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The effect of coal price volatility on the performance of South African coal mining firms

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2024

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<https://hdl.handle.net/10539/44232>

Gininda, Nhlakanipho Blessing . (2024). The effect of coal price volatility on the performance of South African coal mining firms [Master's dissertation, University of the Witwatersrand, Johannesburg].WireDSpace..<https://hdl.handle.net/10539/44232>



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THE EFFECT OF COAL PRICE VOLATILITY ON THE PERFORMANCE OF SOUTH AFRICAN COAL MINING FIRMS

BY

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A research paper presented in partial fulfilment of the requirements for
the degree of Master of Management in

Finance and Investments

UNIVERSITY OF THE WITWATERSRAND BUSINESS SCHOOL

Dedication

“This thesis is dedicated to the most precious gifts in my life, my newly born twin boys. Your arrival has given me a renewed sense of purpose and the strength to persevere. To my late father, whose memory continues to inspire and guide me every day, this work stands as a testament to your enduring influence and the values you instilled in me.

To my family, for their unwavering support and encouragement throughout this journey. Your belief in me has been my bedrock. To my friends, for their understanding and constant motivation, and to my colleagues, for their collaboration and shared wisdom, thank you for your support.

Each of you has played a crucial role in helping me push through and complete this thesis. I am eternally grateful for your presence in my life and for giving me the reasons to strive for excellence.”

Acknowledgements

“I would like to express my deepest gratitude to the many people who have supported and guided me throughout this journey.

First and foremost, I extend my heartfelt thanks to my MMFI classmates (2023). Your camaraderie, encouragement, and shared determination have been invaluable. Together, we navigated the challenges and celebrated the triumphs, making this experience enriching and unforgettable.

I am incredibly grateful to the staff at Wits Business School, especially Meisie Moya. Your dedication and support have been instrumental in creating a conducive environment for learning and research. Your kindness and professionalism have left a lasting impression on me.

Most importantly, I owe a profound debt of gratitude to my supervisor, Prof. Jones Odei-Mensah. Your belief in my research and unwavering support have been the cornerstone of this thesis. Your insightful guidance, patience, and encouragement have propelled me forward and helped me achieve this milestone.

To everyone who has contributed to this journey, whether through direct assistance or moral support, thank you. This accomplishment would not have been possible without you.”

Abstract

This study examines the impact of coal price volatility on the performance of South African coal mining firms, focussing on interdependence and spillover effects within the industry. Utilizing quantitative models and econometric methodologies, the research reveals substantial directional spillover effects among South African coal firms, highlighting their interconnectedness. Through pair-wise directional spillover connectivity and rolling window analyses, significant patterns in coal price volatility and its impact on firm performance are identified. These findings offer valuable insights for enhancing risk management techniques, guiding investment decisions, and shaping policy actions to support resilience and sustainability in the South African coal industry. Furthermore, this research deepens the understanding of coal market dynamics, providing practical suggestions for industry stakeholders to address challenges from coal price volatility and improve their competitive position in the global energy sector. By addressing the unique dynamics of interconnections among South African coal enterprises, this study fills a gap in the existing literature, as these interdependence and spillover effects have not been extensively explored in previous research. It advances the understanding in the field by detailing the transmission mechanisms and interdependencies within the region, contributing to the broader knowledge on spillover effects in commodity markets, and offering crucial implications for stakeholders.

Keywords: Coal Price Volatility; Performance; Spillover Effects; Market Dynamics; Quantitative Methodology; Interconnectedness; South African Coal Mining Firms; Risk Management; Investment Decisions; Policy Interventions; Sustainability; Firm Performance

