**University of São Paulo**
**“Luiz de Queiroz” College of Agriculture**

# Econophysics applications to the Brazilian ethanol-sugar sector´s prices

**Derick David Quintino**

Thesis presented to obtain the degree of Doctor in Science Area: Applied Economics

**Piracicaba**
**2022**

**Derick David Quintino**
**Economist**

# Econophysics applications to the Brazilian ethanol-sugar sector´s prices

versão revisada de acordo com a Resolução CoPGr 6018 de 2011

Advisor:
Prof. Dr. **HELOISA LEE BURNQUIST**

Thesis presented to obtain the degree of Doctor in Science. Area: Applied Economics

**Piracicaba**
**2022**

**Dados Internacionais de Catalogação na Publicação**
**DIVISÃO DE BIBLIOTECA – DIBD/ESALQ/USP**

Quintino, Derick David

Econophysics applications to the Brazilian sugar-ethanol sector´s prices / Derick David Quintino. - - versão revisada de acordo com a Resolução CoPGr 6018 de 2011. .  - - Piracicaba, 2022.

82 p.

Tese (Doutorado)  - - USP / Escola Superior de Agricultura “Luiz de Queiroz”.

1. Preço de etanol hidratado 2. Preço de emissão de carbono 3. Preço relativo etanol-gasolina 4. DFA 5. DCCA I. Título

**DEDICATÓRIA**

À minha mãe Sueli David, por todo seu amor para com seus filhos e netos.

**AGRADECIMENTOS**

A Deus, por todas as coisas.
A minha mãe Sueli, por tudo o que fez e faz em minha vida. A maior benção que recebi de Deus.
Ao meu pai, Sebastião Paulo Quintino (*in memoriam*) e minha irmã Daliana, por tudo o que fizeram por mim, inclusive nos momentos mais difíceis. Aos meus sobrinhos, Maria Júlia, João Gabriel e Luis Paulo, por todo o amor. Também agradeço às orações da minha avó Virgilina.
À Maria Angélica Galluzzi, por todo amor e apoio em minha preparação ao processo seletivo e primeiro ano de doutorado.
Aos meus grandes amigos, Márcio Vitorelli, Eduardo Vitorelli e Rodolfo Margato, por serem pessoas incríveis.
A minha orientadora, renomada Professora Dra Heloisa Burnquist, referência da área, por aceitar meu pedido de orientação, ensinamentos sobre as complexidades do setor sucroenergético, sugestões e críticas, que foram essenciais para melhorar a qualidade dos trabalhos.
Ao Professor Dr Paulo Ferreira, autor de inúmeros artigos de referência na área de econofísica, pelos ensinamentos com críticas e sugestões, sempre de maneira respeitosa. Essa parceria foi essencial para intensificar meus estudos nesta área. Também agradeço por suas palavras amigas e apoio nos momentos difíceis.
Aos professores doutores que fizeram parte da banca de defesa da tese: Marta Marjotta-Maistro, Leonardo Zilio e Paulo Ferreira, pelas críticas e sugestões.
Aos professores doutores que fizeram parte da banca de qualificação da tese: Marta Marjotta-Maistro, Jeronimo Santos e Luciano Rodrigues, pelas críticas e sugestões.
Ao Professor Dr Carlos Vian, referência da área, meu orientador de monografia e mestrado. Ao longo de vários anos juntos, agradeço seus ensinamentos, conselhos, confiança e amizade.
Ao meu tio e Professor Dr Sérgio David, pelos trabalhos em conjunto realizados, inclusive em parceria com o renomado Prof Dr José Tenreiro Machado (*in memoriam*).
A todos os professores/as do PPGEA-LES, pelos ensinamentos nas disciplinas, bem como aos funcionários, em especial Helena Cardoso, Luciane e Cristiane Cipriano, André, Aline Fermino, Silvana Cristina. Também agradeço às equipes das bibliotecas Central e do LES.
Aos colegas de turma de doutorado pela troca de informações, ideias e estudos em conjunto. Em especial, Cristiane Ogino, Jéssica Campoli, Thiago Péra e Tarcísio Lobato.
À Capes, pelo financiamento da pesquisa. *This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001*. (O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Código de Financiamento 001).

## EPÍGRAFE

*Palavras do pregador, filho de Davi, rei em Jerusalém:*
*Vaidade de vaidades! — diz o pregador, vaidade de vaidades! É tudo vaidade.*
*Que vantagem tem o homem de todo o seu trabalho, que ele faz debaixo do sol?*
*Uma geração vai, e outra geração vem; mas a terra para sempre permanece.*
*E nasce o sol, e põe-se o sol, e volta ao seu lugar, de onde nasceu.*
*O vento vai para o sul e faz o seu giro para o norte; continuamente vai girando o vento e volta fazendo os seus circuitos.*
*Todos os ribeiros vão para o mar, e, contudo, o mar não se enche; para o lugar para onde os ribeiros vão, para aí tornam eles a ir.*
*Todas essas coisas se cansam tanto, que ninguém o pode declarar; os olhos não se fartam de ver, nem os ouvidos de ouvir.*
*O que foi, isso é o que há de ser; e o que se fez, isso se tornará a fazer; de modo que nada há novo debaixo do sol.*
*Há alguma coisa de que se possa dizer: Vê, isto é novo? Já foi nos séculos passados, que foram antes de nós.*
*Já não há lembrança das coisas que precederam; e das coisas que hão de ser também delas não haverá lembrança, nos que hão de vir depois.*
*Eu, o pregador, fui rei sobre Israel em Jerusalém.*
*E apliquei o meu coração a esquadrinhar e a informar-me com sabedoria de tudo quanto sucede debaixo do céu; essa enfadonha ocupação deu Deus aos filhos dos homens, para nela os exercitar.*
*Atentei para todas as obras que se fazem debaixo do sol, e eis que tudo era vaidade e aflição de espírito.*
*Aquilo que é torto não se pode endireitar; aquilo que falta não pode ser calculado.*
*Falei eu com o meu coração, dizendo: Eis que eu me engrandeci e sobrepujei em sabedoria a todos os que houve antes de mim, em Jerusalém; na verdade, o meu coração contemplou abundantemente a sabedoria e a ciência.*
*E apliquei o meu coração a conhecer a sabedoria e a conhecer os desvarios e as loucuras e vim a saber que também isso era aflição de espírito.*
*Porque, na muita sabedoria, há muito enfado; e o que aumenta em ciência aumenta em trabalho.*

Eclesiastes 1:1-18

**CONTENTS**

# RESUMO

## Aplicações de econofísica aos preços do setor de etanol e açúcar brasileiro

A presente tese é composta por um capítulo introdutório seguido de dois artigos independentes, porém relacionados. Os artigos situam-se sob uma mesma temática mais ampla, a saber, sobre as relações de preços do etanol hidratado brasileiro, tanto do ponto de vista de relações com preços internacionais quanto relações internas. O objetivo do capítulo 2 é estudar se os preços de etanol hidratado brasileiro exibem correlação com os preços futuros de emissão de carbono, comparando com outros preços futuros internacionais potencialmente correlacionados: petróleo e gás natural (as principais commodities da área de energia), bem como o açúcar (também produzido a partir da cana-de-açúcar por usinas brasileiras). Utilizou-se o método das correlações cruzadas sem tendência (DCCA, Detrended Cross-Correlation Analysis) com janelas móveis, de modo a captar as correlações de modo dinâmico. O período de análise compreendeu o período de Janeiro de 2010 a Julho de 2020. Os resultados sugerem que existe correlação entre etanol e açúcar de modo significante e uma associação de caráter moderado com petróleo no curto prazo, porém uma relação fraca e de curto-prazo com os preços de emissão de carbono. Ademais, na análise dinâmica das janelas móveis, a força da correlação entre etanol e preços de emissão oscila entre fraca e não significativa. O capítulo 3, por sua vez, tem como objetivo analisar o grau de persistência dos preços relativos de etanol hidratado – gasolina C considerando 15 capitais brasileiras situadas nas 5 grandes regiões do país. Também se analisa o grau de correlação dos preços relativos entre São Paulo, capital do principal estado produtor e consumidor de etanol hidratado, frente as demais capitais. O período analisado situa-se entre maio de 2004 a dezembro de 2020. Os métodos da DFA (Detrended Fluctuation Analysis) e da DCCA são usados para investigar o grau de persistência e correlação, respectivamente, utilizando-se janelas móveis de forma a captar dinamicamente tais estimativas. Encontrou-se que o grau de persistência varia conforme a localidade da capital analisada, o que sugere dinâmicas de preços relativos locais específicas. Quanto às correlações, estas também sugerem que as estimativas são dependentes da localidade das capitais, de forma que regiões mais distantes geograficamente de São Paulo exibem menor correlação de preços relativos. Isto sugere um caráter regionalizado face ao unificado de convergência de preços relativos nacionais.

Palavras-chave: Preços de etanol hidratado, Preços de emissão de carbono, Preço relativo etanol-gasolina, DFA, DCCA

# ABSTRACT


## Econophysics applications to the Brazilian ethanol-sugar sector´s prices

This thesis consists of an introductory chapter followed by two independent but related articles. The articles are situated under the same broader theme, namely, on the price relations of Brazilian hydrated ethanol, both from the point of view of relations with international prices and internal relations. The aim of Chapter 2 is to study whether Brazilian hydrous ethanol prices are correlated with carbon emission futures prices, compared to other potentially correlated international futures prices: oil and natural gas (the main commodities in the energy sector), as well as sugar (also produced from sugarcane by Brazilian mills).The Detrended Cross-Correlation Analysis (DCCA) method was used with sliding windows, in order to capture the correlations dynamically. The analysis comprised the period from January 2010 to July 2020. The results suggest that there is a significant correlation between ethanol and sugar and a moderate association with oil in the short term, but a weak and short-term relationship with carbon emission prices. Furthermore, in the dynamic analysis of sliding windows, the strength of the correlation between ethanol and emission prices ranges from weak to not significant. Chapter 3, in its turn, aims to analyze the degree of persistence of the relative prices of hydrated ethanol – gasoline C, considering 15 Brazilian capitals located in the 5 major regions of the country. It also analyzes the degree of correlation of relative prices between São Paulo, capital of the main producer and consumer state of hydrated ethanol, compared to other capitals. The analyzed period is between May 2004 and December 2020. The DFA (Detrended Fluctuation Analysis) and DCCA methods are used to investigate the degree of persistence and correlation, respectively, using sliding windows. It was found that the degree of persistence varies according to the location of the analyzed capital, which suggests specific local dynamics of relative prices. As for the correlations, these also suggest that the estimates are dependent on the location of the capitals, so that regions that are more geographically distant from São Paulo exhibit a lower correlation degree of relative prices. This suggests a regionalized vis-à-vis unified character of convergence of national relative prices.


Keywords: Hydrous ethanol price, Carbon emissions price, Relative price ethanol-gasoline, DFA, DCCA

# 1. INTRODUCTION

The ethanol-powered car in Brazil recently completed 40 years of existence. This was a direct result of ProÁlcool, launched in 1975. ProÁlcool was an innovative Brazilian program that promoted the ethanol-powered car, an original and sustainable way of dealing with the Brazilian crisis due to shocks in international oil prices. According to former Agriculture Minister Roberto Rodrigues, the ethanol-powered car was "*the father of the flex car*" (RODRIGUES, 2019), launched in Brazil in March 2003.

It is noteworthy that ethanol fulfils an important environmental function, in addition to its economic function: it is an environmentally friendlier substitute for gasoline, by mitigating the emission of greenhouse gases (GHG), and it is of a renewable nature, as it originates from sugarcane in the Brazilian case.

The main products that originate from sugarcane, sugar and ethanol are top products of Brazilian agribusiness. In the case of sugar, Brazil is historically the largest producer in the world and delivers 23% of global supply and 49% of world exports, considering the 2020/21 harvest (UNICA, 2021a). Regarding ethanol, in 2020 Brazil was the second largest global producer, accounting for 31%, only behind the US (RENEWABLE FUELS ASSOCIATION - RFA, 2021). Specifically in the case of ethanol, it is important to highlight that, since the launch of flex vehicles, from March 2003 to October 2021, Brazil has avoided emitting 570 million equivalent CO2 into the atmosphere through the use of ethanol, due to the reduction of up to 90% GHG emissions compared to gasoline. (UNICA, 2021b).

According to William Nordhaus, who like Paul Romer was awarded the Nobel Prize for Economics in 2018, climate change is the main economic challenge of the 21st century. According to Nordhaus (2019, p.1) "*...Humans clearly have succeeded in harnessing new technologies. But humans are clearly failing, so far, to address climate change*". Further on, he adds that (Nordhaus, 2019, p.2) "*…In the modern world, the older global challenges have not disappeared, while new ones have arisen…..Global warming is the most significant of all environmental externalities*". Therefore, it is essential to encourage alternative energy sources that avoid or mitigate negative externalities, as is the case with Brazilian ethanol. Therefore, better understading of the dynamics of ethanol prices is a fundamental step for Brazil's role in this direction.

Since the development of biofuel cars, there has been a very significant development in the literature on Brazilian ethanol price relations since the turn of the new millennium, with the new boom in the ethanol sector.

In this sense, the main motivation of this thesis is to attempt to deepen the understanding of the dynamics of ethanol prices in Brazil, both in relation to potentially related international prices, as well as in regional domestic terms in relation to gasoline. However, it is important to mention that the literature covering the most recent period, after the impeachment of President Dilma Roussef in 2016, has not yet been sufficiently explored. Specifically, there are few studies that have analyzed the recent dynamics of Brazilian ethanol prices in the face of successive shocks and institutional changes that have occurred since then, namely: the change in fuel pricing policy by Petrobras in 2016; the launch of the National Biofuels Policy (RenovaBio) in 2017; the crisis of the 2018 truck drivers' strike; and the health shock due to the COVID-19 global health crisis.

However, the theme is complex and the proposed objective is to help understand the movements of Brazilian ethanol prices in light of recent events, using methods from Econophysics, a very young field of investigation that emerged at the intersection between Physics and Economics, which began to establish its foundations in the early 1990s. In this sense, the intended contributions in this thesis are not in the methodological sense, but in using a robust tool to investigate contemporary economic problems, not only of academic interest, but as relevant to the various economic agents. The robustness of Econophysics is also verified by its broad interdisciplinarity, not only part of the exact sciences, as well as in the biological areas, and, fundamentally, in the humanities, such as finance and economics. (MANTEGNA; STANLEY, 1999).

Specifically, this thesis comprises two articles. In the first text, presented in Chapter 2, we investigate whether Brazilian ethanol prices are correlated with carbon emission prices, compared to international oil and sugar prices. Both oil and sugar prices are commonly monitored by agents in the Brazilian sugar-energy sector, as well as natural gas prices, another energy commodity that has recently reaffirmed its global importance, and with possible relationships with international biofuel prices in recent investigations in the literature.

In Chapter 3, we aim to analyze the behavior and relative price relationships of ethanol-gasoline in the main capitals of Brazil, located in the five major regions of the country. Relative prices are of great importance in determining the demand for ethanol and, therefore, in the objective of making a fuel substitute for gasoline, in a sustainable and environmentally less polluting manner, viable. However, Brazil has continental dimensions, with regional specificities, which justify such an approach.

Importantly, the chapters of this thesis can be understood as independent articles in terms of reading comprehension. However, there is an overlap of themes and authors, as both chapters deal with ethanol prices, nationally and regionally, and are subject to the same institutional shocks and situations that hit the Brazilian economy, and, more specifically, the national sugar-energy sector.

## References

MANTEGNA, R.N.; STANLEY, H.E. (1999). **Introduction to econophysics**: correlations and complexity in finance. Cambridge University Press. 162 p.

RODRIGUES, R. **Um aniversário sustentável**. (2019). Available at: https://campoenegocios.com.br/um-aniversario-sustentavel-por-roberto-rodrigues/. Accessed on: 13 dez. 2021.

NORDHAUS, W. (2019). Climate change: the ultimate challenge for economics. **American Economic Review**, 109(6), 1991-2014.

RENEWABLE FUELS ASSOCIATION - RFA (2021). **Ethanol industry outlook**. Available at: https://ethanolrfa.org/file/274/RFA_Outlook_2021_fin_low.pdf. Accessed on: 28 nov. 2021.

UNICA (2021a). **Açúcar importante fonte de energia**. Available at: https://unica.com.br/setor-sucroenergetico/acucar/. Accessed on: 28 nov. 2021.

UNICA (2021b). **Etanol energia sustentável**. Available at: https://unica.com.br/setor-sucroenergetico/etanol/. Accessed on: 28 nov. 2021.

# 2. CARBON EMISSIONS AND BRAZILIAN ETHANOL PRICES: ARE THEY CORRELATED? AN ECONOPHYSICS STUDY

Note: The article derived from this chapter has already been peer-reviewed and published online. (open access, "*everyone is free to re-use the published material if proper accreditation/citation of the original publication is given;*" https://www.mdpi.com/openaccess)
QUINTINO, D.D.; BURNQUIST, H.L.; FERREIRA, P.J.S. (2021). Carbon Emissions and Brazilian Ethanol Prices: Are They Correlated? An Econophysics Study. **Sustainability**, 13(22), 12862. DOI: https://doi.org/10.3390/su132212862

**Abstract**

Brazil is one of the largest global producers and exporters of ethanol and in 2017 launched RenovaBio, a programme aiming to mitigate greenhouse gas emissions. In parallel to this domestic scenario, there is rapid growth in the world market of carbon production, as well as complex price relations between fossil and renewable energies becoming increasingly important in recent years. The present work aims to contribute to filling a gap in knowledge about the relationship between Brazilian ethanol and other relevant energy-related commodities. We use a recent methodology (Detrended Cross-Correlation Approach—DCCA—with sliding windows) to analyze dynamically the cross-correlation levels between Brazilian ethanol prices and carbon emissions, as well as other possible-related prices, namely: sugar, Brent oil, and natural gas prices, with a sample of daily prices between January 2010 and July 2020. Our results indicate that (i) in the whole period, Brazilian ethanol has significant correlations with sugar, moderate correlation with oil in the short term, and only a weak, short-term correlation with carbon emission prices; (ii) with a sliding windows approach, the strength of the correlation between ethanol and carbon emissions varies between weak and non-significant in the short term.

Keywords**:** Brazilian ethanol prices, Carbon emission prices, Detrended cross-correlation analysis, Sliding windows approach

## 2.1 Introduction

Due to policies stemming from global climate change, many governments encourage the use of biofuels through subsidies or mandate policies [1]. Developing countries, including Brazil, are likely to play an important role in the biofuels market in the coming years [2].

Brazil is an important global player in the ethanol market, and the use of renewable energies is a robust strategy in order to achieve sustainable development. In addition, Brazilian ethanol is fully competitive with gasoline as a substitute fuel, and its use is consolidated through the large fleet of flex-fuel vehicles in Brazil [3]. In addition to ethanol, sugarcane originates another important product for Brazilian and global agribusiness, namely, sugar. Brazil is responsible for at least 50% of all sugar exported on the international market, due to its economically competitive production and export capacity [4].

Santos and Ferreira Filho [5] argue that the substitution of fossil fuels by renewables, ethanol and biodiesel, has the potential to reduce the emission of pollutants without additional cost to the Brazilian GDP.

Goldemberg [6] highlights that Brazilian ethanol production is the most important and structured example of a large-scale renewable energy program in 2000s, and this was a decision supported by civil society and other agents involved in this process, such as the agricultural and industrial sugar-energy sector and the automobile industry. With the advent of flex-fuel cars, Brazil has consolidated its status as an economic reference in the search for sustainability [7]. Brazil was the leader in ethanol production until 2006, but since 2007 the US has taken the lead with Brazil in second position [3].

According to the Energy and Environment Institute [8], in the city of São Paulo (the most populous in the country, with more than 12 million inhabitants), automobiles are responsible for 72.6% of greenhouse gas emissions (GHG). Debone et al. [9] showed that, during the 90 days of social isolation in the city of São Paulo due to the COVID-19 health crisis, there was a significant improvement in air quality, avoiding hundreds of premature deaths and saving up to $ 1.5 billion in health care costs. Therefore, it is important that, considering both the economic point of view, and public and environmental health, there is greater substitution of fossil fuels by renewables. Renewable sources have contributed to lowering the amount of CO2 emissions into the atmosphere, as shown in Figure 1 [10], i.e., by using more ethanol than gasoline, the former acting as a substitute for the latter, there is mitigation of GHG emissions.

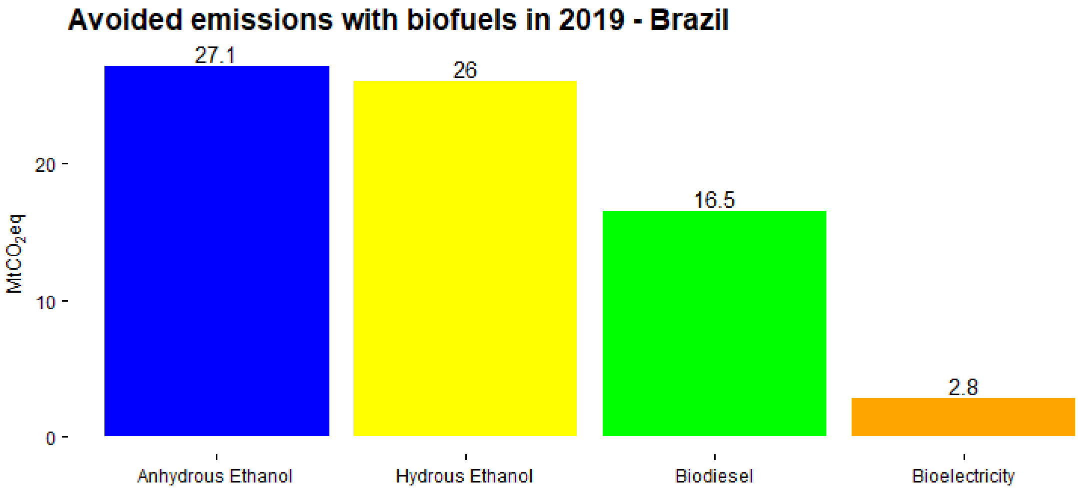


Figure 1. Avoided emissions in Brazil from using biofuels. Source: [10] from [11,12,13]. Adapted by the authors.

Another very important step in this direction was the creation of the National Biofuels Program, RenovaBio, in December 2017 [14]. RenovaBio creates a decarbonization market, through a financial bond called CBIO, which is issued by biofuel producers or importers. These securities are traded on the Brazilian Stock Exchange and are directly linked to the amount of reduction in the emission of greenhouse gases, GHG [15]. RenovaBio's objective was not to create a carbon tax, offer subsidies, or create mandates for the use of biofuels instead of fossil fuels, but to establish a strategic role for biofuels of all types in the national energy matrix, both in terms of energy security and mitigation of GHG emissions [16]. It is important to point out that, through the composition of 27% of hydrated ethanol for the formulation of gasoline, this policy was responsible for a reduction of more than 300 million tons of CO2 in the period from March 2003 (beginning of production of flex-cars) to May 2015 [17]. For comparative purposes, this amount is equivalent to Poland's annual emissions, considered one of the largest pollutants in the world due to the great use of coal [17].

According to Lee and Yoon [18], there are basically three reasons that bring the fossil energy markets closer to the renewable ones: (i) the use of fossil fuels increases carbon emissions; (ii) population and economic growth, especially in emerging countries, boost carbon emissions and their prices; (iii) the use of renewable energies can replace fossil energy and thus reduce carbon emissions. Through the integration of financial markets with energy products, both traditional (oil) and new markets (renewable energy and carbon), the prices of such assets may be more closely correlated.

Dutta [19] studied the relationship between carbon emission prices and biodiesel in the European Union and found that both prices move in the same direction. In addition, price correlations are dynamic, that is, they tend to vary over time. Finally, the author suggests that the price risks of clean energy stocks can be diversified if investors include both renewable energy assets and a commodity volatility index in their portfolio.

Since its inception, the European Union's emissions trading system (EU-ETS) has been very efficient in reducing greenhouse gas (GHG) emissions, and in 2015, the volume of GHGs in the EU−28 was 22% below the 1990s levels, which means a decrease of 1265 million tonnes of CO2 equivalent [20]. In this way, the European Union Allowance (EUA) emerged as an important financial sector. It is noteworthy that the EU-ETS is the largest carbon emission allowance market, representing 84% of the global carbon market value. [20].

