Wood Mackenzie (2019), 2018 global PV operation and maintenance.

Zhang, C., and X. Tu., (2016), The Effect of Global Oil Price Shocks on China’s Metal Markets. Energy Policy 90, 131-139.

**Fig. 1:** Silver prices and solar gross electricity production

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|  |

**Table 1:** Descriptive statistics

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***Series*** | ***Minimum*** | ***Maximum***  | ***Mean*** | ***Std. Deviation*** |
| Silver prices | 15.64 | 130.72 | 43.9970 | 33.6133 |
| Installed solarenergy capacity | 219.57 | 2071.83 | 447.2752 | 454.4378 |
| Solar grosselectricity 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 solarenergy capacity | 1.14(1.08, 1.24) | 1.14(1.08, 1.24) | **1.15****(1.08, 1.25)** |
| Solar grosselectricity 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 solarenergy capacity | 0.97(0.84, 1.15) | **1.11****(0.94, 1.35)** | 1.11(0.94, 1.35) |
| Solar grosselectricity 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 solarenergy capacity | 1.30(1.17, 1.45) | **1.30****(1.18, 1.45)** | 1.31(1.18, 1.47) |
| Solar grosselectricity 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 solarenergy capacity | 0.85(0.67, 1.11) | 0.79(0.62, 1.11) | **0.77****(0.57, 1.14)** |
| Solar grosselectricity 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

|  |  |  |  |
| --- | --- | --- | --- |
|  | b (95% conf. band) | β0 (constant) | β1 (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 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) | γ0 (constant) | γ1 (slope) | d (95% band) | γ0 (constant) | γ1 (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.

1. 1 A proper definition of I(0) is as follows: a process is said to be I(0) if it is covariance stationary, and the infinite sum of its autocovariances is finite; alternatively, in the frequency domain, a process is I(0) if its spectral density function is positive and finite at all frequencies. [↑](#footnote-ref-1)
2. 2 See Gil-Alana and Robinson (1997) for details of the version of the tests used in this application [↑](#footnote-ref-2)
3. 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 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 = 0. Among the few papers dealing with fractional values, see Cheung and Lai (1993) and Gil-Alana (2003). [↑](#footnote-ref-3)
4. 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. [↑](#footnote-ref-4)
5. 5 Empirical applications using this approach include, among others, Jones et al. (2014), Dolatabadi et al. (2015) and Goodness et al. (2017). [↑](#footnote-ref-5)