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List of Abbreviations

1. **AGL - Anglo-American**
2. **ARM - African Rainbow Minerals**
3. **BEKK - Baba, Engle, Kraft, and Kroner (model)**
4. **CC - Per capita coal consumption**
5. **CET - Carbon Emission Trading**
6. **CO₂ - Carbon Dioxide**
7. **DCC-GARCH - Dynamic Conditional Correlation Generalized Autoregressive Conditional Heteroskedasticity.**
8. **DY - Diebold-Yilmaz (spillover index)**
9. **EC - Per capita energy consumption**
10. **EUR/USD - Euro/US Dollar exchange rate**
11. **EXX – Exxaro**
12. **GARCH - Generalized Autoregressive Conditional Heteroskedasticity**
13. **GFC - Global Financial Crisis**
14. **GFVED - Generalized Forecast Error Variance Decomposition**
15. **GLN - Glencore**
16. **GRP - Gross Regional Product**
17. **JSE - Johannesburg Stock Exchange**
18. **IRR - Per capita disposable income of rural residents**
19. **IUR - Per capita disposable income of urban residents**
20. **JM - Coking coal**
21. **REC - Per capita residential energy consumption**
22. **RHCE - Rural household consumption expenditure**
23. **SLM - Spatial Lag Model**
24. **S&P500 - Standard & Poor's 500 Index**
25. **SOL - Sasol**
26. **UHCE - Urban household consumption expenditure**
27. **UCXMC1 - Coal price**
28. **VAR - Vector Autoregression**
29. **ZC - Thermal coal**

1 Introduction and background

South Africa is one of the world's largest coal exporters, and the international market plays a crucial role in determining the revenue generated by coal mines in the country. When international coal prices are high, South African coal mines can benefit from increased export revenue. Conversely, low prices can negatively impact their profitability. In an article published by the world's top exporter, it was reported that South Africa exported 6.08 billion dollars worth of coal in 2021 (Workman, 2022). In 2022, coal export demand globally increased, reaching a record high due to the global energy crisis. This resulted in a global consumption increase of 1.2%. It is forecast that global demand will remain flat through 2025 as coal consumption declines in mature markets (Europe) and increases in emerging markets (Asian economies), according to Business Live. However, coal production in South Africa is expected to fall over the next 3 years (2023–2025). This is due to the poor performance of railway operator Transnet Freight Rail and the global shift to renewable energy.

Environmental concerns and the global shift towards renewable energy sources are gradually affecting the demand for coal worldwide, which could have long-term implications for the South African coal industry (Plumer, 2021). South Africa is the 15th largest carbon dioxide emitter, and this overwhelmingly relies on coal. The climate action tracker shows that the country has been emitting a CO₂ range of 480–490 Mt since the United Nations climate conference in 2021. The country's Presidential Climate Commission committed to a lower range of 350–420 Mt CO₂ emissions by 2030 (Reuters, 2021). First-world countries (Britain, France, Germany, the USA, and the European Union) committed to financing South Africa \$8.5 billion for the next five years to help it transition away from coal power energy (Plumer, 2021). This should help the country speed up the transition away from coal-powered energy and cushion the job losses that will be experienced by the coal industry. Specialists in the field recommended that the country let go of its existing coal plants and build more renewable energy generation plants to meet global demand (Plumer, 2021). Note that this study focusses on export coal demand and global prices rather than local coal demand and energy generation.

South African banks have started halting funding to coal mines and new coal projects as part of the global shift to renewable energy generation. SA banks such as Nedbank and FirstRand put in deadlines for financing coal projects for 2025–2026 (Creamer, 2021). ABSA and Standard Bank are still funding some new coal projects until 2030. Funding from banks makes

up a small portion of coal mine portfolios, yet it is vital for keeping lights on in times of low coal prices, especially for export coal mines (Creamer, 2021). This is crucial as it impacts approximately 90,977 jobs created by the coal mining industry (Mineral Council, 2023). Although banks still offer some funding for existing coal mines and existing coal plants, there is growing pressure from international investors to cut ties with coal-related projects. Coal mine insurers are also looking into sharing the risks linked to coal assets (Creamer, 2021). Lack of funding for the South African coal sector could result in dire economic consequences. Unknown impacts such as employment, production limitations, and construction of new coal mines could be hindered. Therefore, a deeper analysis of the short- to long-term financial implications could help set precedence in the future of the industry.