Dutta and Bouri [20] found that a rise in carbon emission prices tends to increase Brazilian ethanol prices, supporting the hypothesis that carbon emissions and ethanol prices move in the same direction. The authors claim that this result is not surprising, given that higher carbon prices encourage investments in ethanol, which can cause an increase in its price. They also found that the intensity of volatility jumps varies with time, and it is persistent, that is to say, a high probability of many (few) jumps today tends to be followed by many (few) jumps tomorrow.

It is important to note that the relationship between Brazilian ethanol prices and carbon emissions is little explored in the literature, and to the best of our knowledge, the only work is the innovative investigation by [20].

Our investigation aims to expand the investigation of [20] by verifying whether carbon emission prices are correlated with Brazilian hydrated ethanol prices, in different time scales, both in the short and long run. This issue is relevant because the questions about the impact of carbon emission prices upon a key biofuel source, such as bioethanol, tend to focus on its early stages.

There are a myriad of agents (government, industry, and financial institutions, among others) that are interested in whether these price linkages have different horizons such that different investment returns can be expected over time. Therefore, we intend to offer new evidence that could be important to the society as a whole and in particular to policymakers and investors.

The findings of Dutta and Bouri [20] would lead to the expectation that a rise in carbon emission prices is positively related to ethanol prices, such that these should move in the same direction. However, new questions arise when the long-run trends are important for decision making. Assuming that a great amount of investment is made on less-carbon emission fuel production, such as bioethanol, it could be expected that in the short run, a positive relationship between the price at both ethanol and CO2 emissions could prevail. However, as more bioethanol is produced, its price tends to decrease. Should one expect that carbon emission prices are also expected to decrease due to that? What if people start to value more those companies that invest in decreasing CO2 emissions not necessarily related to fuel production? Is there any reason to expect that CO2 related bonds would also decrease in the longer run? In this paper, we expect to bring new evidence to contribute to this debate.

Therefore, the main objective of this research is to investigate the cross-correlation between Brazilian ethanol prices and carbon emission prices. Besides analysis of the degree of association between ethanol and carbon emission prices, we also analyze the relationship with oil prices (as a dirty energy), natural gas (a quasi-dirty one), and sugar prices, due to Brazilian sugar and ethanol originating in sugarcane [3].

Using daily data, and including underexplored commodities in relation to biofuels, such as carbon emission prices, which have the appeal of being environmentally friendly, we also contribute to the growing literature on ESG investments. Secondly, we use a recent and robust methodology, a dynamic version of the DCCA, as we consider a sliding windows approach [21,22], which in addition to having the relevant properties of its static counterpart, can provide a dynamic view of the forces of association and thus the effects of shocks on market movements, as well as their changes and trends. Thirdly, as our sample has a daily periodicity, it provides a larger sample and a high frequency follow-up between these markets. The size of the sample is another important feature of this study, being in line with the study by Dutta and Bouri [20], which ends in 2017, allowing us to capture important effects such as the beginning of RenovaBio, launched in 2017, the 2018 lorry-driver crisis, and the emergence of COVID-19 on the global stage.

We develop a dynamic cross-correlation analysis (DCCA) as proposed by [21,22], using a sliding windows approach. The DCCA coefficient was proposed by [23] in order to analyze the correlation of two series efficiently [24], with desirable properties [25] and in various time scales, not restricted to the short-term versus long-term dichotomy.

This article is structured as follows: after this introduction, Section 2 contains the review of the literature, Section 3 presents the methods and data, Section 4 analyzes the results, and finally, Section 5 presents the conclusions.

**2.2 Brief Literature Review**

The literature contains several studies and debates about the relationship between the prices of ethanol and other assets, as is the case of the debate on food versus fuel prices, which can be followed through an excellent survey by [2]. In particular, Table 1 identifies the main investigations in this survey that involve Brazilian ethanol directly. For a more comprehensive view, involving not only ethanol but also biofuels in general in several countries or economic blocks, with emphasis on the US and European Union, see [2].

**Table 1**. Some papers analyzing Brazilian ethanol.

| Reference | Period | Main Findings |
|---|---|---|
| Rapsomanikis and Hallam [26] | 2000–2006 | Oil prices determine both sugar and ethanol prices and there is no evidence of causal relationship from oil to ethanol and from ethanol to sugar |
| Serra et al. [27] | 2000–2008 | Evidence of relationship between food (sugar) and fuel (ethanol) in prices and volatilities |
| Kristoufek et al. [28] | 2002–2014 | Evidence of relationship between prices of ethanol and sugar (Brazil) and corn (USA) |
| Bentivoglio et al. [29] | 2007–2013 | Food (sugar) and fuel (gasoline) prices influence ethanol prices, but there is no evidence that ethanol impacts food prices |
| Capitani et al. [30] | 2010–2016 | Weak relationship between ethanol prices (USA and Brazil) |
| Dutta [31] | 2003–2016 | Oil and sugar prices affect Brazilian ethanol prices, but sugar is not influenced by ethanol. |

Source: adapted from [2]

In economics and finance, there is substantial literature already developed that has applied the DCCA method with the purpose of calculating cross-correlations in a robust framework. Those studies dealing with finance and sustainability include, among many others, the climate's influence on stock prices [32] and the analysis of agricultural futures prices [33]. In addition, Wang et al. [34] studied the cross-correlations between energy markets (oil and natural gas) and carbon emission markets, through the DCCA and multifractal DCCA. Another application concerns the correlation between oil prices and renewable energy stock prices [35]. Fan et al. [36] studied the relationship between carbon prices and coal prices, in seven main locations in China, via DCCA. Ferreira et al. [37] used the DCCA to verify the possibility of portfolio diversification via assets of renewable energy companies. Ferreira and Loures [38] is another recent example of applying the DCCA in the context of renewable energy. In this case, to verify the correlation between the S&P Global Clean Energy Index and the New York Stock Exchange (NYSE) and oil prices.

Among previous studies related to the ethanol market (or related goods) in Brazil via DCCA, Siqueira Jr [39] et al. analyzed the correlations and cross-correlations in the Brazilian market for commodities (including sugar) and shares on the Brazilian stock exchange. More recently, Nascimento Filho et al. [40] studied the cross-correlations in the gasoline retail market in the main Brazilian capitals and Murari et al. [41] performed a comparative analysis of the Brazilian gasoline and ethanol markets. Lima et al. [42] studied the cross-correlations and partial cross-correlations of ethanol, sugar, and oil in Brazil.

### 2.3 Material and methods

The present work uses daily data of future prices of carbon emissions (EU allowance) and Brazilian ethanol prices in the spot market. Oil prices (Brent type) are a reference for the Brazilian market [43,44], as well as for natural gas prices, which is also an important energy commodity [18,34]. Sugar prices refer to the New York contract number 11 (Sugar #11) due to its high liquidity and since it is a common price index used by agents operating in the Brazilian market (both domestic and international). Natural gas is the second largest energy commodity, but crude oil (WTI and Brent) is the main asset in this category, with more traded goods and financial contracts. According to Li [45], as of January 2016, natural gas accounts for 8.7% of the Dow Jones Commodity Index (DJCI), while crude oil accounts for 19.7%. Natural gas prices refer to the NYMEX Natural Gas Futures.

Therefore, these have been chosen as control variables (benchmark). We consider continuous future prices for the present analysis, since these assets are highly liquid for hedging or risk diversification for global economic agents. Carbon emissions, oil, natural gas, and sugar prices were collected through the Quandl platform (www.quandl.com, accessed on 23 August 2021). Regarding hydrated ethanol prices, we selected spot prices for the São Paulo market, calculated daily by CEPEA (Center for Advanced Studies on Applied Economics, https://www.cepea.esalq.usp.br/br, accessed on 23 August 2021). We chose to use the spot prices of Brazilian ethanol rather than the future prices of the Brazilian Stock Exchange (B3), since we considered it more representative of the market dynamics. As pointed out by

[30,46,47], the futures contracts of the domestic stock exchange have low liquidity, with few contracts traded, being characterized as a thin market.

Energy commodities, more specifically oil and natural gas, have become an asset class used widely for diversification, hedging, or speculation. Investors, hedgers, speculators, and policy-makers have used these commodities as an alternative investment instrument, in order to protect themselves from equity market risk [48].

The analysis period is from 25 January 2010 to 31 July 2020, with a total of 2428 observations. The beginning of the sample is according to the emergence of the daily hydrated ethanol price indicator in Brazil. Figure 2 illustrates the behavior of price returns , $r(t)$, defined by $r(t) = \ln p_t - \ln p_{t-1}$,where $p_t$ is the asset price on date *t*.

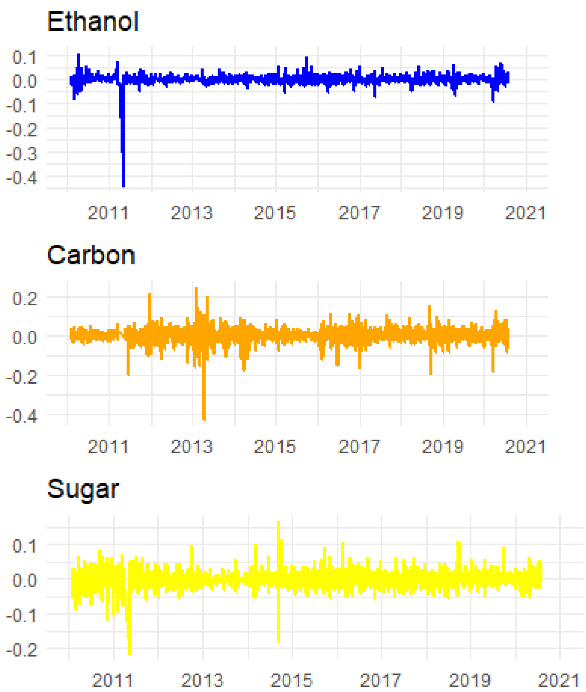


Figure 2. Price returns of Brazilian hydrated ethanol, oil, carbon emission, natural gas and sugar.

Aiming to analyze the cross-correlations between Brazilian ethanol prices and carbon emissions prices, we use the dynamic DCCA with sliding windows, as recently proposed by [21,22] and also implemented as empirical strategy by [49,50]. Therefore, we present the DCCA proposed by [51] and DCCA correlation coefficient stated by [23]. In order to clarify the steps of the DCCA procedure, we split it into five steps, following the presentation of [40,41]

i) Consider two series $x_k$ and $y_k$ where $k = 1,2, \dots , N$, with equidistant observations and calculate $x(t) = \sum_{k=1}^{t} x_k$ and $y(t) = \sum_{k=1}^{t} y_k$ ;

ii) Next, we divide the sample in boxes of dimension $n$ and so divided into $(N - n)$ overlapping boxes. The purpose of this procedure is to calculate local trends $\tilde{x}(t)$ and $\tilde{y}(t)$ of each series through ordinary least squares (OLS) and estimate the trend of each box, linear in our case, and the size of each box is in the interval between $4 \leq n \leq N/4$ ;

iii) Subsequently, we calculate the difference between the original series and the estimated trend, in order to obtain series without trend (detrended), and thus, we calculate the detrended covariance of the residues of each box of both series, which are given by $f_{DCCA}^2 = \frac{1}{n-1} \sum_{k=1}^{i+n} (x_k - \tilde{x}_k)\,(y_k - \tilde{y}_k)$ ;

iv) Afterwards, we have the sum of covariance of all boxes of size *n*, in order to obtain the detrended covariance given by $F_{DCCA}^2(n) = \frac{1}{N-n} \sum_{i=1}^{N-n} f_{DCCA}^2$. The process is continued for all lengths of the boxes, in order to obtain an expression for the relationship between DCCA fluctuations as a function of *n*. More specifically, the purpose is to find a relationship between $F_{DCCA}^2(n) \sim n^{\lambda}$, where the parameter $\lambda$ is the relevant one to evaluate the long-term cross-correlation. If $\lambda > 0.5$, the series demonstrates a persistent long-term cross-correlation; in the case of $\lambda < 0.5$, we have anti-persistent behaviour, and finally if $\lambda = 0.5$, there is no relationship between the variables;

v) Zebende [23] established the concept of the DCCA coefficient, $\rho_{DCCA}$, based on the relationship between DFA (Detrended Fluctuation Analysis) and DCCA, as $\rho_{DCCA}(n) = \frac{F_{DCCA}^2(n)}{F_{DFA\{x\}}(n)\, F_{DFA\{y\}}(n)}$, where $DFA_{\{x\}}$ and $DFA_{\{y\}}$ measure the degree of long-term dependence of each individual series, according to the definition of [52].

According to [24], the DCCA coefficient is efficient. Furthermore, it is between -1 as the minimum value (perfect anti-correlation) and +1 as the maximum value (perfect correlation), namely, $-1 \leq \rho_{DCCA} \leq 1$, and in case of a null value ($\rho_{DCCA} = 0$) we have the absence of correlation [24]. In addition, the critical values of $\rho_{DCCA}$ as a function of time scales were calculated by [53], so that we can test its statistical validity.

Similar to [22], we use a moving sample with 500 observations, and due to the use of sliding windows, we can have scales between 4 and 128 days. In addition, considering that we have data on a daily basis, the 128-day interval (about 6 months) can be seen as a long-term analysis. A useful illustration of how the sliding window calculation is performed, given the sample size and as a function of time dynamics, is illustrated in Figure 3.

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $X(t)$ = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | ... | 500 | 501 | 502 | 503 | 504 | ... | N |
| $Y(t)$ = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | ... | 500 | 501 | 502 | 503 | 504 | ... | N |
| $n(1)$ = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | ... | 500 | → | $\rho_{DCCA}(1)$ | | | | |
| $n(2)$ = | | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | ... | 500 | 501 | → | $\rho_{DCCA}(2)$ | | | |
| $n(3)$ = | | | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | ... | 500 | 501 | 502 | → | $\rho_{DCCA}(3)$ | | |
| $n(4)$ = | | | | 4 | 5 | 6 | 7 | 8 | 9 | 10 | ... | 500 | 501 | 502 | 503 | → | | $\rho_{DCCA}(4)$ |
| ... | | | | | | | | | | | | | | | | | | ... |
| $n(k)$ = | | | | | | | | | | | | | | | | | $\rho_{DCCA}$ | $(k)$ |

Figure 3. Example of the sliding window procedure (adapted from [22]).

## 2.4 Results and Discussions

Figure 4 shows the results of the correlation coefficients between ethanol and the remaining commodities over time scales between 4 and 256 days (approximately 1 year). Values located between the lower and upper limits (dashed lines) are not statistically significant, whereas values above the upper limit and below the lower one has significance.

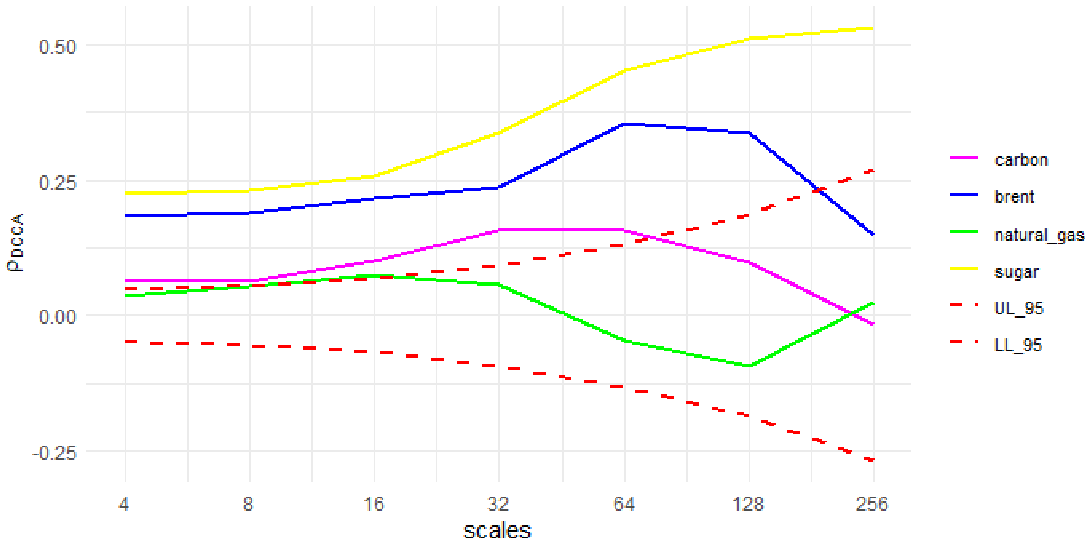


Figure 4. Detrended cross-correlation analysis coefficient - $\rho_{DCCA}$ - between ethanol and the remaining commodities, for the whole time period, depending on n (time scales, in days). Dashed lines represent lower and upper critical values to analyze the absence of correlation, according to [53].

It can be seen that ethanol has a positive correlation with sugar during all the time scales, with an increased correlation in the long run (higher time scales). Regarding the other commodities, we can also see a significant and positive relationship with oil, during most of the time scales, although, in the long run, it is not significant. Regarding carbon, and despite the significance of the correlationship up to 64 days, correlation levels are lower, and, in the long run, they are not significant. Finally, considering natural gas, the evidence is of non-significance of the correlations.

In view of the recent changes in the dynamics of energy prices in the world, due to the coronavirus crisis and geopolitical aspects related to oil prices [18], as well as in the Brazilian ethanol market, with the new fuel pricing policy and the lorry-driver crisis [54], it is important to verify how the temporal dynamics of cross-correlations are dealt with.

In our next step, we will analyze the correlation dynamically, considering a fixed window (w) of 500 days, with time scales of 4, 8, 16, 32, 64, and 128 days. Figure 5, Figure 6, Figure 7, Figure 8, Figure 9 and Figure 10 have the values of the detrended cross-correlation analysis coefficient, $\rho_{DCCA}$, as well as the confidence interval, namely, values of $\rho_{DCCA}$ that are between the dashed lines indicate that the correlation is not statistically significant. On the contrary, if the values of $\rho_{DCCA}$ are outside the dashed line limits (i.e., higher or lower values), they indicate that the correlations are statistically significant. Next, we will elucidate the results for each calculated time interval. For robustness purposes, we also employed the correlations using other window sizes, namely w = 250 (windows of about one year) and w = 750 (windows of about three years). The figures are presented in Appendix (Figure A1, Figure A2, Figure A3, Figure A4, Figure A5, Figure A6, Figure A7, Figure A8, Figure A9, Figure A10 and Figure A11) and show qualitatively similar results.

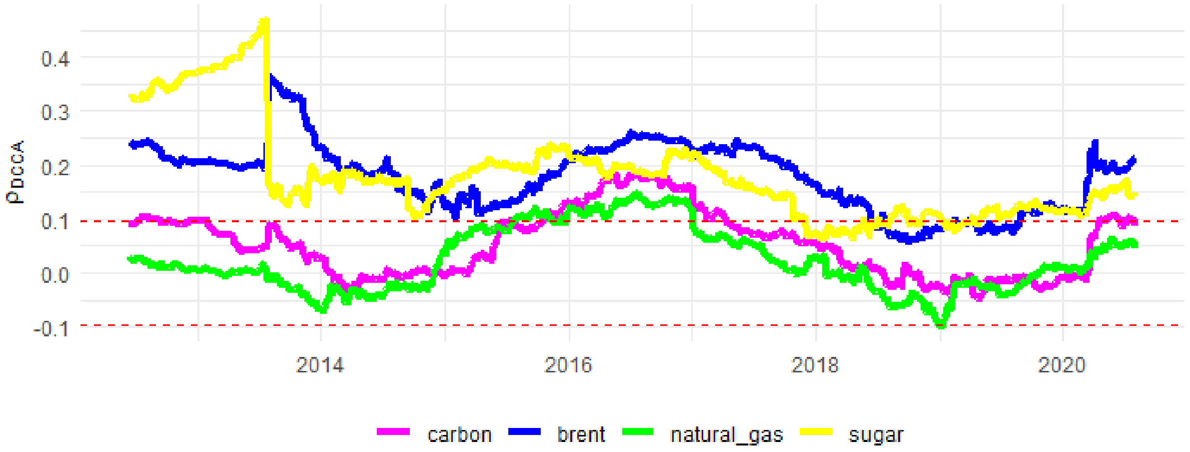


Figure 5. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 4 days and window size w = 500. Dashed lines represent critical values for statistical significance, according to [53].

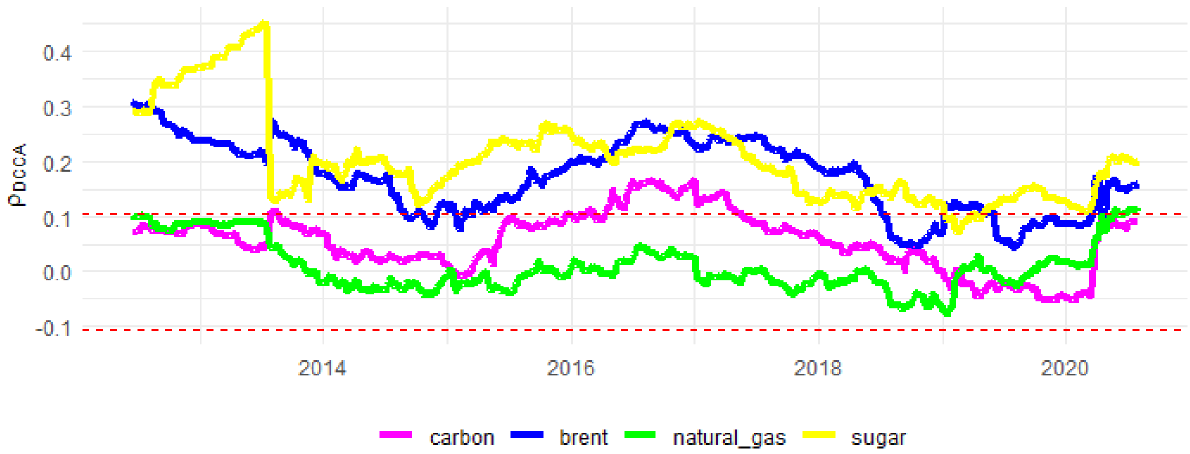


Figure 6. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 8 days and window size w = 500. Dashed lines represent critical values for statistical significance, according to [53].

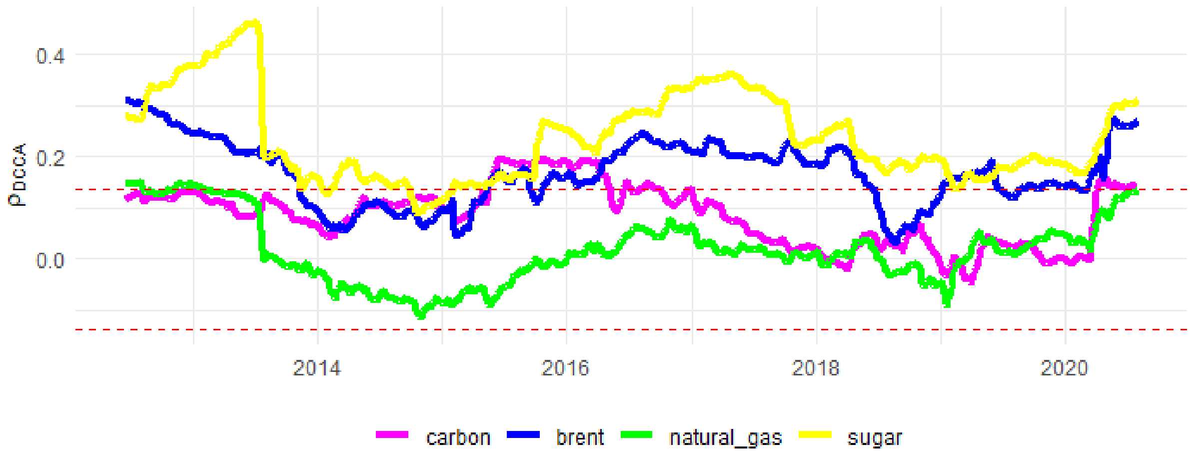


Figure 7. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 16 days and window size w = 500. Dashed lines represent critical values for statistical significance, according to [53].