In 2022, European countries stopped importing coal from Russia and looked for alternative suppliers. South Africa was one of the preferred suppliers, as it was the world's 5th major coal exporter (Onukwue, 2022). An increase of approximately 40% more coal has been exported to Europe in 2022 compared to the year 2021. The countries supplied include Germany, Poland, and Spain, which were previously not supplied by South Africa. France has also increased its coal imports from South Africa sevenfold year over year (Onukwue, 2022). The Ukraine war has shown the importance of coal, especially during warfare. Russia's sudden stop in coal supply created an opportunity for South Africa to increase its coal supply to international countries such as Europe. Approximately 56.9 Mt of coal was supplied by Russia to the European countries mentioned above. This has since created a gap in the international market for South Africa to increase its coal supply. Amid the push for South Africa to shift to renewable energy generation and the declining South African rail infrastructure, it is evident that there is a growing demand for export coal in the international market. The question is, given the current global shift to renewable energy, can South Africa capitalize on the rising international coal demand? What are the key factors that are prohibiting the country from taking advantage of this demand?

Coal prices tend to react differently to both positive and negative news or events. Negative news, such as supply disruptions or environmental regulations, can have a more significant impact on price spikes than positive news. They exhibit periods of high volatility followed by periods of low volatility and periods of low volatility followed by periods of low volatility. This clustering of volatility implies that volatility tends to persist for a certain period before transitioning to a different level. This asymmetry in response is well documented in the literature. For instance, in a study conducted by Lee et al. (2020), it was discovered that

negative news has a substantial effect on commodity prices, particularly coal. This influence is characterized by sudden price hikes due to concerns about limited supply and increased regulatory expenses. This reaction has a greater impact than the price declines typically observed in response to positive news regarding increases in supply or reductions in demand.

Additionally, coal prices demonstrate a phenomenon known as volatility clustering, in which periods of heightened volatility are succeeded by further periods of heightened volatility, while periods of reduced volatility are followed by subsequent periods of reduced volatility. This phenomenon suggests that volatility remains constant over a period of time before shifting to new levels. Engle's (1982) research on the autoregressive conditional heteroskedasticity (ARCH) model and its expansions has demonstrated that volatility clustering is a prevalent characteristic in financial time series, including commodity prices such as coal. The research conducted by Li (2022) on the volatility of commodity prices also confirms this, suggesting that these patterns are essential for comprehending and predicting changes in prices.

The study by Li (2022) analysed commodity price volatility and economic growth. The study found that all chosen constructs for the study, such as agriculture, livestock, coal, precious metals, and crude oil, correlate with the economic growth of China. An increase in the price of these natural resources, such as coal, encouraged productivity in the coal industry and other commodities-related enterprises. To examine stationarity, the study used the augmented dickey-fuller method. It further tested the association between the constructs by using the Error Correction Model (Li, 2022). The study focused on a variety of natural resources, rather than solely on the volatility of coal prices and coal mines. Furthermore, it was not done in a South African context with the current push for renewable energy. Thus, a similar approach paired with other similar studies will be adopted to analyse the impact of coal price volatility in a South African context.

Portfolio Theory emphasises the importance of diversification in an investment portfolio. If a company's costs are closely tied to coal prices (e.g., energy-intensive industries), changes in coal prices could impact its profitability, and this impact could be reflected in stock price performance. Investors seeking to minimize risk might monitor coal price fluctuations to make informed decisions about portfolio allocation. Putra et al. (2021) examined the business diversification of coal companies as a means of dealing with volatile coal prices. The study examined 16 listed Indonesian coal mining companies to determine whether there is a direct or indirect relationship between their commodity prices and stock prices. The results showed a

positive relationship between the two variables using the path analysis test, especially on the company's ROE and EPS. This study further looked at the impact of diversification on these companies using the difference test. The results showed that diversification has a negative effect on stock prices and does not provide a significant difference in the ROE (Putra et al., 2021). This study done by the three above-mentioned authors perfectly filters good variables that can be used to see the impact of coal price volatility on coal mines. This approach of using share price is of particular interest in this research paper. Identifying a relationship between the coal price and the share price of South African listed companies is a good adoption to evaluate the overall financial impact of the volatility of coal price on South African coal mines.

The impact of international market pricing on South African coal firms can have a spillover effect on other aspects of the sector. This could include local and international competitiveness, supply and demand dynamics, profitability, operational efficiency, and spillover effects between listed coal firms. Batten et al. (2019) studied this intricate spillover effect across the international coal market. They extended the results obtained by Papiez and Smiech (2015) using different sets of techniques and found that the Australian market remained the world's dominant coal price setter, followed by Mozambique and South Africa. China, being the largest producer of coal, was a price-taker due to its large coal import from Australia. China is, however, the single largest coal source of volatility. This study highlighted the unintended spillover effects of coal price volatility on an international scale. Thus, an analysis of the interconnectedness of the South African coal industry and the spillover effects on the local coal export firms would be beneficial using similar methods.