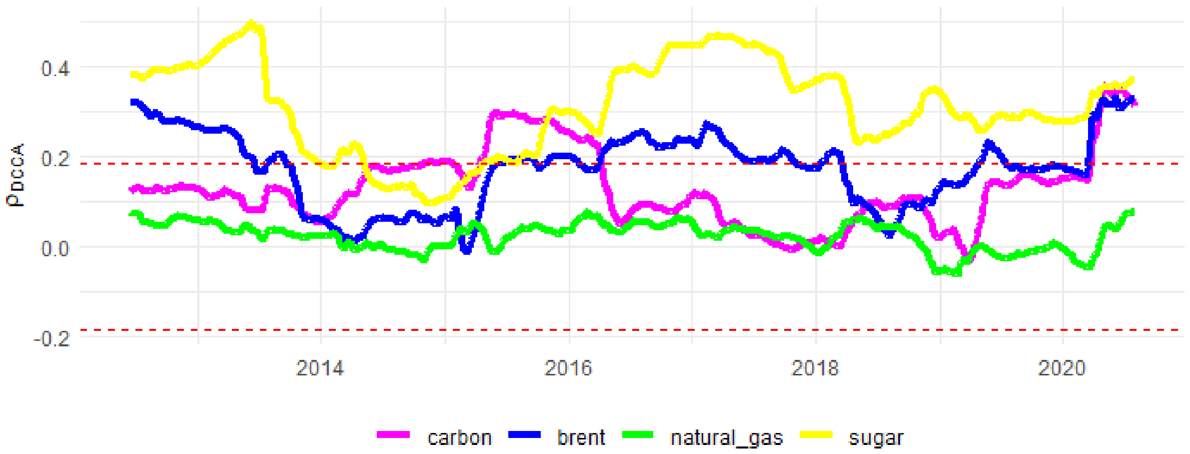


Figure 8. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 32 days and window size w = 500. Dashed lines represent critical values for statistical significance, according to [53].

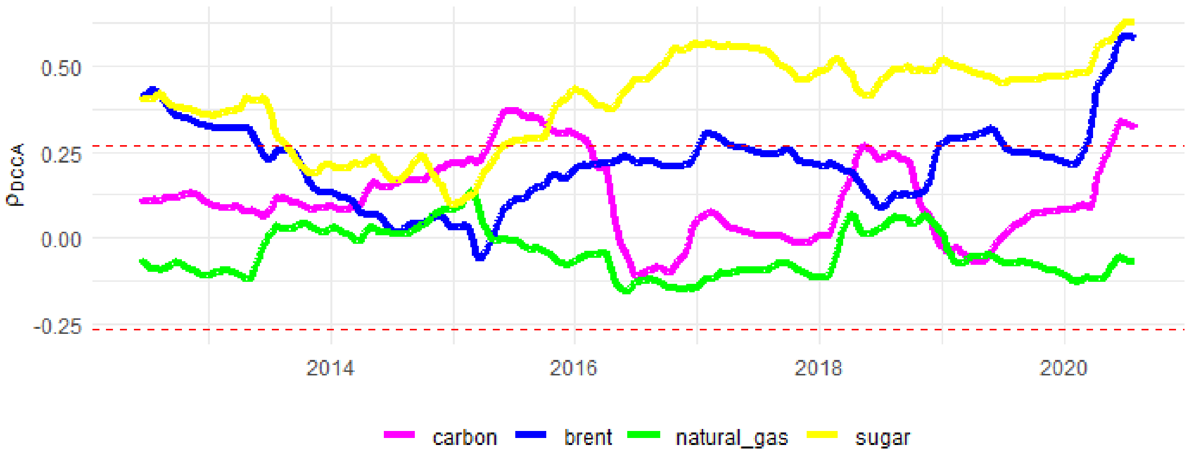


Figure 9. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 64 days and window size w = 500. Dashed lines represent critical values for statistical significance, according to [53].

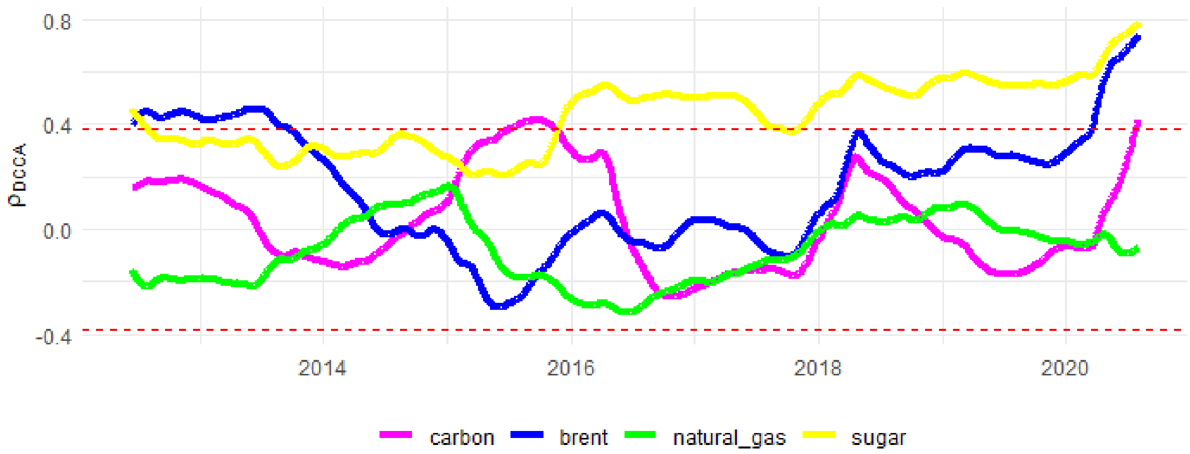


Figure 10. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 128 days and window size w = 500. Dashed lines represent critical values for statistical significance, according to [53].

In the four-day time interval (Figure 5), with the exception of a short time between 2016 and 2017, the correlation of ethanol with carbon emissions is not statistically significant, but is of weak magnitude, lower than 0.2. Similar behavior occurs with the correlation with natural gas. In relation to oil and sugar, the correlation is significant during most of the period under analysis, although with higher correlation levels until the end of 2013. In the case of oil, this result could be related to the sharp drop in its price, from approximately USD 100 per barrel in August 2014 to values close to USD 50 in January 2015 [55]. When considering both the 8-day window (Figure 6) and the 16-day window (Figure 7), the results are very similar, with no qualitative changes in the analysis made in the very short period of 4 days.

Changes in the pattern of correlations can be seen in the time scale of 32 days (Figure 8). We continue to observe a positive and almost always significant correlation with sugar price. Regarding carbon emissions, non-significant correlations are found, except in the period between 2015 and 2016, as well as more recently, in 2020, with the joint crisis of oil and coronavirus. In this case, in the post-COVID-19 period, the ethanol correlation gains strength and shows practically the same correlation pattern with oil. Regarding oil, correlation levels are significant at the beginning of the sample, as well as during some months between 2016 and 2017, and at the end of the sample post-2020, which could be related to the impact of the COVID-19 pandemic.

In the longer scales, namely 64 days (Figure 9) and 128 days (Figure 10), corresponding to the long run, we can see that ethanol just shows some significant correlation with sugar, especially post-2016, and more marginally with oil prices pre-2014, again showing strong force only during the COVID-19 pandemic period (post-2020). In this sense, we have evidence of the segmentation between the different assets, namely, sugar and oil versus carbon emissions and natural gas.

In addition, as stated by [56], the time varying correlation between crude oil and gas is not constant over time, because the two prices follow a completely divergent path, and this is why the correlation between them is reduced. The authors suggest that the shale revolution might have affected this volatility spillover. Therefore, in our investigation, this helps to explain why we have different correlation estimates between ethanol and oil and between ethanol and natural gas.

In order to develop the Brazilian ethanol market, aiming to be a global agent contributing to the fight against global warming, it is necessary to invest on three important fronts, among others: (i) productivity increases in the ethanol supply, (ii) greater energy efficiency of bi-fuel cars (flex), and (iii) ethanol price risk management mechanisms.

Firstly, Brazilian ethanol production has grown at an average rate of 1.2% per year in the last decade, much lower than the explosive growth of the 1970s, when ProÁlcool was created, and in the 2000s, with the emergence of flex fuel cars [16]. Almost all ethanol produced in Brazil is first generation ethanol, and therefore, it is necessary to invest in technological development for second generation (2G) ethanol [16,57]. This is already produced in Brazil, but the conversion process is still not established, and it is expected to be economically attractive by 2025 [16,57].

Regarding the second item, in 2012, through Decree 70819/12, the government’s Inovar-Auto program was launched, aiming to boost the level of innovation in the Brazilian automobile industry through incentives for investment in R&D, in order to produce safer and efficient use of energy, as only a small fraction of vehicles have energy-efficient technologies [58]. However, there was no evidence of the expected effect. On the contrary, it turned out to be a protectionist measure, giving tax exemption to domestic producers, in the face of international competition [58]. Furthermore, despite the high profit margin of the Brazilian automobile industry compared to those of the US and the European Union, large companies employ low-cost technologies for the domestic supply [58].

Finally, sugarcane, a raw material used in the production of both sugar and ethanol, has production cycles, with a harvest every 12 or 18 months, which is reflected in the seasonality of its final prices [41]. The first quarter of the year is the off-season period, where ethanol prices tend to be higher if there is not enough in stocks at mills and/or distributors [3]. The hydrated market is more dynamic than the anhydrous one (mixed with gasoline) and more subject to seasonality and competitive conditions in regional markets [47]. According to [59], a liquid ethanol futures market could reduce the different sources of uncertainty that affect biofuel prices, in order to provide more predictable bases for future prices and thus help manage the risk of these industries more efficiently. However, in the Brazilian case, as highlighted above, ethanol futures contracts did not show sufficient strength to create liquidity and thus does not offer a consolidated ethanol price risk management tool in the domestic market [30,46,47].

In this paper, we aim to contribute to understanding more clearly the possible connections of ethanol prices and therefore contribute to filling the gap regarding the third item.

## 2.5 Conclusions

In this article, using a robust dynamic cross-correlation methodology recently proposed by [21,22] and empirical evidence based on fresh data from the Brazilian ethanol spot prices and carbon emissions futures prices, we calculate the correlation between January 2010, the start of the Brazilian ethanol daily indicator, and July 2020. As a comparative framework for energy prices, the correlations of the Brazilian ethanol with the prices of Brent oil, natural gas, and sugar were also calculated. The price relations of carbon emissions and ethanol prices have not yet been sufficiently explored, and in this investigation, we seek to contribute to filling this gap. To the best of our knowledge, the notable exception is the investigation of [20].

The cross-correlations were considered in two scenarios: the first with a complete sample, and the second through sliding windows of 500 observations (approximately 2 years considering daily time series), in different time scales: 4, 8, 16, 32, 64, and 128 days. As a robustness test, we also consider other windows sizes (250 and 750 observations), which bring in general similar qualitative results of our basis scenario of 500 observations.

In the analysis of the complete sample, we observed that ethanol has a weak correlation with carbon emission prices, and only in the short term, that is, considering the scale of up to 64 days. In relation to sugar, as expected, we obtained an expressive and increasing positive association with larger scales. In comparison with oil prices, there is a statistically significant correlation, only in the short term, in our case, the period of less than 128 days, about 6 months. Finally, with natural gas, we do not observe any significant association.

Our results with regard to correlation between Brazilian ethanol with carbon emissions prices are somewhat different from those obtained by [20], which showed the existence of a positive correlation. Here, we have evidence of a weak or even non-significant correlation, mainly in the short run. Furthermore, the moving windows show that the correlation is time-dependent, varying according to the period analyzed, because in certain periods and specific time scales, no significant correlation is observed. However, it is important to note that the use of different methodologies and databases could be also relevant in explaining the different results.

In this sense, we believe that our results make an important contribution to decision-making by private sector agents in forming their portfolio and seeking assets with the potential to diversify market risks or hedging strategies, depending on the time horizon of analysis and the degree of protection they want to achieve. In addition to the long-term view, represented here by just over 10 years of series coexistence, moving windows provide a view of the short-term dynamics of the correlations between such assets. The results are also important for policy-makers, giving important information on the price dynamics of carbon emissions and Brazilian ethanol, as these prices reflect the trade-off of non-renewable energy versus an important source of clean energy.

It is important to note that our results also have implications for researchers. We found evidence that ethanol's relationships with both oil and sugar are non-linear, and thus, the use of time series techniques that take this into account are appropriate in order to have a more robust view of the possible existence of such relationships. Furthermore, with the use of sliding windows, we have evidence of time-dependent behavior, with greater or lesser levels of correlation depending on current situations, such as the lorry drivers' strike (May 2018) that paralyzed the Brazilian economy for weeks, as well as structural supply and demand shocks, in the wake of the outbreak and worsening of the COVID-19 crisis. Such shocks, especially if accompanied by changes in international oil prices, can cause great oscillation in the normal conditions of renewable energy prices, including Brazilian ethanol.

We also consider it could be interesting to use other different methodologies to assess the possible correlation changes in different market conditions, such as the cross-quantilogram methodology (see, for example, [60]), this being a possibility for future research.

## References

1. Figueira, S.R.F.; Burnquist, H.L.; Bacchi, M.R.P. Forecasting fuel ethanol consumption in Brazil by time series models: 2006–2012. **Appl. Econ**. 2010, 42, 865–874. [CrossRef]

2. Janda, K.; Kristoufek, L. The Relationship between Fuel and Food Prices: Methods and Outcomes. **Annu. Rev. Resour. Econ**. 2019,11, 195–216. [CrossRef]

3. David, S.A.; Quintino, D.D.; Inacio Junior, C.M.C.; Machado, J.T. Fractional dynamic behavior in ethanol prices series. **J. Comput.Appl. Math**. 2018, 339, 85–93. [CrossRef]

4. Costa, C.C.; Burnquist, H.L.; Guilhoto, J.J.M. Special safeguard tariff impacts on the Brazilian sugar exports. **J. Int. Trade Law Policy** 2015, 14, 70–85. [CrossRef]

5. Santos, J.A.D.; Ferreira Filho, J.B.D.S. **Substituição de Combustíveis Fósseis por Etanol e Biodiesel no Brasil e Seus Impactos Econômicos**: Uma Avaliação do Plano Nacional de Energia 2030. 2017. Available online: http://repositorio.ipea.gov.br/handle/11058/8231 (accessed on 15 July 2020).

6. Goldemberg, J. Ethanol for a Sustainable Energy Future. **Science** 2007, 315, 808–810. [CrossRef]

7. Coelho, S.T.; Goldemberg, J.; Lucon, O.; Guardabassi, P. Brazilian sugarcane ethanol: Lessons learned. **Energy Sustain. Dev**. 2006,10, 26–39. [CrossRef]

8. IEMA. **Inventário De Emissões Atmosféricas Do Transporte Rodoviário De Passageiros No Município De São Paulo**; IEMA: Sao Paulo, Brasil, 2020; Available online: http://emissoes.energiaeambiente.org.br/graficos (accessed on 10 September 2020).

9. Debone, D.; Da Costa, M.; Miraglia, S. 90 Days of COVID-19 Social Distancing and Its Impacts on Air Quality and Health in Sao Paulo, Brazil. **Sustainability** 2020, 12, 7440. [CrossRef]

10. EPE. Empresa de Pesquisa Energética. **Análise de Conjuntura dos Biocombustíveis**. 2019. Available online: http://www.mme.gov.br (accessed on 15 July 2020).

11. EPE. **Balanço Energético Nacional 2020**: Ano-Base 2019; Empresa de Pesquisa Energética: Rio de Janeiro, Brazil, 2020. Available online: www.epe.gov.br (accessed on 15 July 2020).

12. Rosa, L.P.; Oliveira, L.B.; Costa, A.O.; Pimenteira, C.A.; Mattos, L.B. Geração de Energia a partir de resíduos sólidos. In Tolmasquim, M.T (Coord) **Fontes Alternativas**, 515; Editora Interciência, COPPE, UFRJ: Rio de Janeiro, Brazil, 2003.

13. MCTI. **Fatores de Emissão de CO2 Para Utilizações que Necessitam do Fator Médio de Emissão do Sistema Interligado Nacional do Brasil, Como, por Exemplo, Inventários Corporativos**; Ministério da Ciência, Tecnologia e Inovação: Brasília, Brazil, 2020. Available online: www.mct.gov.br (accessed on 15 July 2020).

14. BRASIL. Lei n_ 13.576, de 26 de Dezembro de 2017. **Dispõe sobre a Política Nacional deBiocombustíveis (RenovaBio) e dá Outras Providências**; Diário Oficial da União: Brasília, Brazil, 2017. Available online: www.planalto.gov.br (accessed on 15 July 2020).

15. Klein, B.C.; Chagas, M.F.;Watanabe, M.D.B.; Bonomi, A.; Maciel Filho, R. Low carbon biofuels and the New Brazilian National Biofuel Policy (RenovaBio): A case study for sugarcane mills and integrated sugarcane-microalgae biorefineries. **Renew. Sustain. Energy Rev**. 2019, 115, 109365. [CrossRef]

16. Karp, S.G.; Medina, J.D.C.; Letti, L.A.J.; Woiciechowski, A.L.; de Carvalho, J.C.; Schmitt, C.C.; Penha, R.D.O.; Kumlehn, G.S.; Soccol, C.R. Bioeconomy and biofuels: The case of sugarcane ethanol in Brazil. **Biofuels Bioprod. Biorefining** 2021,15, 899–912. [CrossRef]

17. da Rocha Lima Filho, R.I.; de Aquino, T.C.N.; Neto, A.M.N. Fuel price control in Brazil: Environmental impacts. **Environ. Dev.Sustain**. 2021, 23, 9811–9826. [CrossRef]

18. Lee, Y.; Yoon, S.-M. Dynamic Spillover and Hedging among Carbon, Biofuel and Oil. **Energies** 2020, 13, 4382. [CrossRef]

19. Dutta, A. Impact of carbon emission trading on the European Union biodiesel feedstock market. **Biomass-Bioenergy** 2019,128, 105328. [CrossRef]

20. Dutta, A.; Bouri, E. Carbon emission and ethanol markets: Evidence from Brazil. **Biofuels Bioprod. Biorefining** 2019,13, 458–463. [CrossRef]

21. Guedes, E.F.; Zebende, G.F. DCCA cross-correlation coefficient with sliding windows approach. **Phys. A Stat. Mech. Appl**. 2019, 527, 121286. [CrossRef]

22. Tilfani, O.; Ferreira, P.; Boukfaoui, E.; Youssef, M. Dynamic cross-correlation and dynamic contagion of stock markets: A sliding windows approach with the DCCA correlation coefficient. **Empir. Econ**. 2021, 60, 1127–1156. [CrossRef]

23. Zebende, G. DCCA cross-correlation coefficient: Quantifying level of cross-correlation. **Phys. A Stat. Mech. Appl**. 2011, 390, 614–618. [CrossRef]

24. Kristoufek, L. Measuring correlations between non-stationary series with DCCA coefficient. **Phys. A Stat. Mech. Appl**. 2014, 402, 291–298. [CrossRef]

25. Zhao, X.; Shang, P.; Huang, J. Several fundamental properties of dcca cross-correlation coefficient. **Fractals** 2017, 25, 1750017. [CrossRef]

26. Rapsomanikis, G.; Hallam, D. Threshold Cointegration in the Sugar-Ethanol-Oil Price System in Brazil: Evidence from Nonlinear Vector Error Correction Models; FAO Commodity and Trade **Policy Research Working Paper**, 22; FAO: Rome, Italy, 2006.

27. Serra, T.; Zilberman, D.; Gil, J. Price volatility in ethanol markets. **Eur. Rev. Agric. Econ**. 2011, 38, 259–280. [CrossRef]

28. Kristoufek, L.; Janda, K.; Zilberman, D. Comovements of ethanol-related prices: Evidence from Brazil and the USA. **GCb Bioenergy** 2016, 8, 346–356. [CrossRef]

29. Bentivoglio, D.; Finco, A.; Bacchi, M.R.P. Interdependencies between biofuel, fuel and food prices: The case of the Brazilian ethanol market. **Energies** 2016, 9, 464.

30. Capitani, D.H.D.; Junior, J.C.C.; Tonin, J.M. Integration and hedging efficiency between Brazilian and US ethanol markets. **Contextus** 2018, 16, 93–117. [CrossRef]

31. Dutta, A. Cointegration and nonlinear causality among ethanol-related prices: Evidence from Brazil. **GCB Bioenergy** 2018, 10, 335–342. [CrossRef]

32. Cao, G.; Han, Y. Does the weather affect the Chinese stock markets? Evidence from the analysis of DCCA cross-correlation coefficient. **Int. J. Mod. Phys**. B 2014, 29, 1450236. [CrossRef]

33. Cao, G.; He, C.; Xu,W. Effect of Weather on Agricultural Futures Markets on the Basis of DCCA Cross-Correlation Coefficient Analysis. **Fluct. Noise Lett**. 2016, 15, 1650012. [CrossRef]

34. Wang, G.-J.; Xie, C.; Chen, S.; Han, F. Cross-Correlations between Energy and Emissions Markets: New Evidence from Fractal and Multifractal Analysis. **Math. Probl. Eng**. 2014, 2014, 197069. [CrossRef]

35. Paiva, A.S.S.; Rivera-Castro, M.A.; Andrade, R.F.S. DCCA analysis of renewable and conventional energy prices. **Phys. A Stat. Mech. Appl**. 2018, 490, 1408–1414. [CrossRef]

36. Fan, X.; Li, X.; Yin, J. Dynamic relationship between carbon price and coal price: Perspective based on Detrended Cross-Correlation Analysis. **Energy Procedia** 2019, 158, 3470–3475. [CrossRef]

37. Ferreira, P.; Loures, L.; Nunes, J.; Brito, P. Are renewable energy stocks a possibility to diversify portfolios considering an environmentally friendly approach? The view of DCCA correlation coefficient. **Phys. A Stat. Mech. Appl**. 2018, 512, 675–681. [CrossRef]

38. Ferreira, P.; Loures, L.C. An Econophysics Study of the S&P Global Clean Energy Index. **Sustainability** 2020, 12, 662.

39. Siqueira, E.L., Jr.; Stoši´c, T.; Bejan, L.; Stoši´c, B. Correlations and cross-correlations in the Brazilian agrarian commodities and stocks. **Phys. A Stat. Mech. Appl**. 2010, 389, 2739–2743. [CrossRef]

40. Filho, A.N.; Pereira, E.; Ferreira, P.; Murari, T.; Moret, M. Cross-correlation analysis on Brazilian gasoline retail market. **Phys. A Stat. Mech. Appl**. 2018, 508, 550–557. [CrossRef]

41. Murari, T.B.; Filho, A.S.N.; Pereira, E.J.; Ferreira, P.; Pitombo, S.; Pereira, H.B.; Santos, A.A.; Moret, M.A. Comparative Analysis between Hydrous Ethanol and Gasoline C Pricing in Brazilian Retail Market. **Sustainability** 2019, 11, 4719. [CrossRef]

42. Lima, C.R.A.; de Melo, G.R.; Stosic, B.; Stosic, T. Cross-correlations between Brazilian biofuel and food market: Ethanol versus sugar. **Phys. A Stat. Mech. Appl.** 2019, 513, 687–693. [CrossRef]

43. Cavalcanti, M.; Szklo, A.; Machado, G. Do ethanol prices in Brazil follow Brent price and international gasoline price parity? Renew. **Energy** 2012, 43, 423–433. [CrossRef]

44. Goldemberg, J.; Schaeffer, R.; Szklo, A.; Lucchesi, R. Oil and natural gas prospects in South America: Can the petroleum industry pave the way for renewables in Brazil? **Energy Policy** 2014, 64, 58–70. [CrossRef]

45. Li, B. Pricing dynamics of natural gas futures. **Energy Econ**. 2019, 78, 91–108. [CrossRef]

46. Quintino, D.D.; David, S.A. Quantitative analysis of feasibility of hydrous ethanol futures contracts in Brazil. **Energy Econ**. 2013, 40, 927–935. [CrossRef]

47. Quintino, D.D.; David, S.A.; Vian, C.E.D.F. Analysis of the Relationship between Ethanol Spot and Futures Prices in Brazil. **Int. J. Financ. Stud**. 2017, 5, 11. [CrossRef]

48. Aloui, D.; Goutte, S.; Guesmi, K.; Hchaichi, R. **COVID 19's Impact on Crude Oil and Natural Gas S&P GS Indexes**; 2020; SSRN 3587740. Available online: https://halshs.archives-ouvertes.fr/halshs-02613280 (accessed on 18 November 2021).

49. Tilfani, O.; Ferreira, P.; El Boukfaoui, M.Y. Revisiting stock market integration in Central and Eastern European stock markets with a dynamic analysis. **Post-Communist Econ**. 2020, 32, 643–674. [CrossRef]

50. Tilfani, O.; Ferreira, P.; Dionisio, A.; El Boukfaoui, M.Y. EU Stock Markets vs. Germany, UK and US: Analysis of Dynamic Comovements Using Time-Varying DCCA Correlation Coefficients. **J. Risk Financ. Manag**. 2020, 13, 91. [CrossRef]

51. Podobnik, B.; Stanley, H.E. Detrended Cross-Correlation Analysis: A New Method for Analyzing Two Nonstationary Time Series. **Phys. Rev. Lett**. 2008, 100, 084102. [CrossRef]

52. Peng, C.-K.; Buldyrev, S.; Havlin, S.; Simons, M.; Stanley, H.E.; Goldberger, A.L. Mosaic organization of DNA nucleotides. **Phys. Rev. E** 1994, 49, 1685–1689. [CrossRef] [PubMed]

53. Podobnik, B.; Jiang, Z.-Q.; Zhou,W.-X.; Stanley, H. Statistical tests for power-law cross-correlated processes. **Phys. Rev. E** 2011, 84, 066118. [CrossRef]

54. David, S.A.; Inácio, C.M.C., Jr.; Quintino, D.D.; Machado, J.A.T. Measuring the Brazilian ethanol and gasoline market efficiency using DFA-Hurst and fractal dimension. **Energy Econ**. 2020, 85, 104614. [CrossRef]

55. Reboredo, F.H.; Lidon, F.; Pessoa, M.; Ramalho, J.C. The Fall of Oil Prices and the Effects on Biofuels. **Trends Biotechnol**. 2016, 34, 3–6. [CrossRef] [PubMed]

56. Perifanis, T.; Dagoumas, A. Price and Volatility Spillovers Between the US Crude Oil and Natural Gas Wholesale Markets. **Energies** 2018, 11, 2757. [CrossRef]

57. Bakker, E. Netherlands Enterprise Agency: 2018. **Brazil Determined to Increase Role of Biofuels**. Available online: https://www.rvo.nl/sites/default/files/2018/01/brazil-determined-to-increase-role-of-biofuels.pdf. (accessed on 18 November 2021).

58. Melo, C.A.; Jannuzzi, G.D.M.; Santana, P.H.D.M. Why should Brazil to implement mandatory fuel economy standards for the light vehicle fleet? **Renew. Sustain. Energy Rev**. 2018, 81, 1166–1174. [CrossRef]

59. Uddin, G.S.; Hernandez, J.A.; Wadström, C.; Dutta, A.; Ahmed, A. Do uncertainties affect biofuel prices? **Biomass- Bioenergy** 2021, 148, 106006. [CrossRef]

60. Han, H.; Linton, O.; Oka, T.; Whang, Y. The cross-quantilogram: Measuring quantile dependence and testing directional predictability between time series. **J. Econ**. 2016, 193, 251–270. [CrossRef]

61. Guedes, E.F.; Silva-Filho, A.M.; Zebende, G.F. **GMZTests**: Statistical Tests. R package version 0.1.3. 2020. Available online: https://CRAN.R-project.org/package=GMZTests (accessed on 2 July 2021).

# 3. RELATIVE PRICES OF ETHANOL-GASOLINE IN THE MAJOR BRAZILIAN CAPITALS: AN ANALYSIS TO SUPPORT PUBLIC POLICIES

**Abstract**
The use of biomass as an energy source has advanced in recent decades, given scientific evidence that it is a solution to the environmental problems faced globally. In this context, biofuels derived from biomass have a prominent role. Among the countries where this alternative is most promising, Brazil stands out, just behind the USA. It is therefore necessary to assess whether such replacement is economically viable. For such an assessment, the behavior of the relative price of bioethanol/gasoline is crucial. In the present work, the degree of temporal persistence of relative prices, considering the existence of shocks to which they are exposed is evaluated, considering 15 important Brazilian capitals, via Detrended Fluctuation Analysis (DFA). The degree of correlation is also evaluated through the Detrended Cross-Correlation Analysis (DCCA) between fuel prices in São Paulo, the capital of the most populous state and main producer of bioethanol, with the capitals of the 14 states selected for the analysis. The period of analysis takes place between 2004 and 2020. We found that the degree of persistence varies significantly depending on the capitals analyzed, which means that price variations are localized and demand regional stimulus policies. Furthermore, it was found that the correlation with São Paulo is less intense in the most geographically distant capitals. Such evidence is important and complementary to infer how integrated the national bioethanol market is, in order to support public policies aimed at its consolidation.

Keywords: Ethanol-gasoline relative price, Hurst, Cross-correlation, Fuel retail market, Biofuel policy

## 3.1 Introduction

Much of the economic work focused on analysing relative fuel prices aims to identify their main drivers for better understanding of their dynamics and support strategies to reduce volatility and possible negative consequences for economies as a whole. In recent decades, it has become increasingly important to identify alternatives to fossil fuels in the global context. In Brazil, ethanol, a biofuel produced from sugarcane and corn, has been a consolidated alternative since the 1970s.

Theoretically, there are several advantages in the existence of an alternative to a strategic good in defining logistics costs, particularly for the service sector (tourism, home deliveries, postal services, food deliveries), distribution and access to goods in the retail trade (supermarkets, restaurants, and many other products purchased via the internet), in addition to other activities involving light transport such as cars and motorcycles. This advantage is most strongly expressed by the reduction in exposure to price volatility and related costs. Changes in price volatility can also affect other variables by changing, for example, costs.

Product homogeneity is a characteristic of competitive markets. Differentiated or substitute products do not stimulate competition, but other forms of markets, such as monopolistic competition, do so, when they are in the same category and can be differentiated by quality. The aforementioned costs could be reduced, particularly those of holding inventories (conceptually, not equal to the cost of storage), interest (opportunity cost of financial resources), financing of insurance operations against unexpected changes in prices, increasing transparency and facilitating the administration of services involving automotive transport. However, as such markets hardly operate in competitive conditions, market failures of different natures occur, requiring government intervention through public policies, given the strategic importance of fuel in the economy.

Thus, many studies seek to analyse the behaviour of price series, based on the concept of an efficient market for evaluation and proposal of adjustments, when necessary. Numerous researchers have already looked for past data, which can explain and infer future values, and therefore, how close the market is to efficiency. However, this concept is still subject to intense debate in the academic community.

One way to provide theoretical foundations and facilitate understanding of market responses to policies that may affect fuel prices is by analysing the behaviour of relative ethanol-gasoline prices, more specifically in the case of hydrous ethanol and gasoline C (ethanol anhydrous added to gasoline). In Brazil, this is particularly interesting, given the importance of flex-fuel vehicles, which represented 67.1% of the fleet in 2018 (SINDIPEÇAS, 2019), mostly in the fleet of light vehicles.

In Brazil, there is a history of government intervention in the market. Costa and Burnquist (2016) analysed the impacts of gasoline prices on the prices and supply of hydrated ethanol, between 2006 and 2015. The authors concluded that the effects depend on the period analysed, as the results of intervention in gasoline prices are sometimes harmful and sometimes beneficial to the consumption of hydrous ethanol, as a substitute for gasoline at lower relative prices.

It should be noted, however, that gasoline C and hydrated ethanol have a different energy efficiency, the latter being advantageous only when the relative price (ethanol-gasoline) is less than 70%, due to the lower yield of hydrated ethanol (FIGUEIRA et al., 2010; EL MONTASSER et al., 2015; LAURINI 2017). It is important to note, therefore, that the prices of hydrous ethanol and gasoline C have peculiarities in the Brazilian scenario, being two distinct products and perfect substitutes in the case of flex-fuel cars (DEBNATH et al., 2017).

According to Fama (1991), the Efficient Market Hypothesis (EMH) is verified when prices reflect all available information, so that it is not possible to obtain abnormal profits using only the set of available information. This concept works with the idea of a random walk in time series, against other types of behaviour, such as persistence and anti-persistence, in which the idea of predictability is embedded.

In the case of light automotive fuels in Brazil, the predictability of relative price changes means exploring the behaviour of the relative price (hydrated ethanol-gasoline C), to assess the degree of price persistence, as well as the synchronization (cross-correlation) of relative prices between different regions, through correlation analysis, focusing on the retail market in the main Brazilian capitals.

Therefore, this analysis aims to evaluate the degree of persistence of variations in relative prices, as well as the degree of correlation of changes in relative prices of São Paulo with other important Brazilian capitals.

To do so, an up-to-date, state-of-the-art methodology is used to capture accurately whether there is joint efficiency between fuel markets in different regions of the country. If this is not identified, it is considered useful to assess whether markets work efficiently at least in individual terms.

We analyse the correlation between the relative price of São Paulo versus other important Brazilian capitals of states that can produce and/or consume ethanol in greater volume, which allows inferences regarding the degree of predictability of prices, in different Brazilian capitals, as well as the degree of correlation between relative prices in these capitals and in the city of São Paulo, capital of the main hydrous ethanol producing state and with the largest automotive fleet in the country. This can determine the degree of persistence of relative ethanol prices, according to Barros et al. (2014) and El Montasser et al. (2015), as well as whether this relative price has a national or regional character, in line with Laurini (2017) and Nascimento Filho et al. (2021).

In principle, there are reasons to expect there will be no correlation between the relative price pairs of São Paulo and the various other Brazilian capitals, as the exogenous factors that influence ethanol supply are different. For example, the supply of ethanol derived from agro-industrial products may be reduced if weather conditions are not favourable. (SAMANEZ et al., 2014). In the case of gasoline C, one of the main determinants has been the new price policy adopted by Petrobras in 2016, which provides for the internalization of variations in oil prices in the international market, in addition to differentiated tariffs between ethanol and gasoline, favouring consumption of hydrated ethanol when international oil prices are high (DAVID et al., 2020).

Thus, the analysis of local fuel prices is justified to support the formulation of policies for the sector, for regulatory agencies and other market participants involved in the commercialization and consumption of fuels, such as distributors, retails and consumers. It has also been observed that fuel price behaviour problems are even more important in emerging economies, which are more vulnerable to energy price and/or exchange rate shocks (da Costa et al., 2017).

The present research contributes to the investigation regarding the persistence of relative price variations, as well as the degree of correlation between them. The persistence of fuel prices is important, as it provides an indication of the degree of predictability of the price trajectory, in line with the approach by David et al. (2020) for hydrous ethanol and gasoline prices. From an exogenous shock in prices, the results allow understanding of the expected behaviour of the series. In turn, the degree of correlation analysed in this work is important to assess whether the movements of price variations show synchronized behaviour between São Paulo and the other capitals, in order to identify whether the movements are characteristic of a unified or regionalized market.

The structure of this article is as follows: after this introduction, section 3.2 presents an overview of regional aspects of ethanol and gasoline pricing at the retail level in Brazil; section 3.3 presents a literature review; section 3.4 describes the methodology and data used; section 3.5 discusses the main results, and finally, section 3.6 elaborates the final conclusions.

## 3.2 Regional aspects and pricing of ethanol and gasoline in Brazilian retail market

First, it is important to highlight in general terms how fuel prices are formed, and then highlight the regional specificities, by product, of the fuel pricing process in Brazil.

### 3.2.1 Pricing of gasoline and ethanol at retail markets

Law No. 9,478 of August 1997, the Petroleum Law, effective as of 2002, introduced changes that deregulated the fuel pricing process, aiming for greater efficiency if these are determined by the laws of market supply and demand. The Petroleum Law instituted the Brazilian National Council for Energy Policy (CNPE) and the Brazilian National Agency for

Petroleum, Natural Gas and Biofuels (ANP), operationalizing a gradual liberalization of prices, in order to converge with those practised in the international market (ALMEIDA et al., 2015). Despite this Law, Petrobras maintained its dominant position in the refining activity, determining prices in the domestic market. (QUINTINO AND DAVID, 2013)

This event led to structural changes in the dynamics of the Brazilian fuel market. It is important to point out that, according to Marjotta-Maistro and Barros (2003), as of January 2002, the fuel sector began to operate as a free market, with deregulated prices at the refinery. From then, the importation of petroleum derivatives by private companies was allowed.

Regarding the formation of fuel prices in Brazil, the retail price of gasoline is composed of four components: i) the realization price of the producer or importer; ii) cost of anhydrous ethanol; iii) taxes (ICMS, a local government tax, defined by each state) and (PIS/PASEP and COFINS – federal taxes) and CIDE (contribution whose primary objective is to maintain roads in good condition); and iv) sales margins for distributors and resale via gas stations. It is important to note that retail prices remained practically constant at the refinery, with low volatility in the subsequent links of the chain, between 2006 and 2015. The variations were mainly due to changes in wholesale and retail profit margins, as well as variations in anhydrous ethanol prices (MORAES and ZILBERMAN, 2014).

Although the deregulation policy in fuel distribution aimed to increase market competitiveness, what was really observed was a significant increase in the concentration of the hydrous ethanol distributor market, measured by the HHI index between 2006 and 2015. The concentration in the hydrous ethanol market is lower than that of gasoline or diesel, as the ethanol wholesale market is more dispersed and facilitates logistics for small distributors (PAULILLO et al., 2016). However, in 2021, plants located in the Northeast were authorized to deliver ethanol directly to gas stations, due to the political lobbies of local agents.

Distribution and retail margins vary depending on the fuel, as each one has different costs, in addition to different market structures. Regarding fuel retail in the composition of the margins, there are both fixed costs and expenses (e.g. land, environmental impact analysis, “flag” in the case of branded gas station, taxes) and variables (freight, water, electricity, operating and financial expenses, among others) (EPE, 2020a).

At the end of 2019, Brazil had more than 40,970 gas stations, 38.2% located in the Southeast, 25.6% in the Northeast, 19.2% in the South, 9% in the Midwest and 8% in the North. (ANP, 2020).

The large number of gas stations in Brazil could suggest that it is a highly fragmented, competitive market, where each one considers it has no power over the prices of the product it sells. However, despite a relatively high number of participants, it is not a market that operates according to perfect competition, being a frequent target of investigation by the antitrust authorities in Brazil, which recurrently bring to light the formation of cartels (DA SILVA et al., 2014)

Quintino and David (2013) show there was a significant increase in the concentration of ethanol distributors between 2004 and 2011, due to various mergers and acquisitions by major market players. Table 1 shows the degree of concentration in 2019. Da Silva et al. (2014) argue that the problem of gasoline price asymmetry between distributors and service stations is not a national problem, but contingent on each specific city or region.

Table 1. Market share of the main distributors, by type of fuel, in 2019

| **Distributor** | **Gasoline C** | **Hydrous ethanol** |
|---|---|---|
| BR | 23.40% | 16.70% |
| Ipiranga | 19.30% | 17.10% |
| Raízen | 16.90% | 19.40% |
| Others | 40.40% | 46.80% |

Source: Own elaboration with data from ANP (2020)

In addition to economic concentration, another important point to be highlighted is the role of taxes in the formation of fuel prices.

According to Decree 9101/2017, the main taxes applied to fuels are: the tax on circulation of goods and services (ICMS), defined by each state, (PIS/PASEP, COFINS) and the Contribution for Intervention in the Economic Domain (CIDE). Despite its primary objective, CIDE is identified as the main mechanism to induce the consumption of ethanol rather than gasoline. This was established in 2001 and although not created for this specific purpose, it is the main public policy instrument to stimulate the demand for ethanol, when applied to gasoline (DA COSTA et al., 2017; MARGARIDO et al., 2020).

ICMS is a state tax, but 25% is appropriated by the municipality where the fuel is sold. At least 75% corresponds to the added value of state revenue along the value added chain generated in the corresponding municipality. Thus, a municipality that has a refinery receives a higher transfer of state ICMS than other municipalities. There have been no taxes on fuel imports and exports in Brazil since 2002. In addition, there are no rules establishing the distribution of such resources within the competence of the Federal Government. (EPE, 2020b).

### 3.2.2 Regional aspects of ethanol supply in Brazil

Historically, sugarcane is grown mainly in the state of São Paulo, in the Centre-South, and in the states of Bahia, Pernambuco and Paraíba, in the Northeast. It is also worth mentioning that sugarcane is a perennial crop, so the supply response to changes in its prices can take 2 to 4 years. (MACZYNSKA et al., 2019)

The Midwest region gained importance with the expansion of ethanol production activity in the mid-2000s, considering that it has flat lands and an appropriate climate for high productivity (VIAN, 2003). As opposed to when Proálcool was launched, when the region was practically ignored, after the launch of flex-fuel vehicles in 2003, the Midwest region became the main area for expanded sugarcane production. (MORAES and BACCHI, 2015). In addition, as an incentive factor for this region, there was an increase in land prices in São Paulo (ZILIO and LIMA, 2015), pushing production costs, combined with the productive decline of the Northeast Region, a traditional sugar-producing region.

The costs associated with increased mechanization, as well as the inflation of land prices through competition for arable areas, motivated the search for other suitable land, in order to minimize production costs, with a focus on the states of Goiás and Mato Grosso do Sul, where production has grown greatly in the last 40 years (GRANCO et al., 2017). The states of Goiás and Mato Grosso do Sul began to expand their production more significantly in the 2000s, becoming the main producing states in the country after the state of São Paulo.

Table 2 shows the high growth rate of Brazilian production of hydrous ethanol in the period 2006-2010, accompanied by growth in all regions of Brazil, especially in the Southeast, with an increase of approximately 187.2%, starting from a high base of comparison, considering that it represented 62.5% of the total supply in the previous period (2001-05) and reached 68.3% in 2006-10. During this period, a reversal in the contribution to total supply began, with the Midwest region overtaking the Northeast.

However, the crisis occurred in 2011-15, when the Midwest and North regions were the only ones showing growth compared to the previous period. However, the North Region's share was still quite small (0.5% of the national supply), while the Midwest Region's share practically doubled, from 16.6% to 32%. Finally, in the last period (2015-2020), all regions showed growth, except for the South Region. In short, throughout the period, the Southeast region was still the major supplier of ethanol, but there was a deconcentration of the total supply, as the Midwest region became more representative to the detriment of the Northeast and South regions.

Therefore, one would expect an increase in the convergence of relative prices between the Midwest and the Southeast, especially São Paulo, to the detriment of the Northeast and South regions, which lost their relative share. Throughout the period, the North Region did not have a significant share in the supply, despite the growth in regional supply.

Table 2. Average five-year production of hydrous ethanol in Brazil, in thousand cubic meters, by the 5 major geographic regions, and their respective shares in the total supply.

| **Period** | **Brazil** | N | %(N) | NE | %(NE) | SE | %(SE) | S | %(S) | M | %(M) | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2001-05 (P1) | 6158.5 | 11.6 | 0.2% | 755.5 | 12.3% | 3851.7 | 62.5% | 661.3 | 10.7% | 878.4 | 14.3% | 100.0% |
| 2006-10 (P2) | 16193.3 | 33.7 | 0.2% | 1035.7 | 6.4% | 11063.1 | 68.3% | 1378.7 | 8.5% | 2682.1 | 16.6% | 100.0% |
| 2011-15 (P3) | 15772.6 | 84.6 | 0.5% | 800.5 | 5.1% | 8858.6 | 56.2% | 986.4 | 6.3% | 5042.5 | 32.0% | 100.0% |
| 2016-20 (P4) | 21014.1 | 94.4 | 0.4% | 962.0 | 4.6% | 11574.4 | 55.1% | 900.5 | 4.3% | 7482.7 | 35.6% | 100.0% |
| **Var %** | | | | | | | | | | | | |
| 2006-10 (P2/P1) | 162.9% | 190.6% | | 37.1% | | 187.2% | | 108.5% | | 205.3% | | |
| 2011-15 (P3/P2) | -2.6% | 151.0% | | -22.7% | | -19.9% | | -28.5% | | 88.0% | | |
| 2016-20 (P4/P3) | 33.2% | 11.7% | | 20.2% | | 30.7% | | -8.7% | | 48.4% | | |

Source: Own calculation with data from ANP (2010) and ANP (2020)

**3.3 Literature Review**

After the resurgence of ethanol as a possible substitute for gasoline in Brazil, with the advent of the bi-fuel car, launched in 2003, there is extensive literature on the possible relationship between ethanol prices and other commodities, especially “food x fuel”. This debate concerns possible co-movements in food and energy prices, in particular the effect of policies to stimulate the production of biofuels in the face of rising food prices.

Janda and Kristoufek (2019) conduct an excellent survey on the main work on this topic. Many of the studies cited involve, in addition to food prices, oil prices, which can have a great influence on commodity prices as a whole, and in particular, on ethanol prices, both in the US and Brazil.

Another recently explored topic is the possible relationship between Brazilian ethanol spot and futures prices at the Brazilian Exchange, B3 (Quintino et al., 2017; Capitani et al., 2018), as well as the possible relationship between ethanol prices in the Brazilian and USA markets (CAPITANI et al., 2018; DUTTA, 2020; HERNANDEZ et al., 2020; QUINTINO et al., 2021).

Following recent concerns about global warming and ways of decarbonizing the economy, there are ESG (Environmental, Social and Governance) investments, including investments in companies that seek to follow environmentally correct practices in the production process. This tends to favour investments that contribute to mitigating the effects of greenhouse gas emissions (GHG), gradually becoming more evident in the market. Carbon emission prices emerge as a need for pricing this externality, as well as its possible relationship with prices of other renewable energies, such as Brazilian ethanol (DUTTA and BOURI, 2019).

Other studies seek to determine the impacts of different sources of market uncertainties on biofuel prices. Uddin et al. (2021) used the VIX (Market Volatility Index), EPU (Economic Policy Uncertainty Index), GPR (Geopolitical Risk Index) and St Louis Fed Financial Stress Index (FSI) to analyse the influence of uncertainties on biofuel prices, including Brazilian ethanol. In the context of the Brazilian domestic market, there are investigations into the degree of persistence of national ethanol prices at the producer level (David et al., 2018), as well as national retail prices of ethanol and gasoline (DAVID et al., 2020).

Specifically in relation to the relative price of Brazilian ethanol-gasoline, Barros et al. (2014) studied the degree of persistence of ethanol and gasoline consumption in Brazil, as well as its relative price, between 2000 and 2012, concluding that ethanol and gasoline consumption are persistent, with an order of integration lower than the unit, and therefore with a mean reversion tendency. However, for the relative price, the estimated coefficient was higher than the unit, which suggests non-reverting behaviour to the mean and character of permanence in response to shocks.

El Montasser et al. (2015), with a sample from 2000 to 2012 and based on the right-tailed ADF test, commonly used to test the formation of price bubbles, verified the occurrence of 2 bubbles in the relative ethanol-gasoline price in this period: the first starting in June 2006 and collapsing in March 2007; and the second, starting in June 2010 and lasting until the end of the sample, in December 2012. The first coincided with President Lula's re-election campaign, and the second with the withdrawal of CIDE in 2008 and the government's attempts to use policies to freeze gasoline prices.

Laurini (2017) analysed the evolution of the relative prices of ethanol-gasoline in Brazil between 2007 and 2014, through a continuous spatial model, which allows analysing the distribution of prices continuously in space and time, concluding that after 2009 hydrous ethanol lost competitiveness to gasoline C. More specifically, in 2007-2009 ethanol was competitive in most of the Brazilian territory, but gradually lost competitiveness from 2010 onwards, where it showed an advantage in only part of the Southeast region.