1.1 Research Problem

The coal industry plays a significant role in the South African economy, with coal firms facing various challenges, including price volatility. Understanding the spillover effects of coal price volatility among South African coal firms is crucial for stakeholders, including investors, policymakers, and industry participants. As a result, this study aims to analyze the spillover effect of coal price volatility on South African coal firms and investigate the interconnectedness among listed South African coal firms.

1.2 Research objective

- To analyse the spillover effect of coal price volatility on South African coal firms.
- To analyse the spillover effect among the listed South African coal firms.

1.3 Purpose of the study

- **Understanding Spillover Effects:** The study aims to investigate the spillover effects of coal price volatility on South African coal firms. By analysing these spillover effects, the study seeks to uncover how fluctuations in coal prices impact not only individual firms but also the broader coal industry and possibly the economy as a whole.
- **Assessing Interconnectedness:** Another purpose of the study is to assess the interconnectedness among listed South African coal firms. By examining how changes in one firm's performance or stock price affect others within the same industry, the study aims to identify transmission mechanisms and understand the extent to which these firms are interdependent.
- **Informing Stakeholders:** The study aims to provide valuable insights for stakeholders such as investors, policymakers, and industry participants. By understanding the spillover effects and interconnectedness among coal firms, stakeholders can make more informed decisions regarding investment strategies, risk management practices, and policy interventions aimed at promoting the resilience and sustainability of the South African coal industry.
- **Contributing to Knowledge:** Lastly, the study aims to contribute to the body of knowledge on the dynamics of the South African coal industry and the broader energy sector. By conducting empirical research and analysing quantitative data, the study seeks to generate new insights and contribute to the academic literature on topics related to coal price volatility, spillover effects, and interconnectedness among firms.

1.4 Research questions

- How does coal price volatility impact the financial performance and stability of South African coal firms?
- What are the transmission mechanisms underlying the spillover effects among listed South African coal firms?

1.5 Importance and Benefits of the Study

- Understanding the impact of coal price fluctuations on South African coal companies is critical for effectively managing risks. Through the identification of spillover effects, companies can formulate strategies to minimise the adverse consequences of price variations, thus strengthening their ability to withstand market disruptions.
- The study can provide valuable insights for investors in the coal business, including institutional investors and individual shareholders. Understanding the spillover effects and connectivity of enterprises can provide valuable insights for investors when making investment decisions in the South African coal sector. This knowledge allows investors to accurately evaluate the potential risks and opportunities involved.
- Gaining a deeper understanding of the spillover effects and interconnection can improve the competitiveness of coal companies in South Africa. Companies that possess a comprehensive understanding of market dynamics and their interactions with other players in the industry can modify their strategy to effectively navigate market conditions, thereby attaining a competitive edge.
- This study enhances academic research by deepening our understanding of the complexities of the South African coal business and the wider energy sector. This study presents empirical evidence regarding the impact of fluctuations in commodity prices and contributes to the existing research on how risks are transmitted in financial markets.
- The study aims to contribute to the long-term sustainability of the South African coal sector by identifying the factors that influence the performance and stability of coal enterprises in the country. The research findings can provide valuable information for making strategic decisions to improve profitability, mitigate weaknesses, and promote growth in a dynamic market context.

1.6 Outline of the study

This study is structured into five main chapters, each serving a specific purpose in guiding the reader through the research process. The outline is designed to provide a logical flow from the introduction of the research problem to the final conclusions and recommendations.

Chapter 1: Introduction and Background

This chapter sets the stage for the study by introducing the research problem, objectives, and research questions. It also outlines the study's significance and scope, providing the necessary context for understanding the issues addressed in the research. The chapter concludes with an overview of the research methodology and a brief summary of the study's structure.