Nascimento Filho et al. (2021) studied the behaviour of the relative prices of ethanol-gasoline, within the scope of fuel distributors and dealers, comparing the pre- and post-implementation periods of the fuel import price parity policy in Brazil, in the main capitals of the country, between 2012 and 2019. This policy resulted in the end of the artificial control of gasoline prices, which allowed ethanol to become more competitive, especially in periods of high international oil prices. For this purpose, nonparametric Mann-Whitney and Levene tests were used. They verified that, after the change in the pricing policy, there was an increase in the median and in the coefficients of variation of relative prices in most of the capitals analysed, especially in the distribution market segment. This suggests that Petrobras' new pricing policy has unequally affected relative prices among the various Brazilian capitals.

Here, we advance the investigation by Nascimento Filho et al. (2021), with a larger sample, which includes the period from the beginning of the launch of flex-fuel cars to the first impacts of the COVID-19 pandemic. In addition, we use a robust methodology of dynamic analysis, using sliding windows, which allows dynamic analysis of the price trajectory, in view of the static analysis between delimited periods.

The next section specifies the methods and data in the present research.

## 3.4 Methods and data

In the present work, the empirical strategy involves use of DFA (Detrended Fluctuation Analysis) and DCCA (Detrended Cross-Correlation Analysis) coefficients, which will be defined in the next item.

### 3.4.1 Methods

As previously highlighted, we want to assess the degree of persistence of price variations in the main Brazilian capitals (Manaus, Rio Branco, Belém, Fortaleza, Recife, Salvador, Goiânia, Brasília, Cuiabá, São Paulo, Rio de Janeiro, Belo Horizonte, Curitiba, Florianópolis and Rio Grande do Sul), as well as the degree of correlation between the capital of São Paulo, the main producer and consumer state of ethanol in Brazil, and the other capitals. The data source and choice criteria will be specified in the data subsection.

For this task, we used the econophysics techniques of DFA (Detrended Fluctuation Analysis) and DCCA (Detrended Cross-Correlation Analysis).

DFA, developed by Peng et al. (1994) initially to analyse the behaviour of DNA, has been extended to many other areas, including economics and finance.

DFA is calculated as follows. Let $x_i$ a time series, with $i = 1, \dots, N$ , and equidistant observations. The following X(k) is a cumulative sum of the detrended series, given by the equation 1:

$$\mathrm{X(k)} = \sum_{\mathrm{i=1}}^{\mathrm{N}} (\mathrm{x_i} - \langle \mathrm{x} \rangle) \text{ , } 1 \leq k \leq N \tag{1}$$

where $\langle x \rangle$ refers to average of $x$.

After, $X(k)$ is divided into non-overlapping boxes of size *n* (box size). For each box, a local trend $\tilde{X}_k$ is estimated via Ordinary Least Squares (OLS). The next step is to create a detrended series of each box *n*, in order to obtain the expression of the equation 2:

$$\mathrm{F(n)} = \sqrt{\frac{1}{\mathrm{N}} \sum_{\mathrm{k=1}}^{\mathrm{N}} \left(\mathrm{X}_k - \tilde{\mathrm{X}}_{\mathrm{k}}\right)^2} \tag{2}$$

Doing this procedure for every window of dimension *n*, where $4 \leq n \leq N/4$, we have a power law given by $F(n) \propto n^H$, a log-linear relationship whose parameter of interest is the Hurst coefficient *H*. After calculating *H*, the following result possibilities will be obtained:

i) 0 < H < 0,5, anti-persistent series, or simply means reversal behavior. That is, there is a greater than 50% probability that a negative value will be preceded by a positive one. The strength of this behavior will depend on how close the H is to zero;

ii) H = 0,5 series has a random walk distribution (white noise, efficient market), meaning that is has no long memory. Thus, the variation of the cumulative deviations must increase proportionally to the square root of the time variable;

iii) 0,5 < H < 1 persistent series, there is a probability of repetition of a value above 50%.

iv) H =1 identifies a pink noise and H >1 means that long-range dependence is not explained by a power law, but these two results are incomum in economic and financial time series.

DFA has the advantage of being robust to several time series features, such as non-stationarity (Hwa and Ferree, 2002; Mohti et al., 2019), breaks (Chen et al. 2002) and other nonlinear forms (Hu et al., 2002; Kantelhardt et al. 2002). The application of DFA with moving windows is used in different areas of finance and economics, as for example in the works of Cajueiro and Tabak (2004a, 2004b), Alvarez-Ramirez (2018), Ferreira (2020).

In addition to the DFA, we used the DCCA correlation coefficient ($\rho$DCCA) of Zebende (2011) derivated from DCCA procedure of Podobnik and Stanley (2008), in order to verify the degree of correlation between the capital of São Paulo and the other major Brazilian capitals distributed in all five main regions.

Regarding the DCCA, the first step is also the integration of the series $X_t$ e $Y_t$ according to equation 1. Afterwards, the series are divided into time series of the same length $n$ and are detrended by OLS, that is, the same procedure as the DFA is used to filter the trend of the series. In particular, the objective is to obtain the covariance of the residuals, vis-à-vis the variance, which is the object of the DFA. In algebraic terms, we have:

$$f^2_{DCCA}(n) = \frac{1}{(n-1)} \sum_{k=1}^{i+n} \left(X_k - \tilde{X}_{k,i}\right)\left(Y_k - \tilde{Y}_{k,i}\right) \quad (3)$$

Which is used to calculate the covariance given by:

$$F^2_{DCCA}(n) = \frac{1}{(N-n)} \sum_{i=1}^{N-n} f^2_{DCCA}(n) \quad (4)$$

After doing this for all sizes of $n$ boxes, the DCCA exponent is obtained, by means of a power law. The final step is obtained by:

$$\rho_{DCCA} = \frac{F^2_{DCCA}}{F_{DFA(x)}\, F_{DFA(y)}} \quad (5)$$

The functions $F_{DFA(x)}$ and $F_{DFA(y)}$ are the mean square fluctuations of the series $x_i$ e $y_i$, respectively. As with Pearson's correlation, suitable for evaluating linear relationships, $-1 \leq \rho_{DCCA}(n) \leq 1$. If $\rho_{DCCA}(n) = 1$, there is perfect correlation. In a symmetrical way, if $\rho_{DCCA}(n) = -1$ , there is perfect anti-correlation. When $\rho_{DCCA}(n) = 0$, there is no evidence of correlation between the variables.

The DCCA correlation coefficient is nonlinear, robust to nonstationarity and with desirable properties (Kristoufek, 2014a; Kristoufek, 2014b; Wang et al., 2013; Zhao et al., 2017). The robustness of the correlation coefficient is verified through its use in several areas, and, particularly in energy economics, for example, Reboredo et al. (2014), Pal and Mitra (2018), Paiva et al. (2018), Nascimento Filho et al. (2018), Mitra et al. (2018), Murari et al. (2019), Lima et al. (2019), Fan et al. (2019), Ferreira and Loures (2020).

In order to capture the time-varying dynamics, sliding windows will be used for both DFA and DCCA. The sliding windows will consider 250 observations, consistent with the analysis by Alvarez-Ramirez et al. (2018) and Casa Nova et al. (2021) for DFA and DCCA, respectively.

### 3.4.2 Data

The relative prices were calculated by collecting weekly data of gasoline C and hydrated ethanol prices, obtained from the statistical database of the ANP (Brazilian National Agency of Petroleum, Natural Gas and Biofuels), referring to the period from May 14, 2004 to December 26, 2020 for a total of 855 weeks. Table 3 illustrates the criterion for choosing the municipalities, based on Nascimento Filho et al. (2018, 2021) and Murari et al. (2019), namely: cities with more than 500,000 inhabitants, being the state capital and limited to 3 capitals per region. In this way, we have a representative set covering large capitals and in different regions of the country, which allows a proper diagnosis of local Brazilian specificities.

Table 3. Geographic coordinates of the analyzed capitals.

| Region | City | Latitude | Longitude |
|---|---|---|---|
| North | Belém (BEL) | -1.382051 | -48.477898 |
| | Manaus (MAO) | -3.036105 | -60.046593 |
| | Rio Branco (RBR) | -9.866168 | -67.897189 |
| Northeast | Fortaleza (FOR) | -3.777554 | -38.533172 |
| | Recife (REC) | -8.061129 | -34.871665 |
| | Salvador (SSA) | -12.911014 | -38.331413 |
| Midwest | Brasília (BSB) | -15.869923 | -47.917428 |
| | Cuiabá (CGB) | -15.594821 | -56.091696 |
| | Goiânia (GYN) | -16.601095 | -49.144543 |
| Southeast | Belo Horizonte (BHZ) | -19.846098 | -43.963296 |
| | Rio de Janeiro (RIO) | -22.913002 | -43.180002 |
| | São Paulo (SAO) | -23.589592 | -46.660721 |
| South | Curitiba (CWB) | -25.442395 | -49.240417 |
| | Florianópolis (FLN) | -27.670175 | -48.545944 |
| | Porto Alegre (POA) | -29.993399 | -51.175563 |

Source: Murari et al. (2019)

By restricting attention to prices, some variations in the local market are not considered, such as fleet size, logistical conditions, fuel distribution, among others, in line with recent investigations by Nascimento Filho et al. (2018, 2021) and Murari et al. (2019). The present text advances in the sample dimension, from the beginning of the series in May 2004 to December 2020, including the COVID-19 crisis, which strongly shook the global economy, especially the Brazilian economy, one of the countries most affected by the pandemic.

Table 4 presents the descriptive statistics. The capitals of São Paulo (SAO) and Rio de Janeiro (RIO), both in the Southeast region, and Belém (BEL) in the North region, were the only ones to show extreme fluctuations, of maximum and minimum, in levels less than two digits. RIO presented the smallest drop recorded, of only -5%, followed by Florianópolis (FLN), with -8%. Among the biggest increases, we have Cuiabá, CGB, (17%), followed by Brasília, BSB, (16%) and Goiânia, GYN, (15%), all in the Midwest region. In terms of asymmetric distribution, the largest are also located in the Midwest region (CGB, BSB and GYN).

Positive asymmetries mean that positive returns are more frequent than negative ones. It is worth mentioning that increases in the relative price of hydrous ethanol-gasoline C occur more frequently than decreases. Regarding the most negative asymmetries, these are Manaus

(MAO), in the North Region, and Fortaleza (FOR) and Recife (REC), both in the Northeast. Finally, with regard to kurtosis, the most leptokurtic distributions, associated with higher values, are Rio Branco (RBR) and Manaus (MAO), both in the North Region, followed by CGB, (Midwest). The lowest levels occurred in RIO (Southeast), FLN (South) and SAO (Southeast).

### 3.5 Results

After initial inspection of the distribution of price returns, given by the logarithm return of the series, given by $r(t) = \ln(p_t) - \ln(p_{t-1})$, where $p_t$ is the relative price of ethanol-gasoline, we verified the degree of persistence of the series through the Hurst coefficient via DFA, with a static analysis with the total sample and, then, dynamically through the sliding windows.

Table 4. Descriptive statistics of hydrous ethanol/gasoline C returns by capitals, between May/04 to Dec/20.

| City - Region | Id | Mean | Std Dev | CoefVar | Max | Min | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|
| Belém – N | BEL | 0.0002 | 0.01 | 79.98 | 0.07 | -0.09 | -0.34 | 6.06 |
| Belo Horizonte - SE | BHZ | 0.0002 | 0.01 | 79.09 | 0.05 | -0.10 | -0.76 | 5.79 |
| Brasília - M | BSB | 0.0002 | 0.02 | 99.03 | 0.16 | -0.12 | 0.47 | 8.59 |
| Cuiabá - M | CGB | 0.0003 | 0.03 | 94.75 | 0.17 | -0.16 | 0.71 | 11.30 |
| Curitiba - S | CWB | 0.0006 | 0.02 | 34.29 | 0.11 | -0.11 | 0.46 | 6.82 |
| Florianópolis - S | FLN | 0.0004 | 0.02 | 47.78 | 0.14 | -0.08 | 0.42 | 4.58 |
| Fortaleza - NE | FOR | 0.0004 | 0.02 | 38.83 | 0.10 | -0.12 | -1.82 | 11.06 |
| Goiânia - M | GYN | 0.0003 | 0.03 | 78.73 | 0.15 | -0.18 | -0.49 | 10.72 |
| Manaus - N | MAO | 0.0002 | 0.03 | 143.21 | 0.13 | -0.22 | -2.01 | 12.04 |
| Porto Alegre - S | POA | 0.0007 | 0.02 | 27.71 | 0.09 | -0.11 | -0.56 | 6.79 |
| Recife - NE | REC | 0.0004 | 0.02 | 61.67 | 0.10 | -0.13 | -1.41 | 8.51 |
| Rio Branco - N | RBR | 0.0001 | 0.01 | 89.67 | 0.10 | -0.09 | 0.25 | 13.45 |
| Rio de Janeiro - SE | RIO | 0.0005 | 0.01 | 25.83 | 0.08 | -0.05 | 0.38 | 3.36 |
| Salvador - NE | SSA | 0.0002 | 0.02 | 69.41 | 0.11 | -0.12 | -0.42 | 9.47 |
| São Paulo - SE | SAO | 0.0007 | 0.02 | 25.13 | 0.09 | -0.09 | 0.17 | 5.19 |

Source: Research results

Table 5. DFA estimates for Brazilian capitals

| City | Hurst | | StdDev |
|---|---|---|---|
| MAO-N | 0.34 | ± | 0.02 |
| REC-NE | 0.42 | ± | 0.01 |
| FOR-NE | 0.47 | ± | 0.03 |
| SSA-NE | 0.47 | ± | 0.02 |
| FLN-S | 0.49 | ± | 0.02 |
| GYN-M | 0.49 | ± | 0.03 |
| BSB-M | 0.49 | ± | 0.03 |
| BEL-N | 0.52 | ± | 0.01 |
| RBR-N | 0.52 | ± | 0.02 |
| CGB-M | 0.55 | ± | 0.03 |
| POA-S | 0.57 | ± | 0.03 |
| CWB-S | 0.59 | ± | 0.04 |
| BHZ-SE | 0.61 | ± | 0.03 |
| RIO-SE | 0.64 | ± | 0.03 |
| SAO-SE | 0.66 | ± | 0.04 |

Source: Research results

Among all the capitals analysed in Table 5, Manaus (North), Recife and Salvador (Northeast) show anti-persistent behaviour ($H < 0.5$). This means that positive returns tend to be followed by negative returns, and vice versa. In contrast, with evidence of persistent behaviour ($H > 0.5$), we have: Belém (North Region), Cuiabá (Midwest), Porto Alegre and Curitiba (South) and the capitals of the Southeast, namely, Belo Horizonte, Rio de Janeiro and Sao Paulo. Among the capitals whose results oscillate around the efficiency hypothesis ($H = 0.5$) are: Fortaleza and Salvador (Northeast), Florianópolis (South) and Goiânia and Brasília (Midwest). In regional terms, therefore, we have evidence that the largest producer and consumer region of gasoline and ethanol presents returns with a long-term dependence behaviour, while in the other regions, the behaviour of returns has no well-defined pattern.

### 3.5.1 Analysis of the degree of persistence (DFA) of ethanol/gasoline relative price returns

The analyzes concerning the DFA with sliding windows, for all regions (North, Northeast, Midwest, Southeast and South), to be discussed in the respective sub-items, refer to Figure 1.

#### 3.5.1.1 North

In the North Region, after 2010 the relative price of Manaus (MAO) presents values lower than those of efficiency in almost the entire period, with the exception of a short period in the second half of 2015. Belém (BEL) presents higher values until the end of 2015, and after that period oscillates around the efficiency level from 2017 until the end of the sample in December 2020, after showing lower values in 2016.

In Rio Branco (RBR), there was a large fluctuation in the dynamic behaviour: between 2009 and 2010, the values were significantly higher than the efficiency values, and they started to fluctuate at this level, but with great volatility, between 2011 and the beginning of 2019, except for a short period in 2015, when there was strong anti-persistent behaviour. Since the second half of 2019, however, the values have been systematically above the efficient reference.

Regarding the most recent dynamics, very different values of coefficients can be observed in these three capitals: persistence (RBR), anti-persistence (MAO) and around efficiency (BEL).

#### 3.5.1.2 Northeast

For Salvador (SSA), the coefficient fluctuated above the efficiency value throughout the period, especially until the beginning of 2014. In later periods, the values were closer to the reference level, but almost always at higher levels, until the end of the period. Fortaleza (FOR) also showed strong persistence until 2015, and only in mid-2016 was there a shift to values below efficiency, whose declining trend remained until mid-2018, where a change in trend can be noted, that of an increase towards efficiency, until the end of the period.

Finally, in Recife (REC) we have anti-persistence values up to 2011, where the upward trend continues until early 2013. Between 2013 and 2014, it fluctuates at high levels, until it shows a downward trend in 2015. Between 2015 and 2016, the movements take place around efficiency, and in 2017 and 2018, the values decline and begin to operate in the space of anti-persistence. Between 2019 and 2020, the slope of the trend is reversed, and the indices start to show positive trend values towards the reference level.

Therefore, after presenting different dynamics, mainly REC at the beginning of the period and SSA after the middle of the sampling window, in a more recent period the three coefficients start to oscillate with values closer to each other and to the efficiency level.

#### 3.5.1.3 Midwest

In the entire sample, Cuiabá (CGB) always presents persistent values, and does not show a strong downward or upward trend, but oscillates around a high level of persistence. In turn, Brasília (BSB) shows a similar behaviour until the end of 2010, but as of 2011, it starts to fluctuate at lower levels than CGB and therefore closer to the efficiency value. Finally, with regard to Goiânia (GYN), until mid-2015 its behaviour is very similar to CGB, but from this point, an abrupt change in behaviour is evident. In 2016, with values already below the reference level, it oscillates in the anti-persistence interval, until the end of the sample.

Therefore, also in this region we have 3 different behaviours for the return of the relative prices at the end of the period, with BSB and especially CGB showing persistence, and GYN with anti-persistence behaviour.

#### 3.5.1.4 Southeast

In the whole sample, Belo Horizonte (BHZ) presents behaviour above the reference. However, from mid-2015, the values start to fluctuate at lower levels, but still higher than the reference, showing persistence. Rio de Janeiro (RIO) presents behaviour similar to that of BHZ until 2012, when it moves and starts to show a declining trend until mid-2016, exhibiting anti-persistent behaviour, although for a very short period. However, at the end of 2016, RIO converged again to the behaviour of BHZ, of a persistent nature, which remained until the end of the period.

Finally, until 2010 São Paulo (SAO) presents very similar behaviour to that of RIO, and between 2011 and 2014, it shows similar dynamics to BHZ. After 2016, however, SAO shows a systematic behaviour of greater persistence, moving away from efficiency, compared to the two capitals of the same region, until the end of the period.

3.5.1.5 South

In Curitiba (CWB), the behaviour observed was of high persistence throughout the sample period, and, additionally, a period of high volatility in early 2016. A possible factor is that production in this state is more directed to sugar for export, to the detriment of ethanol. Porto Alegre (POA) does not produce sugarcane, and presents behaviour similar to that of CWB in the initial phase, although with greater volatility, until mid-2014. Then it starts to oscillate closer to the reference index, although with higher values, which configures the persistence character. Florianópolis (FLN) also starts with a high coefficient, but with a downward trend, and from 2015 until the end of the period, it oscillates around the efficiency reference.

Thus, at the end of the moving window period, CWB's behaviour diverges from the other southern capitals.

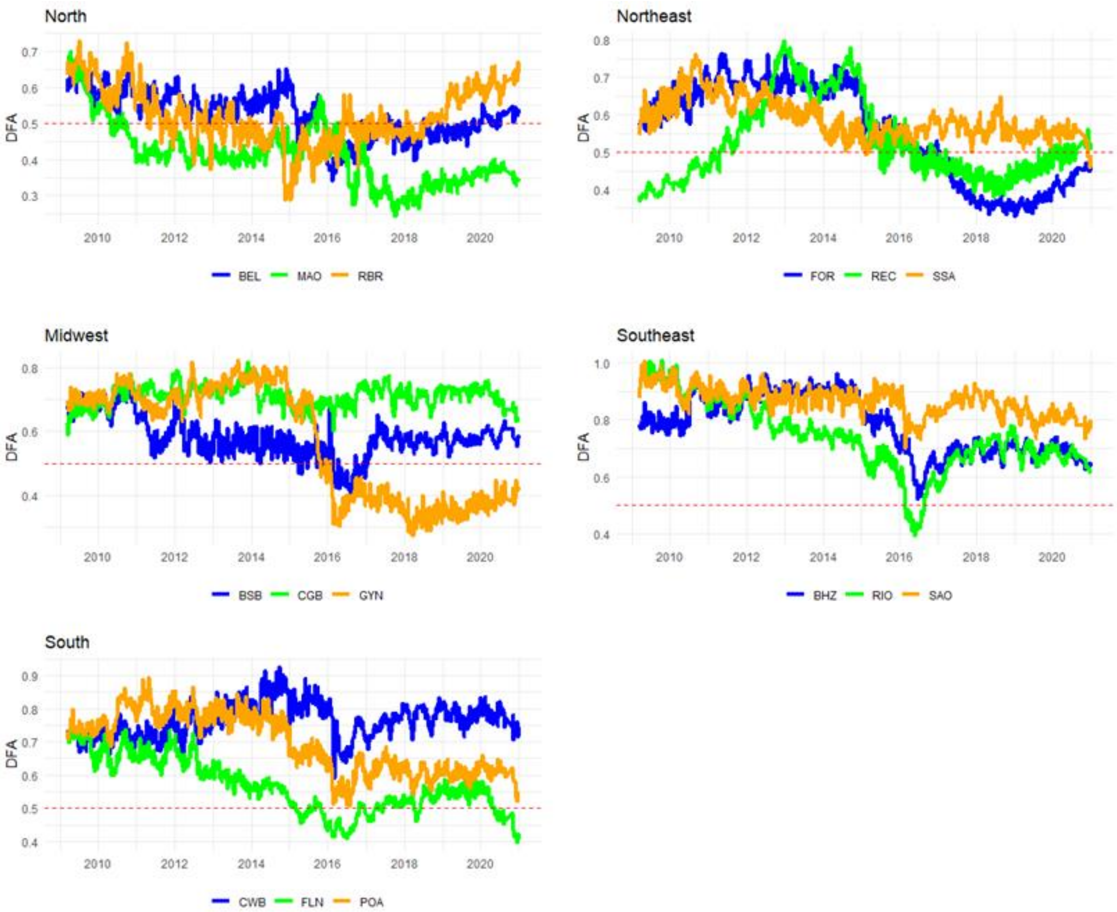


Figure 1. Persistence behavior (Hurst H exponent) in Brazilian capitals through the 250-day moving window. The dashed line (H = 0.5) represents the random walk.

### 3.5.2 Analysis of Detrended Cross-Correlations (DCCA)

#### 3.5.2.1 North

The capitals of the North region did not present a significant correlation in the scales of 4 and 8 weeks (4s and 8s), being brief and of low magnitude (Figure 2). In relation to the other time windows, Manaus (MAO) presents correlation only until mid-2012, mainly in the longer scales of 32s and 64s. Belém (BEL) exhibits a higher magnitude and significant correlation until 2015, in the intermediate scale (16s) and longer scales (32s and 64s), because, like MAO in the most recent period, post-2015, it does not present a significant correlation.

In the Rio Branco market (RBR), returns did not show a significant positive correlation, except for longer stopovers and in the pre-2011 period. On the contrary, in certain periods there is even a negative and statistically significant correlation, which shows the great discrepancy in the behaviour of returns in this capital in relation to São Paulo.

#### 3.5.2.2 Northeast

Among the capitals of the Northeast, Salvador (SSA) has the most significant positive correlation at the beginning of the sampling window (Figure 3). As of 2016, however, it has only a marginally significant positive correlation on the shorter scales, up to 16 weeks. Recife (REC) only showed a positive correlation in the middle of this time interval, except in the 64s scale, when there is no significant association, particularly in the periods of 2013 and 2014, being insignificant in most of the moving window interval.

In relation to Fortaleza (FOR), there was also only some positive correlation in the first half of the window, up to mid-2014, and in the longer-term scales of 32s and 64s. In the most recent period, after 2016, no significant positive association was observed.