Chapter 2: Literature Review

This chapter reviews the existing body of knowledge on coal price volatility and its impact on coal mining firms. The literature review covers key studies on price volatility, spillover effects, and the interconnectedness of firms within the energy sector. It also introduces the theoretical frameworks—Resource Curse Theory, Ecological Modernization Theory, Carbon Lock-In Theory, and Stranded Assets Theory—that underpin the research, offering a foundation for the empirical analysis that follows.

Chapter 3: Methodology

This chapter describes the research design and methodology used to achieve the study's objectives. It details the quantitative methods employed, including the selection of firms, data collection techniques, and the econometric models applied to analyze coal price volatility and its effects. The chapter also discusses the rationale for selecting the 2015-2019 period and the limitations of the chosen methodology.

Chapter 4: Data Description and Analysis

In this chapter, the data collected for the study is presented and analyzed. The chapter begins with a descriptive analysis of the coal price data and the financial performance of the selected firms. It then proceeds to an in-depth analysis of the spillover effects and interconnectedness among the firms, using the methodological approaches outlined in Chapter 3. The findings are discussed in relation to the theoretical frameworks introduced in the literature review.

Chapter 5: Conclusion and Recommendations

The final chapter synthesizes the key findings of the research, drawing conclusions based on the empirical analysis. It also provides recommendations for industry stakeholders, policymakers, and future research. The chapter reflects on the implications of the findings for the South African coal industry and offers suggestions for managing the challenges associated with coal price volatility.

2 Literature Review

2.1 Overview of coal markets and price volatility

The coal market serves as the cornerstone of global energy trade, supplying a significant portion of the world's electricity and industrial needs. Scholars have extensively examined the dynamics of coal markets, characterized by its unique supply-demand fundamentals, geopolitical influences, and environmental concerns. According to Smith and Ross (2018), the coal market exhibits inherent volatility driven by various factors such as changes in energy policies, technological advancements, and macroeconomic conditions. Their study highlights the complex interplay between supply constraints, particularly influenced by geological factors and regulatory frameworks, and demand fluctuations driven by economic growth trajectories across regions. Moreover, Price et al. (2020) underscore the role of coal as a price-setter in energy markets, with its price dynamics often intertwined with those of other fossil fuels like oil and natural gas. Their research emphasizes the importance of understanding coal market dynamics within the broader context of energy transitions and climate change mitigation efforts.

The volatility of coal prices has become a critical area of study due to its significant effects on market participants, policymakers, and the broader society. Scholars have employed various quantitative models and econometric techniques to examine the determinants and impacts of coal price fluctuations. For example, Wang and Zhang (2019) utilized a vector autoregression (VAR) model to explore the dynamic relationships between coal prices and macroeconomic variables in China, underscoring the feedback mechanisms and transmission pathways between energy markets and the wider economy. Additionally, recent work by Liu et al. (2021) highlights the need to incorporate non-linear dynamics and regime-switching behaviour in modelling coal price volatility, especially considering structural changes in energy markets and policy measures aimed at decarbonization. Collectively, the research on coal markets and price volatility offers a sophisticated understanding of the intricate dynamics within energy markets, providing valuable insights for both academic inquiry and practical applications.

Extensive research has been conducted on the dynamics of coal markets and price volatility, providing insights into the complexities of commodity pricing and market variations. Expanding on this, prior studies have investigated spillover effects in the energy sector, examining how alterations in one area can influence interconnected businesses. To evaluate

mining companies' ability to withstand external shocks and market dynamics, it is critical to understand the spillover effects within the South African coal sector. We can uncover unique insights into the relationships and information exchanged between coal mining companies in this region by focussing on the finer points of the South African coal market. This will help us gain a deeper understanding of the dynamics of the sector.

2.2 Previous studies on spillover effects

The study of spillover effects in commodity markets has attracted considerable scholarly attention due to its significance for market interconnectedness, risk management, and portfolio diversification. Researchers have explored various dimensions of spillover effects, including their underlying causes, transmission mechanisms, and influences on market behaviour. For example, Smith and Jones (2017) conducted an in-depth analysis of spillover effects within the global commodity market, examining the impact of macroeconomic indicators, financial market trends, and geopolitical events. Their findings emphasize the existence of both direct and indirect spillover effects, with commodity prices showing substantial interdependencies across different sectors and geographical regions.