#### 3.5.2.3 Midwest

Brasília (BSB) has practically no significant correlation in the 4s scale, and a weak and moderate character in the 8s and 16s scales, respectively, until early 2016, since in the subsequent period there is no significant association (Figure 4). On the other hand, the correlation strength increases in the longer scales of 32s and 64s until the beginning of 2016, and after this period, a positive association is observed in the rest of the sample, although with a lower relationship. Cuiabá (CGB) shows some positive correlation in the short scales of 4s, 8s and 16s until the beginning of 2016. In the most recent period, there is practically no positive association in such scales, except in the period after 2020. In contrast, in the longer ranges of 32s and 64s, CGB shows a significant positive correlation. Finally, Goiânia (GYN), with the exception of the 4s scale, almost always shows a positive correlation in the other scales and sample period, and in the same way, a stronger association with the other capitals of this region, with few exceptions in the entire period analysed.

#### 3.5.2.4 Southeast

On the 4s scale, Rio de Janeiro (RIO) and Belo Horizonte (BHZ) walk very close, with a significant correlation, until early 2016, where BHZ shows stability in its correlation, while RIO no longer shows a significant positive association (Figure 5). For the other time scales, RIO has a higher correlation against BHZ, but this scenario changes after 2016, with BHZ surpassing the strength of correlation against RIO. It is worth mentioning that in the longer scales of 32s and 64s, however, there is a convergence of such correlations, of strong magnitude.

This strong correlation between the returns of the Southeast capitals is not paralleled in any other capital, with the exception of Curitiba (CWB) in the South Region, but neighbouring São Paulo (SAO).

#### 3.5.2.5 South

Curitiba (CWB) is the only southern capital that presents a significant correlation in all temporal scales, as well as in the whole sample (Figure 6). In general, there is a significant correlation already in the shorter scales of 4s and 8s, temporarily interrupted in early 2016 (8s) and 2018 (4s). On the longer scales this break was smoothed out, so that the strong correlation was restored after the temporary shock. Florianópolis (FLN) and Porto Alegre (POA) present very similar behaviour in all time scales, except for the very short term of 4s.

On this scale, specifically, there is no significant correlation post-2015 (FLN) and post-2016 (POA). It is noted that for both capitals, after the shock in mid-2016, on the longer scales of 32s and 64s, there is a partial recovery of the correlation strength shown in the period prior to the shock, but this loses strength and shows a declining trend as it approaches the end of the sample period.

### 3.5.3 Discussion of results

In summary, our main results indicate that, in relation to persistence, different behaviours were shown between the capitals of different regions, as well as in some cases between capitals of the same region. The capitals of the Southeast (BHZ, RIO and SAO) and CWB (South) showed persistent behaviour in the most recent period. The other capitals of the South Region (FLN and POA) tended to show dynamics closer to the random walk in the most recent period.

The capitals of the Midwest (BSB, CGB and GYN) also diverged, BSB and CGB showing persistent behaviour and GYN anti-persistent dynamics. In the Northeast region, after divergent trajectories between the capitals, in the most recent period there is behaviour closer to the random walk, with values close to this reference level. Finally, in the North Region, the biggest divergence between capitals occurs in the most recent period, with persistent behaviour (RBR), random walk (BEL) and anti-persistent (MAO).

With regard to correlation, in the North Region, despite the correlation at the beginning of the sampling window in BEL and MAO on longer scales, in the most recent period a more consistent behaviour of correlation is not observed, in any time scales, except for some occasional temporary situations, but of low magnitude. In the Northeast, the relationship bears a certain similarity to the North, as there was a correlation in SSA at the beginning of the window (in other capitals this also occurred, depending on the time scale considered). However, at the end of the window only SSA showed correlation, in the shorter scales, but with low strength.

In the Midwest, there is a significant correlation only for GYN on the 8 and 16-week scales, while on the longer scales all capitals show a significant positive association. In the Southeast, there is a positive correlation in all time scales considered, with the exception of RIO in the very short term, 4 weeks. Finally, in the South region, only CWB has a positive correlation in the most recent period, in all time scales, with the exception of POA in the long-term scale, but with a downward trend in the correlation strength, towards the absence of correlation.

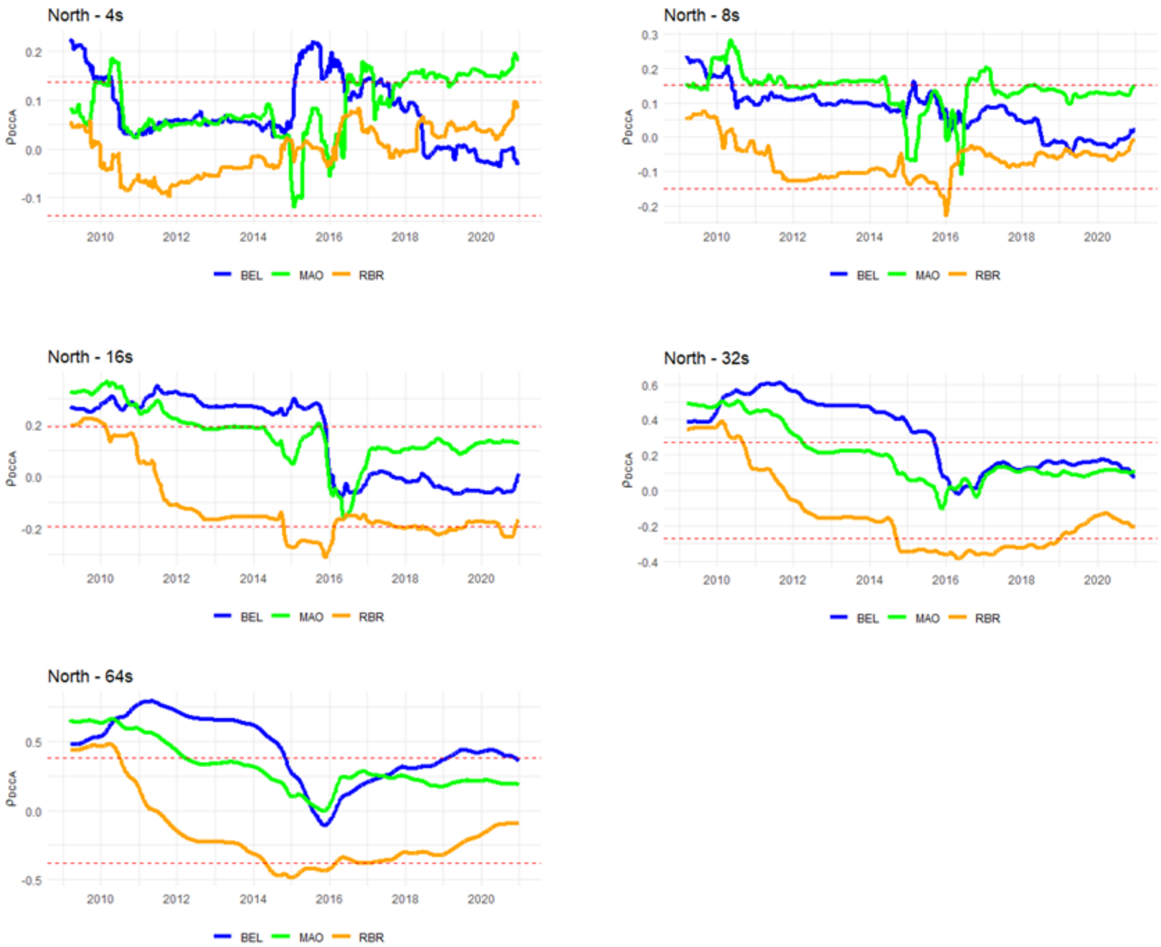


Figure 2. Evolution of $\rho_{DCCA}$ between the relative prices of São Paulo and other capitals in the **North** region, with time scales of **4, 8, 16, 32 and 64** weeks, and moving window w=250. Shaded lines are the upper and lower confidence intervals, in the sense that values between these are not statistically significant, according to the critical values of Podobnik et al. (2011).

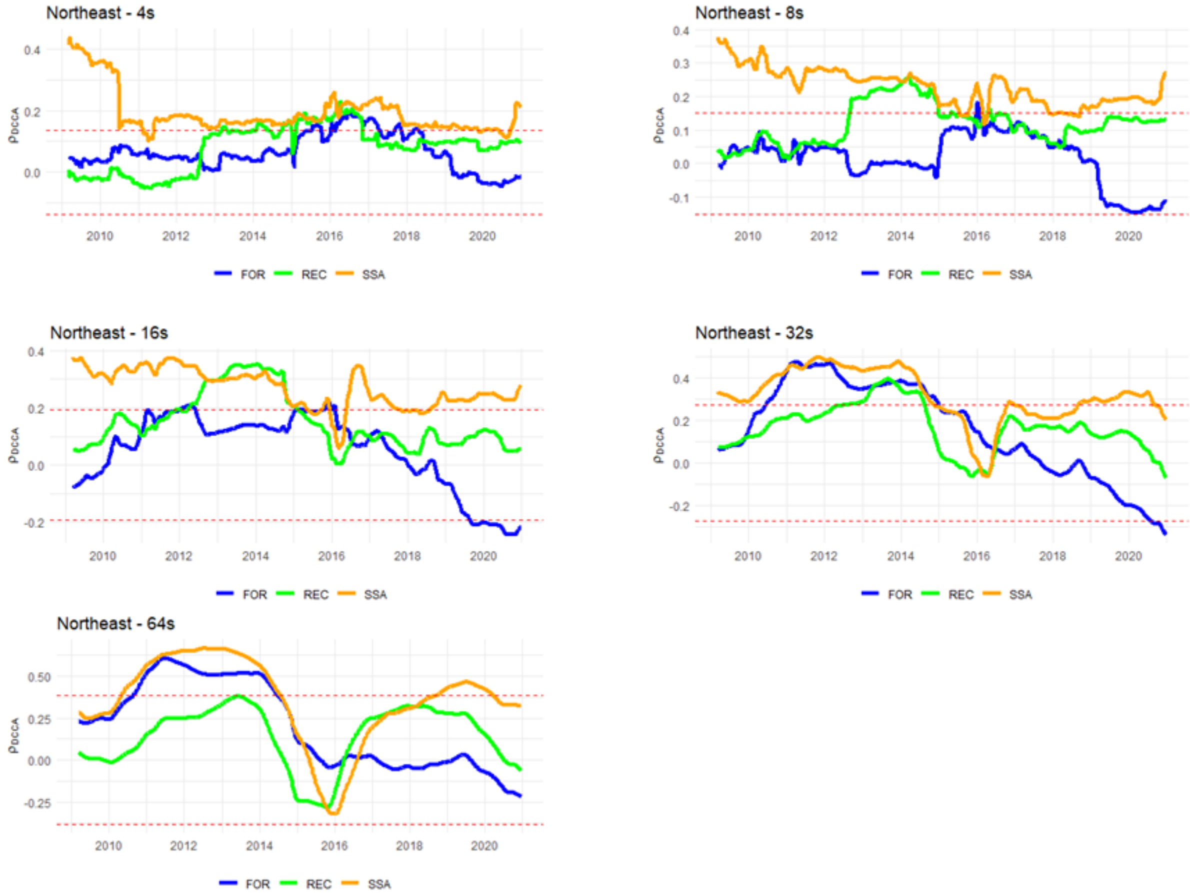


Figure 3. Evolution of $\rho_{DCCA}$ between the relative prices of São Paulo and other capitals in the **Northeast** region, with time scales of **4, 8, 16, 32 and 64** weeks, and moving window w=250. Shaded lines are the upper and lower confidence intervals, in the sense that values between these are not statistically significant, according to the critical values of Podobnik et al. (2011).

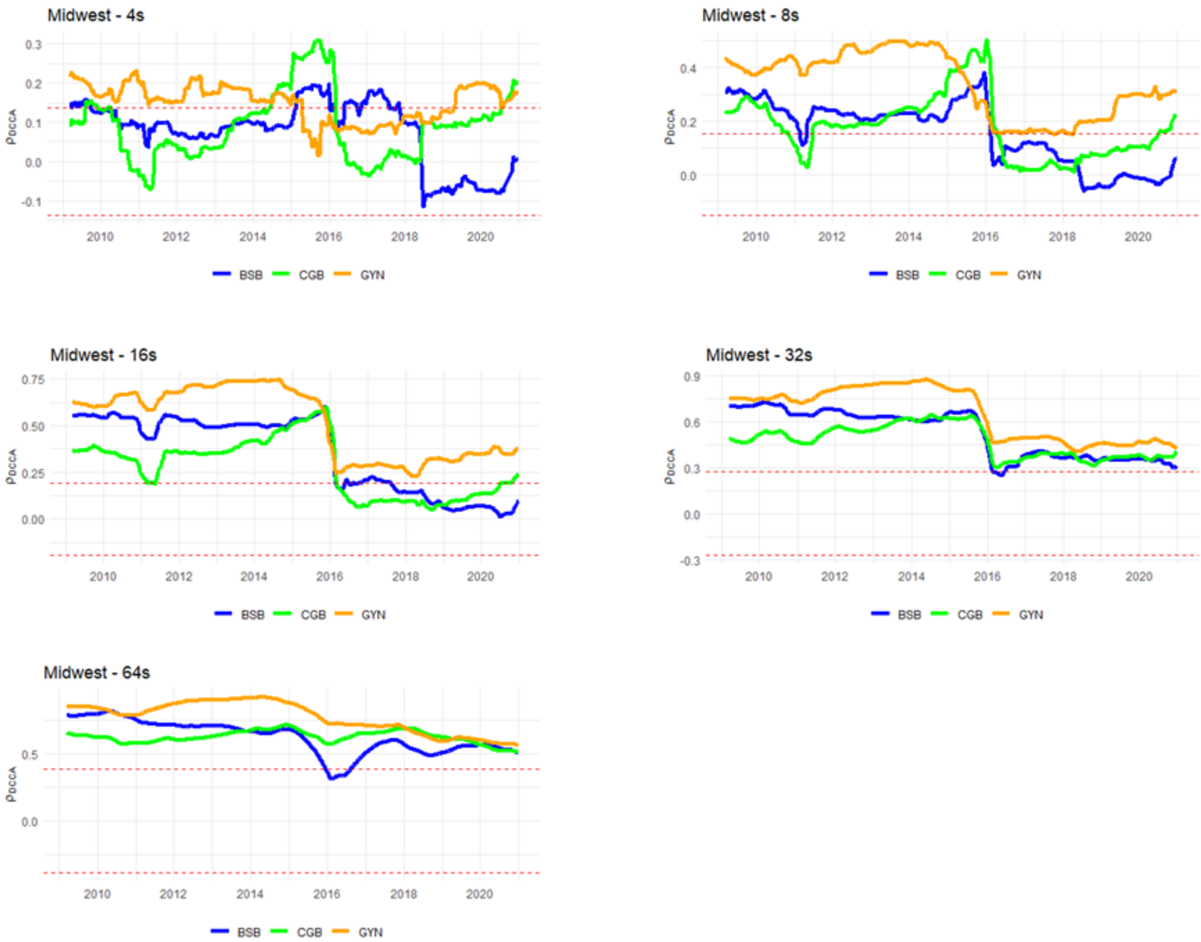


Figure 4. Evolution of $\rho_{DCCA}$ between the relative prices of São Paulo and other capitals in the **Midwest** region, with time scales of **4, 8, 16, 32 and 64** weeks, and moving window w=250. Shaded lines are the upper and lower confidence intervals, in the sense that values between these are not statistically significant, according to the critical values of Podobnik et al. (2011).

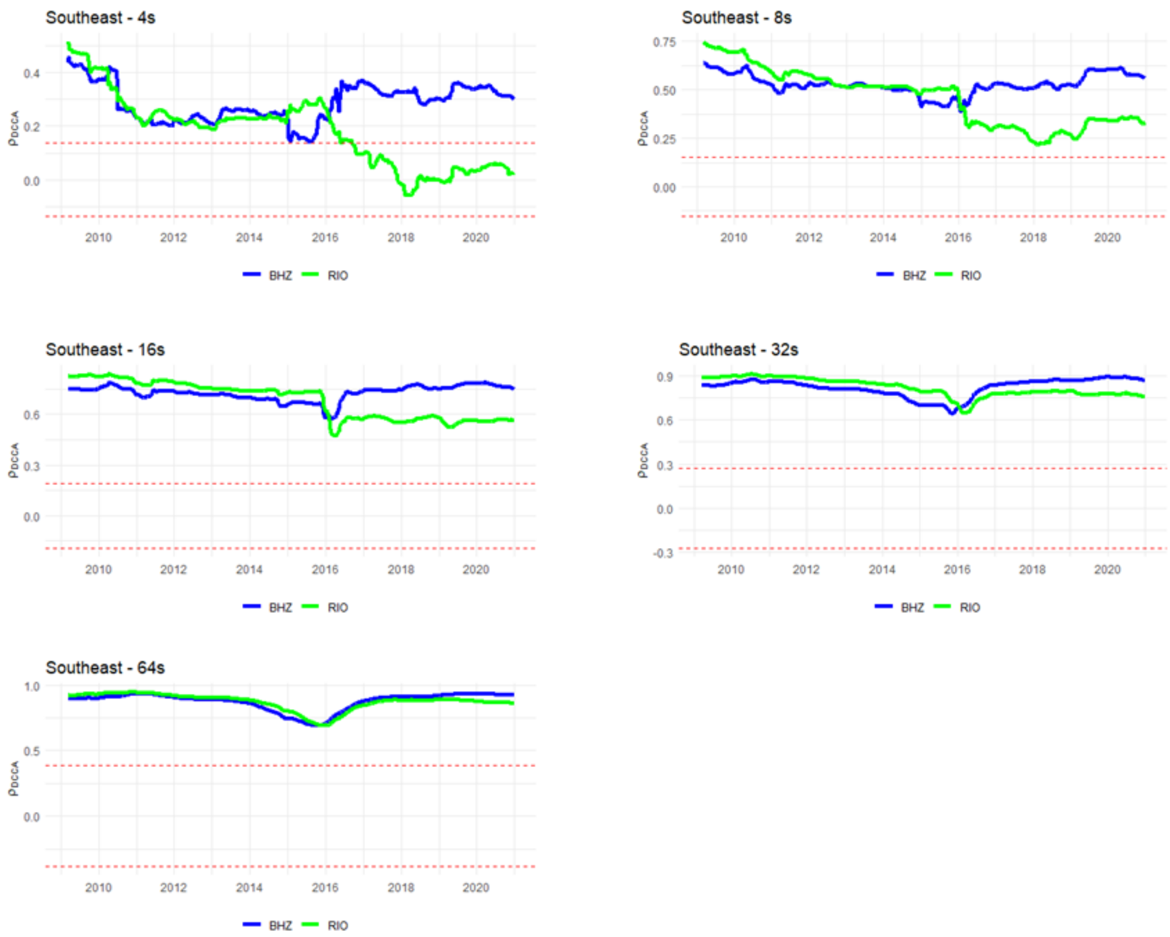


Figure 5. Evolution of $\rho_{DCCA}$ between the relative prices of São Paulo and other capitals in the **Southeast** region, with time scales of **4, 8, 16, 32 and 64** weeks, and moving window w=250. Shaded lines are the upper and lower confidence intervals, in the sense that values between these are not statistically significant, according to the critical values of Podobnik et al. (2011).

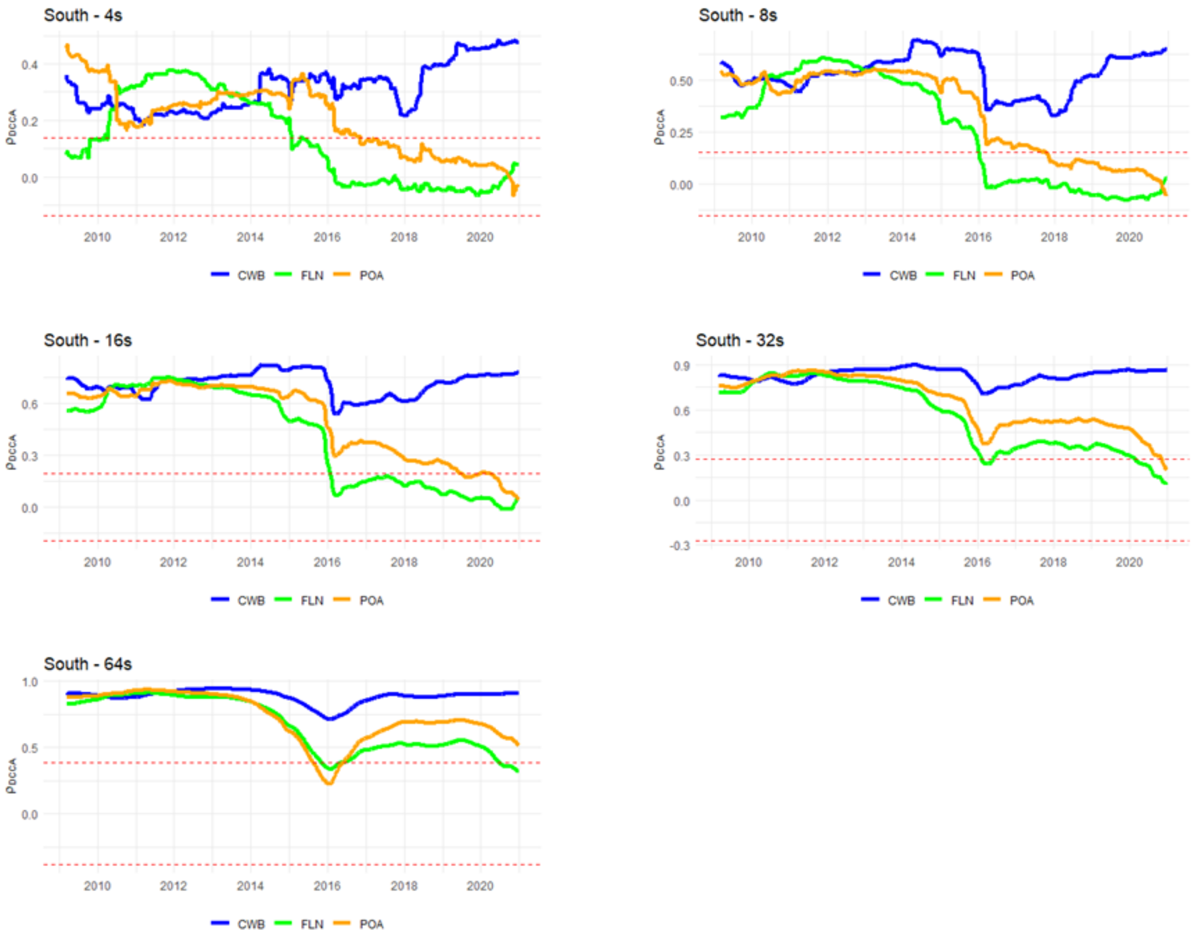


Figure 6. Evolution of $\rho_{DCCA}$ between the relative prices of São Paulo and other capitals in the **South** region, with time scales of **4, 8, 16, 32 and 64** weeks, and moving window w=250. Shaded lines are the upper and lower confidence intervals, in the sense that values between these are not statistically significant, according to the critical values of Podobnik et al. (2011).

## 3.6 Conclusions

The present work aimed to analyse the efficiency of automotive fuel markets, in a market where fuels can be chosen by the consumer, according to their relative price. The degree of persistence in the relative price returns of hydrous ethanol-gasoline C in the main Brazilian capitals was evaluated, as well as the degree of correlation between the relative price return of the city of São Paulo and other Brazilian capitals. The city of São Paulo is the capital of the homonymous state, the main ethanol producing state in Brazil, as well as the state with the largest financial and industrial centre and the largest flex-fuel fleet.

As an empirical strategy, DFA and DFA with sliding windows were used to analyse the degree of persistence of the series of relative prices, in line with the investigations by Alvarez-Ramirez et al. (2018) and Ferreira (2018), as well as the new version of the DCCA cross correlation coefficient (Zebende, 2011), namely dynamic DCCA with sliding windows (TILFANI et al., 2019; Guedes and Zebende, 2019).

Among our main results, it was found that the degree of persistence of capitals in the Southeast has a different pattern from capitals in other states, where the results within the same region differ. There is evidence that in large regions (or states) where the supply of ethanol is greater, such as in the Southeast (SAO and BHZ) and in parts of the Midwest (CGB) and South (CWB), the trajectory of return tends to be persistent. This suggests that in large ethanol producing regions, relative price returns tend to be more predictable and that relative price rises (falls) tend to be followed by rises (falls). In this way, the analysis helps to identify the trends in relative prices after a shock. This helps the formation of expectations for the agents of the fuel chain and for the formulation of policies to the sector. There is evidence that such behavior is not exclusive to the volume produced and consumed, but also related to the number of refiners, where the definition of retail price plays a fundamental role. Currently, there are 13 refineries in Brazil, of which 7 are located in these states (PETROBRÁS, 2022). Note that 4 of these are located in the State of São Paulo (President Bernardes Refinery-RPBC, Paulínia Refinery-Replan, Henrique Lage Refinery-Revap, and Capuava Refinery-Recap), 2 located in Paraná (Shale manufacturing-SIX and Presidente Getúlio Vargas Refinery-Repar), and 1 in Minas Gerais (Gabriel Passos Refinery-Regap).

Regarding the strength of the correlation, it was also found that the regions geographically closer to São Paulo (Southeast region) and relevant suppliers of ethanol, such as the Midwest (on longer time scales) and CWB (in the South region, but neighbouring São Paulo and with relevant production of ethanol), have a stronger price correlation, and with increasing strength as the time scale grows.

However, there is a discrepancy with the other capitals of the South Regions (FLN and POA), as well as the capitals of the North-Northeast Regions. Thus, there is strong evidence of a regionalized character, rather than a national one, of the behaviour of relative ethanol prices in Brazil, especially in the most recent period of the sampling window.

This work can also help private sector agents to diversify investments in fuel retail, by verifying the specific behaviour in each geographical region, as well as varying over time depending on the price policy and/or exogenous shocks. They can consider the regional behaviour of relative prices, in order to minimize portfolio risks at the national level, since the higher the correlation coefficients, the lower the benefits of diversifying investments. In addition, the estimates of the convergence of returns, by associating the strength of the correlation with the number of weeks of lag, can also be valuable information in building traders and brokers’ expectations, since this information is strategic in the commercialization of hydrated ethanol.

Another point is that this methodological tool can also be used by intelligence agencies in the ANP, together with other databases such as wholesale prices, in order to create auxiliary indicators in the analysis of cartelization practices or tacit collusion (Nascimento Filho et al., 2018; Murari et al., 2019). If prices are persistent, when prices rise, they tend to continue rising. In this case, the authorities, together with other metrics, can verify whether this dynamic of increasing relative prices is associated with market conditions (lower ethanol supply, oil price drops, among others) or anti-competitive practices (fraud, cartelization, etc) that distort relative prices.

In the case of cross-correlations, these indicate how a specific location behaves in relation to other capitals in the same region. Thus, there are important elements to assist in the diagnosis, when assessing whether the behaviour (convergent or divergent) has economic fundamentals, or if it is the result of some price distortion.

The CADE (Administrative Council for Economic Defence), after successive increases in the prices at gas stations in a generalized way in all states of the country, began to investigate suspicions of collusion, which can occur not only explicitly, as well as tacitly, through signalization published by the media. Between 2012 and 2020, the sector was fined more than BRL 500 million (ESTADÃO, 2021).

As policy suggestions, there is maintenance of the fuel price policy, in parity with the prices practiced in the international market. A key issue that is difficult to resolve quickly involves a sustainable macroeconomic policy in the long term, which prevents the continuous devaluation of the national currency. In addition to making the internationalization of oil prices less costly, it also acts to control inflation, which also indirectly affects the demand for fuel, by reducing families’ purchasing power.

From the recent Brazilian experience, the government's price control, in addition to causing losses for Petrobras' cash, whose largest shareholder is the government, also resulted in governance problems due to minority shareholders. In particular, a large part of the burden was transferred to the sugar-energy sector, by discouraging the use of ethanol, and thus discouraging investment and the decarbonization of the economy. In addition, favouring the use of ethanol in several locations in Brazil stimulates local economies from the point of view of investments (sugarcane producers, mills and other related activities), in order to generate regional jobs in these locations.

In line with the suggestion of aligning international prices, it is necessary to encourage investments in ethanol throughout Brazil, in order to consolidate it as a viable alternative to gasoline, as well as to meet decarbonization targets. Thus, it is necessary to strengthen public agencies to formulate policies to promote the entire production chain, from sugarcane planters to retail market ethanol.

**References**

Almeida, E. L. F. D., Oliveira, P. V. D., & Losekann, L. (2015). Impactos da contenção dos preços de combustíveis no Brasil e opções de mecanismos de precificação. **Revista Brasileira de Economia Política**, 35(3), 531-556.

Alvarez-Ramirez, J., Rodriguez, E., & Ibarra-Valdez, C. (2018). Long-range correlations and asymmetry in the Bitcoin market. **Physica A: Statistical Mechanics and its Applications**, 492, 948-955.

ANP (2010). **Anuário Estatístico Brasileiro de Petróleo, Gás Natural e Biocombustíveis 2010**. Available at: https://www.gov.br/anp/pt-br/centrais-de-conteudo/publicacoes/anuario-estatistico/arquivos-anuario-estatistico-2010/versao-para-impressao.pdf. Accessed on: 01 jun. 2021.

ANP (2020). **Anuário Estatístico Brasileiro de Petróleo, Gás Natural e Biocombustíveis 2020**. Available at: https://www.gov.br/anp/pt-br/centrais-de-conteudo/publicacoes/anuario-estatistico/arquivos-anuario-estatistico-2020/anuario-2020.pdf. Accessed on: 01 jun. 2021.

ANP (2021). **Série histórica do levantamento de preços**. Available at: https://www.gov.br/anp/pt-br/assuntos/precos-e-defesa-da-concorrencia/precos/precos-revenda-e-de-distribuicao-combustiveis/serie-historica-do-levantamento-de-precos. Accessed on: 01 jun 2021.

Barros, C.P.; Gil-Alana, L.A.; Wanke, P. (2014). Ethanol consumption in Brazil: Empirical facts based on persistence, seasonality and breaks. **Biomass and Bioenergy**, 63, 313-320.

Casa Nova, A., Ferreira, P., Almeida, D., Dionísio, A., & Quintino, D. (2021). Are Mobility and COVID-19 Related? A Dynamic Analysis for Portuguese Districts. **Entropy**, 23(6), 786.

Cajueiro, D.O.; Tabak, B.M. (2004). The Hurst exponent over time: testing the assertion that emerging markets are becoming more efficient. **Physica A: Statistical Mechanics and its Applications**, 336(3-4), 521-537.

Cajueiro, D.O.; Tabak, B.M. (2004). Evidence of long range dependence in Asian equity markets: the role of liquidity and market restrictions. **Physica A: Statistical Mechanics and its Applications**, 342(3-4), 656-664.

Capitani, D.H.D., Junior, J.C.C.; Tonin, J.M. (2018). Integration and hedging efficiency between Brazilian and US ethanol markets. Contextus–**Revista Contemporânea de Economia e Gestão**, 16(1), 93-117.

Chen, Z.; Ivanov, P.C.; Hu, K.; Stanley, H.E. (2002). Effect of nonstationarities on detrended fluctuation analysis. **Physical review E**, 65(4), 041107.

Costa, C.C.D.; Burnquist, H.L. (2016). Impactos do controle do preço da gasolina sobre o etanol biocombustível no Brasil. **Estudos Econômicos** (São Paulo), 46, 1003-1028.

da Costa, C.C.; Burnquist, H.L.; Guilhoto, J.J.M. (2017). The Impact of Changes in Fuel Policies on the Brazilian Economy. **Economia Aplicada**, 21(4), 635-657.

da Silva, A.S.; Vasconcelos, C.R.F.; Vasconcelos, S.P.; de Mattos, R.S. (2014). Symmetric transmission of prices in the retail gasoline market in Brazil. **Energy Economics**, 43, 11-21.

David, S.A.; Quintino, D.D.; Inacio Junior, C.M.C.; Machado, J.T. (2018). Fractional dynamic behavior in ethanol prices series. **Journal of Computational and Applied Mathematics**, 339, 85-93.

David, S.A.; Inacio Junior, C.M.C.; Quintino, D.D.; Machado, J.A.T. (2020). Measuring the Brazilian ethanol and gasoline market efficiency using DFA-Hurst and fractal dimension. **Energy Economics**, 85, 104614.

Debnath, D.; Whistance, J.; Thompson, W.; Binfield, J. (2017). Complement or substitute: Ethanol's uncertain relationship with gasoline under alternative petroleum price and policy scenarios. **Applied Energy**, 191, 385-397.

Dutta, A.; Bouri, E. (2019). Carbon emission and ethanol markets: evidence from Brazil. **Biofuels, Bioproducts and Biorefining**, 13(3), 458-463.

Dutta, A. (2020). Are global ethanol markets a 'one great pool'?. **Biomass and Bioenergy**, 132, 105-436.

El Montasser, G.; Gupta, R.; Martins, A.L.; Wanke, P. (2015). Are there multiple bubbles in the ethanol–gasoline price ratio of Brazil?. **Renewable and Sustainable Energy Reviews**, 52, 19-23.

ESTADÃO. (2021). **Cade vai monitorar o preço dos combustíveis em postos de todo o País**. Available at: https://economia.estadao.com.br/noticias/geral,cade-vai-monitorar-o-preco-de-combustiveis-em-postos-de-todo-o-pais,70003621206. Accessed on: 25 feb 2021.

EPE. Empresa de Pesquisa Energética. (2020a). **Série de formação de preços de combustíveis: margem bruta de distribuição e revenda**. Available at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-413/topico-476/SP-EPE-DPG-SDB-Abast-02-2019_DistrRev.pdf. Accessed on: 25 feb 2021.

EPE. Empresa de Pesquisa Energética. (2020b). **Série de formação de preços de combustíveis: tributos incidentes sobre a comercialização de combustíveis no Brasil**. Available at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-413/topico-562/SP-EPE-DPG-SDB-Abast-01-2020_Tributos_comercializa%C3%A7%C3%A3o.pdf. Accessed on: 25 fev 2021.

Fama, E.F. (1991), Efficient capital markets: II, **The Journal of Finance** 46(5), 1575–1617.

Fan, X.; Li, X.; Yin, J. (2019). Dynamic relationship between carbon price and coal price: perspective based on Detrended Cross-Correlation Analysis. **Energy Procedia**, 158, 3470-3475.

Ferreira, P. (2018). Long-range dependencies of Eastern European stock markets: A dynamic detrended analysis. **Physica A: Statistical Mechanics and its Applications**, 505, 454-470.

Ferreira, P. (2020). Dynamic long-range dependences in the Swiss stock market. **Empirical Economics**, 58(4), 1541-1573.

Ferreira, P.; Loures, L.C. (2020). An Econophysics Study of the S&P Global Clean Energy Index. **Sustainability**, 12(2), 662.

Figueira, S.R.; Burnquist, H.L.; Bacchi, M.R.P. (2010). Forecasting fuel ethanol consumption in Brazil by time series models: 2006–2012. **Applied Economics**, 42(7), 865-874.

Guedes, E.F.; Zebende, G.F. (2019). DCCA cross-correlation coefficient with sliding windows approach. **Physica A: Statistical Mechanics and its Applications**, 527, 121286.

Granco, G.; Caldas, M.M.; Bergtold, J.S.; Sant'Anna, A.C. (2017). Exploring the policy and social factors fueling the expansion and shift of sugarcane production in the Brazilian Cerrado. **GeoJournal**, 82(1), 63-80.

Hernandez, J.A.; Uddin, G.S.; Dutta, A.; Ahmed, A.; Kang, S.H. (2020). Are ethanol markets globalized or regionalized?. **Physica A: Statistical Mechanics and its Applications**, 551, 124094.

Hu, K.; Ivanov, P.C.; Chen, Z.; Carpena, P.; Stanley, H.E. (2001). Effect of trends on detrended fluctuation analysis. **Physical Review E**, 64(1), 011114.

Hwa, R.C.; Ferree, T.C. (2002). Scaling properties of fluctuations in the human electroencephalogram. **Physical Review E**, 66(2), 021901.

Janda, K.; Kristoufek, L. (2019). The relationship between fuel and food prices: Methods and outcomes. **Annual Review of Resource Economics**, 11, 195-216.

Kantelhardt, J.W.; Zschiegner, S.A.; Koscielny-Bunde, E.; Havlin, S.; Bunde, A.; Stanley, H.E. (2002). Multifractal detrended fluctuation analysis of nonstationary time series. **Physica A: Statistical Mechanics and its Applications**, 316(1-4), 87-114.

Kristoufek, L. (2014a). Measuring correlations between non-stationary series with DCCA coefficient. **Physica A: Statistical Mechanics and its Applications**, 402, 291-298.

Kristoufek, L. (2014b). Detrending moving-average cross-correlation coefficient: Measuring cross-correlations between non-stationary series. **Physica A: Statistical mechanics and its applications**, 406, 169-175.

Laurini, M.P. (2017). The spatio-temporal dynamics of ethanol/gasoline price ratio in Brazil. **Renewable and Sustainable Energy Reviews**, 70, 1-12.

Lima, C.R.A.; de Melo, G.R.; Stosic, B.; Stosic, T. (2019). Cross-correlations between Brazilian biofuel and food market: Ethanol versus sugar. **Physica A: Statistical Mechanics and its Applications**, 513, 687-693.

Mączyńska, J.; Krzywonos, M.; Kupczyk, A.; Tucki, K.; Sikora, M.; Pińkowska, H.; Wielewska, I. (2019). Production and use of biofuels for transport in Poland and Brazil–The case of bioethanol. **Fuel**, 241, 989-996.

Marjotta-Maistro, M.C.; Barros, G.S.A.D.C. (2003). Relações comerciais e de preços no mercado nacional de combustíveis. **Revista de Economia e Sociologia Rural**, 41(4), 829-858.

Margarido, M.A.; Dos Santos, G.R.; Vian, C.E.F.; Shikida, P.A.; Bauermann, B.C. (2020). CIDE and elasticity oscillation on the ethanol and gasoline market: Brazilian taxation policy under discussion. **Italian Review of Agricultural Economics**, 75(1), 3-17.

Mitra, S. K., Bhatia, V., Jana, R. K., Charan, P., & Chattopadhyay, M. (2018). Changing value detrended cross correlation coefficient over time: Between crude oil and crop prices. **Physica A: Statistical Mechanics and its Applications**, 506, 671-678.

Mohti, W.; Dionísio, A.; Ferreira, P.; Vieira, I. (2019). Frontier markets' efficiency: mutual information and detrended fluctuation analyses. **Journal of Economic Interaction and Coordination**, 14(3), 551-572.

Moraes, M.A.F.D.; Zilberman, D. (2014). Production of ethanol from sugarcane in Brazil: from state intervention to a free market (Vol. 43). **Springer Science & Business Media**.

Moraes, M.L.D.; Bacchi, M.R.P. (2015). Etanol: do início às fases atuais de produção. **Revista de Política Agrícola**, 23(4), 5-22.

Murari, T.B.; Nascimento Filho, A.S.; Pereira, E.J.; Ferreira, P.; Pitombo, S.; Pereira, H.B.; Moret, M.A. (2019). Comparative analysis between hydrous ethanol and gasoline c pricing in Brazilian retail market. **Sustainability**, 11(17), 4719.

Nascimento Filho, A.S.; Pereira, E.J.A.L.; Ferreira, P.; Murari, T.B.; Moret, M.A. (2018). Cross-correlation analysis on Brazilian gasoline retail market. **Physica A: Statistical Mechanics and its Applications**, 508, 550-557.

Nascimento Filho, A.S.; Saba, H.; dos Santos, R.G.; Calmon, J.G.A.; Araújo, M.L.; Jorge, E.M.; Murari, T.B. (2021). Analysis of Hydrous Ethanol Price Competitiveness after the Implementation of the Fossil Fuel Import Price Parity Policy in Brazil. **Sustainability**, 13(17), 9899.

Pal, D.; Mitra, S.K. (2018). Interdependence between crude oil and world food prices: A detrended cross correlation analysis. **Physica A: Statistical Mechanics and its Applications**, 492, 1032-1044.

Paiva, A.S.S.; Rivera-Castro, M.A.; Andrade, R.F.S. (2018). DCCA analysis of renewable and conventional energy prices. **Physica A: Statistical Mechanics and its Applications**, 490, 1408-1414.

Paulillo, L.F.; Soares, S.S.; Feltre, C.; Marques, D.S.P.; Vian, C.E.F. (2016). **As transformações e os desafios do encadeamento produtivo do etanol no Brasil**. Quarenta anos de etanol em larga escala no Brasil, 187. Available at: https://www3.eco.unicamp.br/nea/images/arquivos/Book_Quarenta_Anos_de_Etanol.pdf. Accessed on: 17 jan. 2022.

PETROBRÁS (2022). **Refinarias**. Available at: https://petrobras.com.br/pt/nossas-atividades/principais-operacoes/refinarias/. Accessed on: 13 jan. 2022.

Podobnik, B.; Stanley, H.E. (2008). Detrended cross-correlation analysis: a new method for analyzing two nonstationary time series. **Physical review letters**, 100(8), 084102.

Podobnik, B.; Jiang, Z.Q.; Zhou, W.X.; Stanley, H.E. (2011). Statistical tests for power-law cross-correlated processes. **Physical Review E**, 84(6), 066118.

Quintino, D.D.; David, S.A. (2013). Quantitative analysis of feasibility of hydrous ethanol futures contracts in Brazil. **Energy Economics**, 40, 927-935.

Quintino, D.D.; David, S.A.; Vian, C.E.F. (2017). Analysis of the relationship between ethanol spot and futures prices in Brazil. **International Journal of Financial Studies**, 5(2), 11.

Quintino, D.D.; Cantarinha, A.; Ferreira, P.J.S. (2021). Relationship between US and Brazilian ethanol prices: new evidence based on fractal regressions. **Biofuels, Bioproducts and Biorefining.**

Reboredo, J.C.; Rivera-Castro, M.A.; Zebende, G.F. (2014). Oil and US dollar exchange rate dependence: A detrended cross-correlation approach. **Energy Economics**, 42, 132-139.

Samanez, C.P.; da Rocha Ferreira, L.; do Nascimento, C.C.; de Almeida Costa, L.; Bisso, C.R. (2014). Evaluating the economy embedded in the Brazilian ethanol-gasoline flex-fuel car: A real options approach. **Applied Economics**, 46(14), 1565-1581.

SINDIPEÇAS (2019). **Relatório da Frota Circulante**. Available at: https://www.sindipecas.org.br/sindinews/Economia/2019/RelatorioFrotaCirculante_Maio_2019.pdf. Accessed on: 5 de jan. 2022.

Tilfani, O.; Ferreira, P.; El Boukfaoui, M.Y. (2019). Dynamic cross-correlation and dynamic contagion of stock markets: a sliding windows approach with the DCCA correlation coefficient. **Empirical Economics**, 1-30.

Uddin, G.S.; Hernandez, J.A.; Wadström, C.; Dutta, A.; Ahmed, A. (2021). Do uncertainties affect biofuel prices?. **Biomass and Bioenergy**, 148, 106006.

Vian, C.E.F. (2003). **Agroindústria canavieira**: estratégias competitivas e modernização. Editora Átomo.

Wang, G.J.; Xie, C.; Chen, Y.J.; Chen, S. (2013). Statistical properties of the foreign exchange network at different time scales: evidence from detrended cross-correlation coefficient and minimum spanning tree. **Entropy**, 15(5), 1643-1662.

Zebende, G.F. (2011). DCCA cross-correlation coefficient: Quantifying level of cross-correlation. **Physica A: Statistical Mechanics and its Applications**, 390(4), 614-618.

Zhao, X.; Shang, P.; Huang, J. (2017). Several fundamental properties of DCCA cross-correlation coefficient. **Fractals**, 25(02), 1750017.

Zilio, L.B.; Lima, R.A.D.S. (2015). Atratividade de canaviais paulistas sob a ótica da Teoria das Opções Reais. **Revista de Economia e Sociologia Rural**, 53, 377-394.

# 4. FINAL REMARKS

The objective of this thesis was to deepen the understanding of Brazilian hydrated ethanol price relationships in two aspects: first, with potentially related commodities of reference in the international market, traded in futures markets; secondly, in relation to relative prices to gasoline that prevailed in the domestic market, in several capitals distributed in the five main macro regions of the country.

In both texts, in methodological terms, the tools developed in the field of Econophysics were used, namely, the statistical techniques originally applied to models of Physics, but which are incorporated into modelling in finance and economics.

Despite the growth of the literature on the price relationships of Brazilian hydrated ethanol, both in relation to international assets and in the relationships between regional relative prices, there are gaps in the literature that deserve attention from the agents involved, namely, agents from the public and private sectors, as well as academics who aim to assist in the elaboration of public policies.

These price relationships have not yet been sufficiently explored after the recent structural changes and economic shocks that have occurred in the Brazilian economy, and more particularly, in the context of the sugar-energy sector. In short, the analysis of the behavior of ethanol prices has a fundamental role, as prices are the synthesis of factors that influence both the supply and demand curves.

Among the main facts that occurred over last half decade, we can mention the new fuel pricing policy, the import parity price (IPP), by Petrobrás in 2016, the creation of the National Biofuel Program, RenovaBio, in 2017, the truck drivers crisis in 2018, and the great socioeconomic shock caused by the emergence of COVID-19.

The first text evaluates whether Brazilian hydrous ethanol spot prices are correlated with carbon emission futures prices, comparing them with other potentially related commodities prices, both in the food segment (sugar) as well as important energy commodities (oil and natural gas). The period considered for the analysis was monthly data from January 2010 until July 2020. For that, a static approach of DCCA (Detrended Cross-Correlation Analysis) and a dynamic view through the construction of sliding windows was used. Among the main results, there was a weak and only short-term correlation between ethanol and carbon emissions prices. Furthermore, through the moving windows, it was found that this correlation varied over time.

Regarding the second article, the objective was to analyze the degree of persistence, via DFA (Detrended Fluctuation Analysis), of the weekly retail relative prices of hydrated ethanol and gasoline C, in the main Brazilian capitals, distributed in the five main macro-regions of the country. We also attempted to evaluate the degree of correlation (DCCA) between the relative prices of the city of São Paulo, capital of the main producing and consuming state of ethanol in Brazil, compared to other capitals. The analyzed period covers from May 2004 to December 2020. It was found that the behavior of relative prices differs between state capitals, as well as the degree of correlation between capitals, including those located in the same region of the country. For a dynamic analysis, moving windows method was used, which suggests that the strength of persistence, as well as the degree of correlation, is also time-varying, depending on the sub-period analyzed. In general, it was concluded that the behavior of relative prices depends on the regional market. In addition, capitals geographically closer to São Paulo tend to present relative prices that are more persistent and also present greater price correlation with the local São Paulo prices.

It is worth noting that a more in-depth understanding of the dynamics of Brazilian ethanol price relationships is increasingly important, with the advent of the 2015 Paris Agreement. In this sense, the strengthening of the ethanol sector is an excellent opportunity to contribute to the search for greater economic growth in a sustainable way, both from the regional socioeconomic point of view, and in terms of its environmental sustainability. Therefore, it is necessary not only to increase ethanol productivity, but also to improve and consolidate institutional mechanisms for promoting the sector and related ones, such as RenovaBio and IPP policy from Petrobrás. By way of conclusion, these three points are explained below.

It is important to point out that the increase in the supply of hydrated ethanol in Brazil must be encouraged through increased productivity and through production in areas already dedicated to agricultural activity, that is, it must not occur in areas intended for natural reserves, especially the Amazon and Pantanal biomes. This is relevant in order not compromise the sustainability of the ecosystem, given that natural reserves play a fundamental role in the absorption of carbon dioxide.

Another point is to improve the way in which producers of biofuels from grains are incorporated into RenovaBio, in order to sustain the growth in the share of corn ethanol in the total supply of hydrous ethanol, including to assist in meeting the targets for reducing emission of carbon dioxide. Furthermore, it is also worth mentioning the improvements in the social aspect: RenovaBio has innovations that are linked to the economic (stimulating the production of biofuels) and environmental components (reducing GHG emissions), however, the social component is not evident. In this sense, there are efforts regarding the creation of a seal of social sustainability that is linked to the program's guidelines.

Last, but not least, the discussion about IPP from Petrobrás has become even more complex in the context of the current year of 2022, as it is an electoral year, with inflationary acceleration, exchange rate at a high level and high oil prices due to the Russia-Ukraine war. In summary, this means high internalized fuel prices in the context of an economy with high inflation and unemployment.

In the short term, a measure that several countries around the globe are using includes reduction of taxes on fuel, in order to alleviate inflationary pressure. However, this can be a controversial measure. Firstly, it is necessary to have a reliable estimate of whether all the subsidies paid by the government will actually reach consumers, as part of the tax reduction may be appropriated by some agent in the production chain, especially fuel distributors and dealers. An important point to emphasize refers to the market structure of the fuel distribution sector in Brazil, in which only a small numbers of companies are responsible for a relevant portion of the supply.

Furthermore, fuel consumption is largely carried out by private agents who are in a privileged position in their economic sector or by families with medium-high and high incomes. In this sense, a policy that focuses on increasing the income of less privileged families could be more effective, in order to mitigate the erosion of their purchasing power caused not only by fuel, but also due to the acceleration of food inflation, which are a relevant part of the consumption basket of the less favoured consumers. Finally, by interfering in the price mechanism, subsidies to fossil fuels end up harming the economy's decarbonization plan, by not discouraging their consumption.

In addition to the short-term measures, there is also a discussion about the deconcentration of Petrobras' participation in the refineries. Thus, if Petrobras has a plan to reduce refining operations in the Brazilian market, through the sale of some refineries, there is a tendency for production units turned private firms to follow more quickly the fluctuations of international oil prices.

On the other hand, there is also a discussion about the end of the IPP policy, in order to “nationalize” the formation of fuel prices in Brazil, given that Brazil is an oil exporter. However, the national production capacity is limited in terms of refineries, which makes the country dependent on gasoline imports. This tends to act as a force for the convergence of national prices to those practiced in the international market. Otherwise, if price convergence is not observed, there could be shortages due to the scarcity of fuel supply in the national territory.

In short, it can be seen that public policies aimed at strengthening the ethanol production sector are complex and interrelated, and the aforementioned factors do not exhaust the difficulties in achieving sustained growth in this sector in Brazil. Thus, it is necessary to treat RenovaBio and IPP policy from Petrobrás, as well as more specific sectoral policies, in a systemic way, since bioenergy is an interdisciplinary area in the formulation of public policies, such as agriculture, energy, transport, among others. Furthermore, even with the hypothesis that an accurate diagnosis of the sector is carried out, the implementation of public policies is a challenge itself, which depends, among other factors, on speed, timing and political-economic circumstances.

In this sense, the present work sought to contribute to filling this gap with a robust methodology, in order to help the economic analysis of the behavior of Brazilian hydrated ethanol prices. Such an analysis is relevant for private agents seeking to diversify investments, as well as for public sector agents regarding the formation of public policies. Additionally, it also aims to contribute to the academic field by assisting in the development of future research, which can extend the present analysis with new data or other research methods.

**APPENDIX**

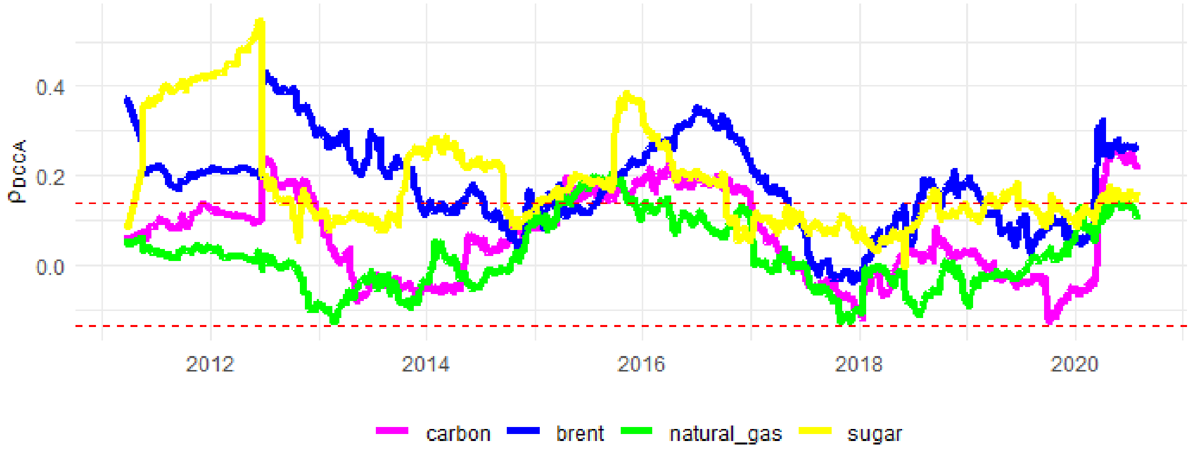


Figure A1. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 4 days and window size w = 250. Dashed lines represent critical values for statistical significance, according to [53].

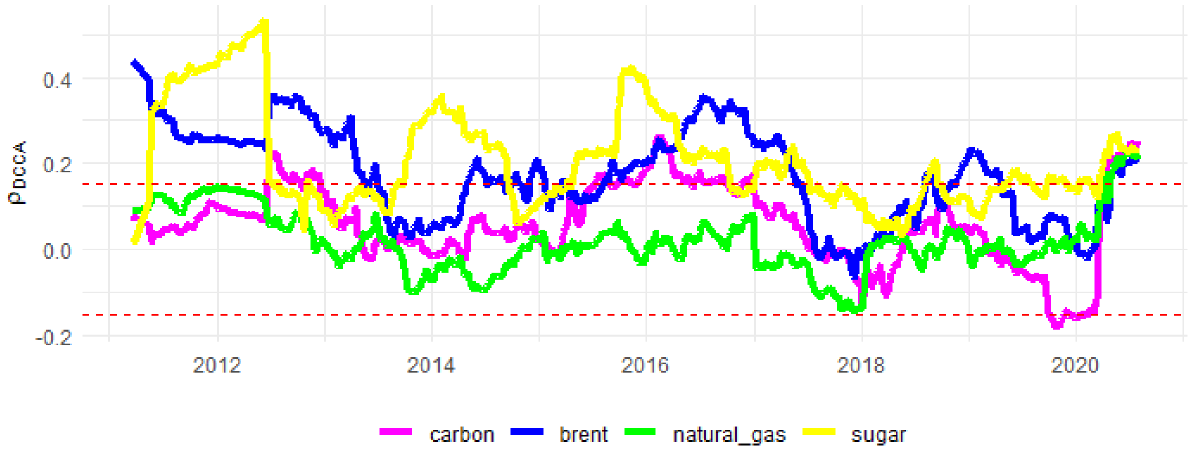


Figure A2. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 8 days and window size w = 250. Dashed lines represent critical values for statistical significance, according to [53].

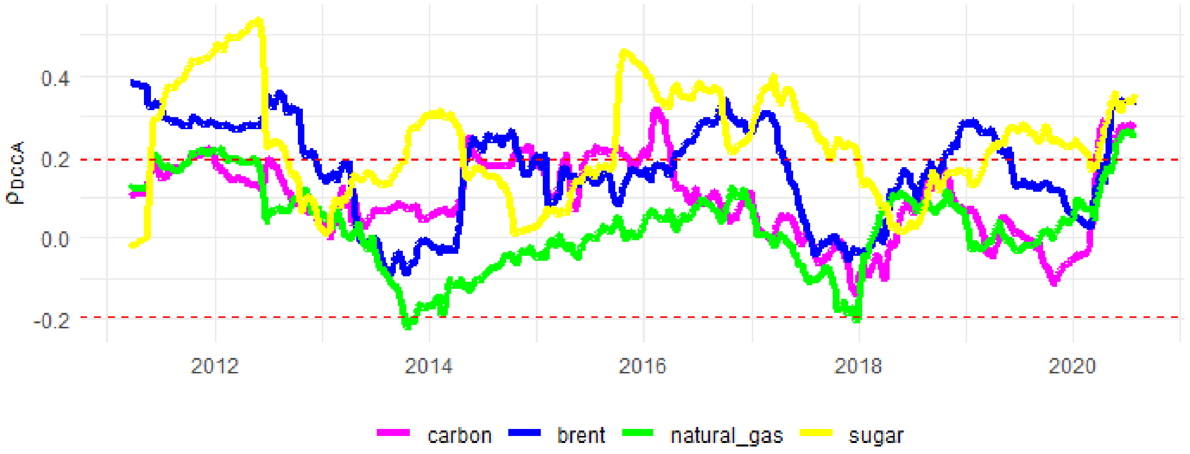


Figure A3. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 16 days and window size w = 250. Dashed lines represent critical values for statistical significance, according to [53].

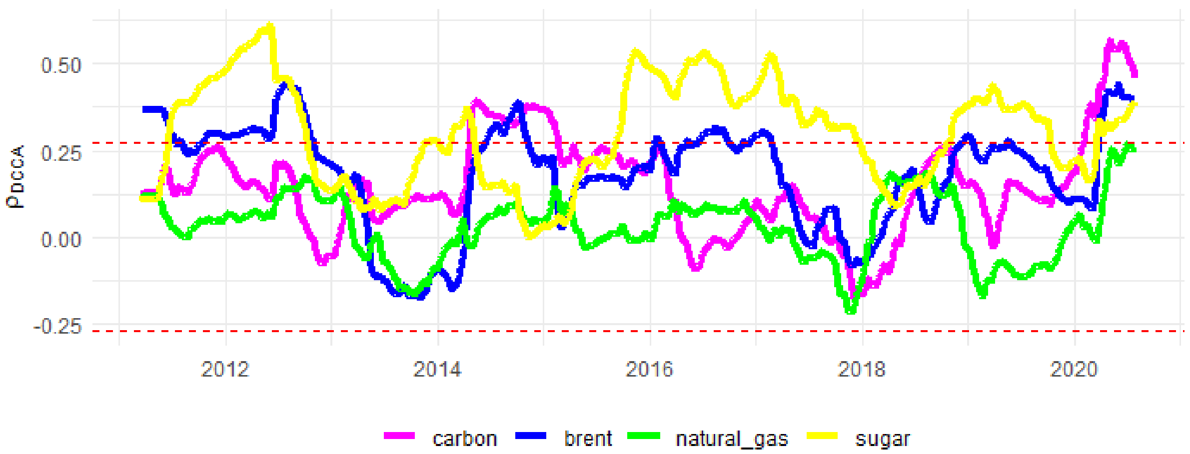


Figure A4. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 32 days and window size w = 250. Dashed lines represent critical values for statistical significance, according to according to [53].

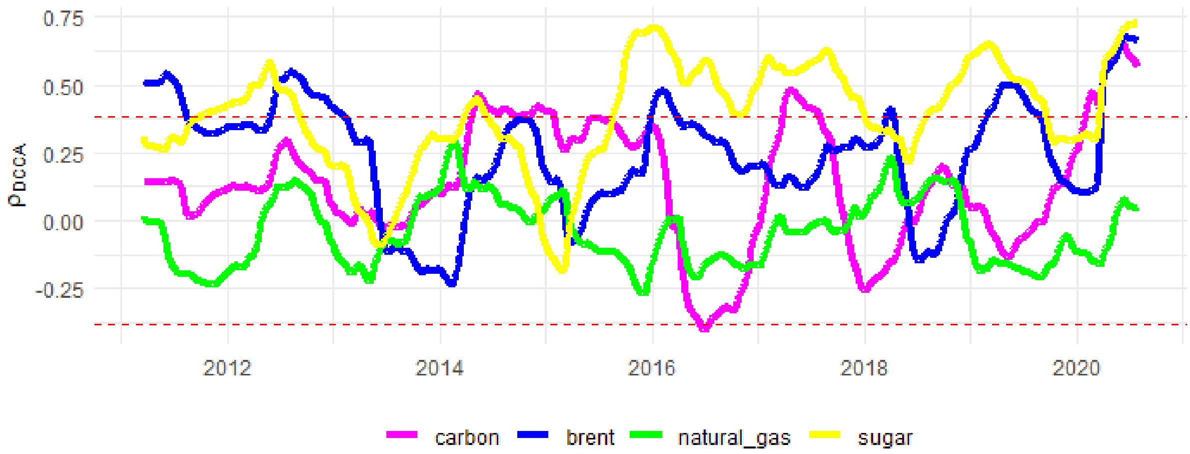


Figure A5. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 64 days and window size w = 250. Dashed lines represent critical values for statistical significance, according to according to [53]

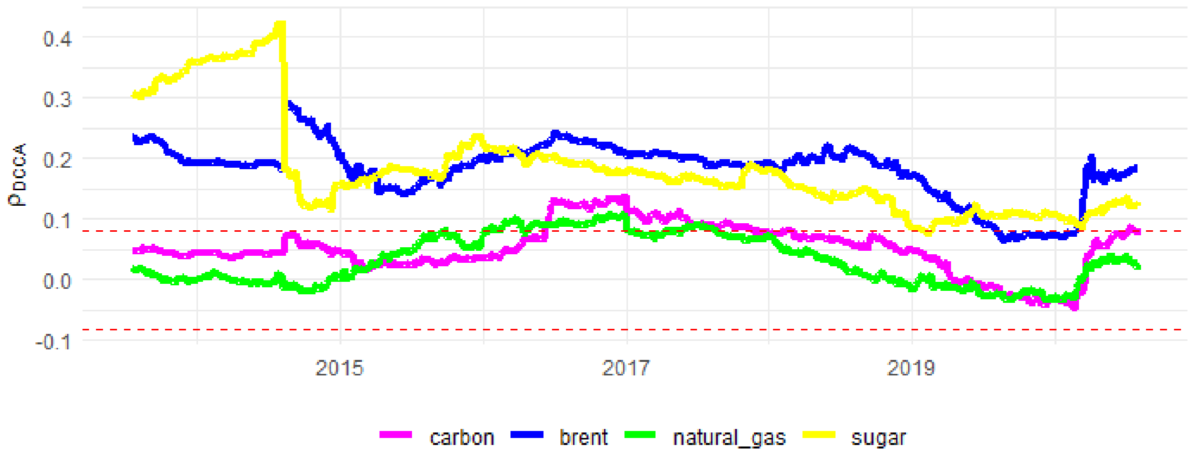


Figure A6. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 4 days and window size w = 750. Dashed lines represent critical values for statistical significance, from the author's calculations via GMZTests R package [61].

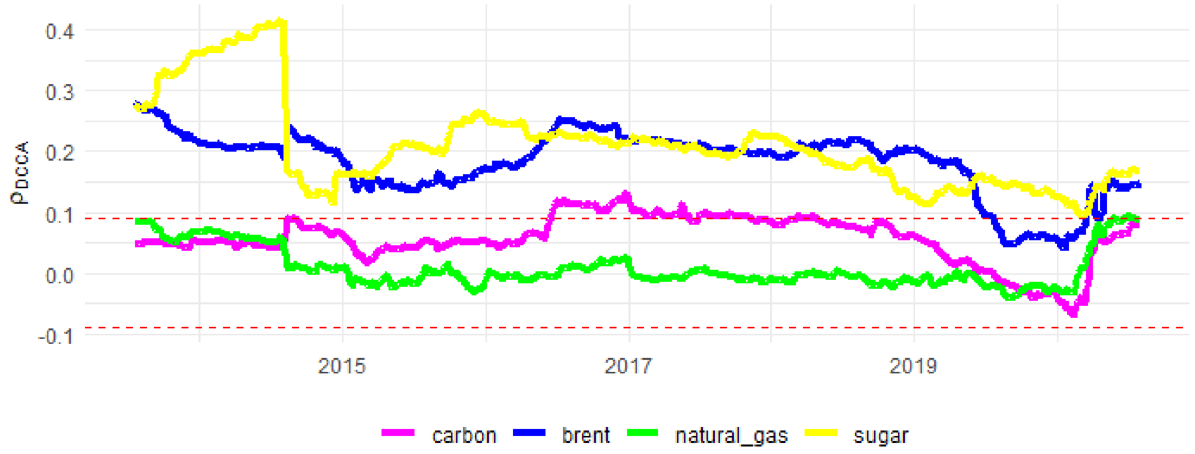


Figure A7. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 8 days and window size w = 750. Dashed lines represent critical values for statistical significance, from the author's calculations via GMZTests R package [61].

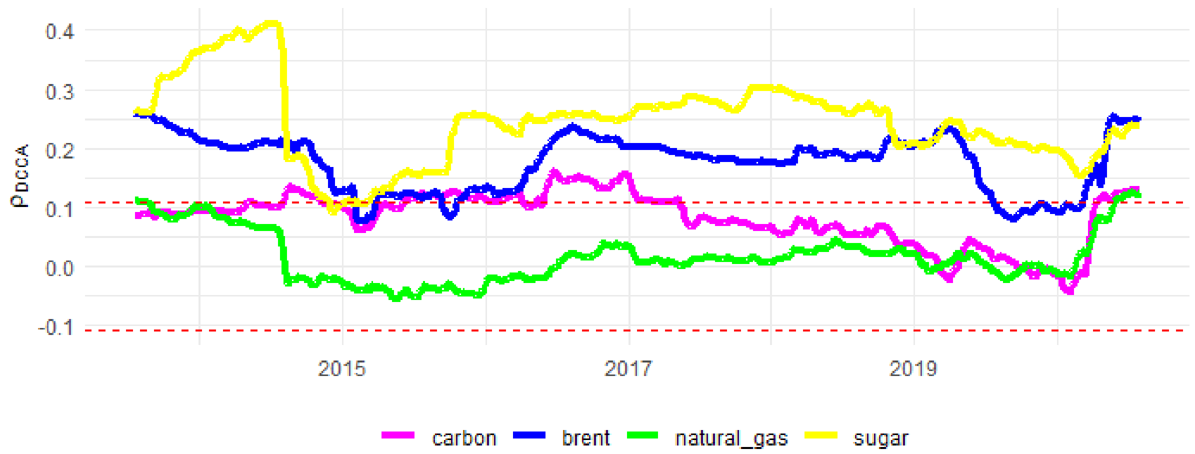


Figure A8. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 16 days and window size w = 750. Dashed lines represent critical values for statistical significance, from author's calculations via GMZTests R package [61].

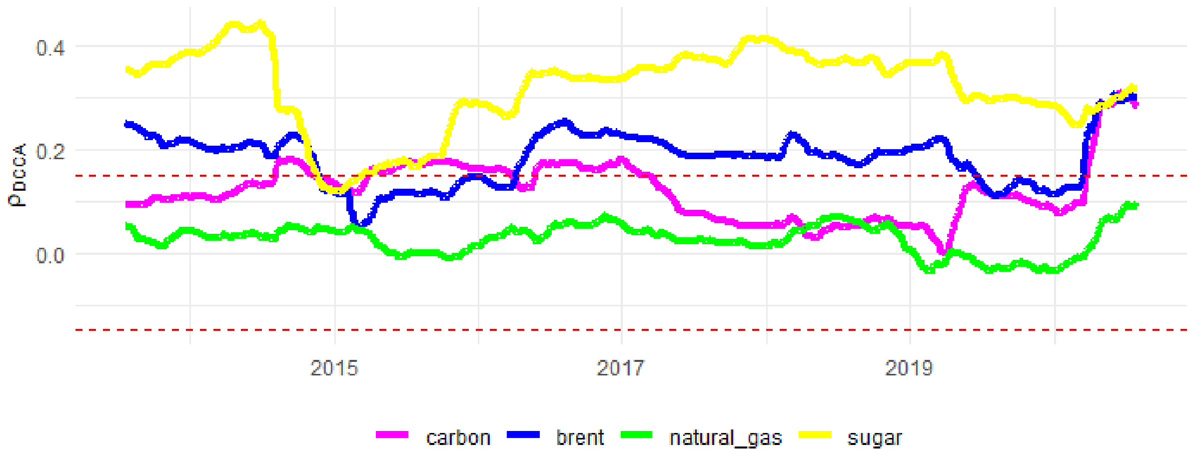


Figure A9. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 32 days and window size w = 750. Dashed lines represent critical values for statistical significance, from the author's calculations via GMZTests R package [61].

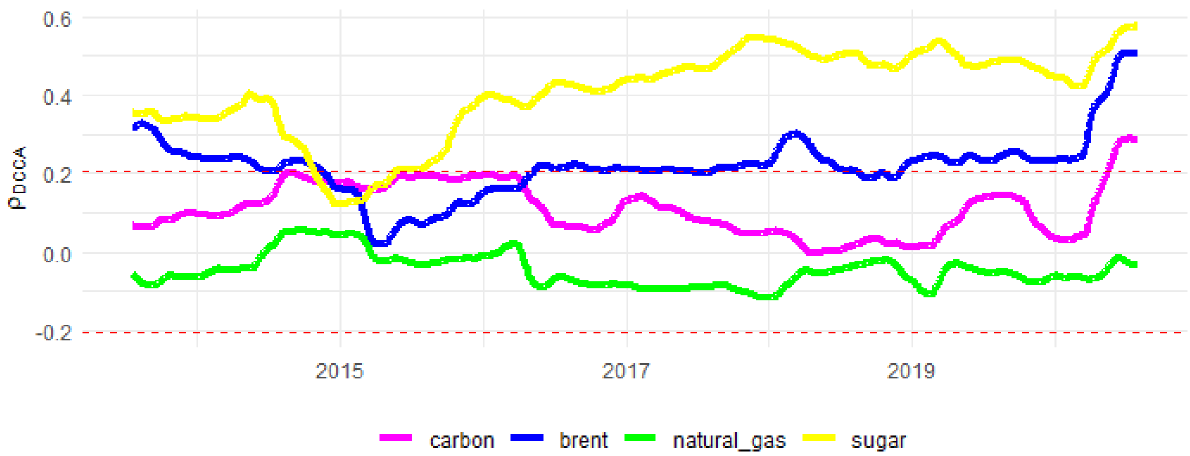


Figure A10. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 64 days and window size w = 750. Dashed lines represent critical values for statistical significance, from the author's calculations via GMZTests R package [61].

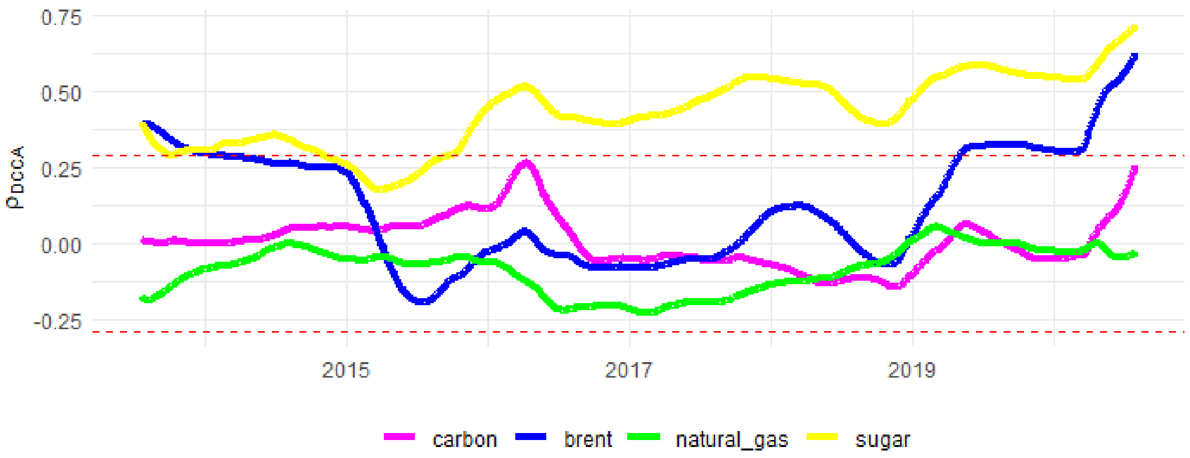


Figure A11. Evolution of the $\rho_{DCCA}$ between ethanol and the remaining commodities with time scales of 128 days and window size w = 750. Dashed lines represent critical values for statistical significance, from the author's calculations via GMZTests R package [61].