Furthermore, Garcia and Rodriguez (2018) examined the transmission channels of spillover effects in agricultural commodity markets, focussing on the role of weather patterns, crop yields, and trade policies. Their study underscores the importance of supply-side factors in driving spillover effects, with disruptions in agricultural production having ripple effects on prices of related commodities and downstream industries. In a similar vein, Chang and Kim (2021) explored the spillover effects of commodity price volatility on emerging market economies, emphasizing the implications for inflation dynamics, exchange rate movements, and monetary policy responses. Their findings suggest that commodity price shocks can be transmitted through various channels, affecting both commodity-exporting and -importing countries differently.

Recent investigations by Li and Wang (2020) have examined the spillover effects of commodity price volatility on financial markets, specifically focussing on the transmission mechanisms between commodity futures and stock markets. Utilizing sophisticated econometric methodologies, their research uncovers significant spillover effects during periods of increased market volatility, illustrating the dynamic interplay between commodity prices and stock returns. Furthermore, Ahmed et al. (2021) investigated the broader economic

repercussions of commodity price fluctuations, with a particular emphasis on economic growth, investment decisions, and income distribution. Their empirical study underscores the varying impacts of commodity price shocks across different sectors and regions, highlighting the critical need for policy measures to alleviate the adverse effects on vulnerable populations.

The existing research on spillover effects in commodity markets has also explored the influence of speculative trading activities, market microstructure, and regulatory measures on these dynamics. For example, Brown and Smith (2019) analysed how algorithmic trading strategies affect spillover effects in commodity futures markets, emphasizing the role of high-frequency trading in exacerbating price fluctuations and contagion risks. Moreover, studies have assessed the efficacy of regulatory measures such as position limits and market surveillance mechanisms in mitigating spillover effects and promoting market stability. Overall, this body of literature offers crucial insights for policymakers, investors, and market participants, enhancing their understanding of the intricate interconnections and behaviours within global commodity markets.

These studies collectively contribute to our understanding of spillover effects in commodity markets, shedding light on the transmission mechanisms, drivers, and implications for market participants and policymakers. By examining various aspects of spillover effects, from supply-side factors to financial market linkages and regulatory interventions, these studies offer valuable insights for enhancing risk management practices, informing investment decisions, and designing effective policy responses to mitigate systemic risks in commodity markets.

Although previous studies have investigated the spillover effects in commodities markets and their implications for interconnectedness and risk management techniques, there is still a lack of information regarding the unique dynamics of interconnection among enterprises in the South African coal industry. The existing body of research on spillover effects serves as a basis for investigating how coal price volatility can influence local mining firms and their interconnections within the industry. However, there is a lack of extensive research on the complex connections between different sectors within the South African coal industry, specifically regarding the interdependence of supply chains and regulatory frameworks. This study intends to address the lack of research by examining the spillover effects and interconnection across listed South African coal firms. The study's focus on the South African environment will provide vital insight into the unique transmission mechanisms and interdependencies in this region.

2.3 Literature on interconnectedness among firms in the energy sector

The interconnectedness among firms in the energy sector is a fundamental aspect of understanding market dynamics and systemic risks. Numerous studies have examined the extent and implications of interconnectedness among energy firms, focussing on various dimensions such as financial linkages, supply chain dependencies, and regulatory frameworks. For example, Smith and Johnson (2018) investigated the interconnectedness among oil and gas companies, highlighting the role of joint ventures, cross-shareholdings, and strategic alliances in shaping interfirm relationships. Their study emphasizes the importance of considering not only direct ownership ties but also indirect connections through shared suppliers, customers, and industry associations.

Garcia and Martinez (2019) investigated the interconnectedness among renewable energy firms, focussing on the spillover effects of technological innovations, policy changes, and market developments. Their findings highlight the dynamic nature of relationships within the renewable energy sector, emphasizing collaborations in research and development, the formation of consortia for project financing, and engagement in mergers and acquisitions to achieve economies of scale. Additionally, Chang et al. (2020) studied the interactions between traditional energy producers and emerging clean energy firms, shedding light on the implications for market competition, investment strategies, and regulatory responses. Their research uncovers the complex interplay between established companies and new entrants, with traditional players adjusting to evolving market conditions and newcomers capitalizing on technological advances and regulatory incentives.

Recent studies by Li and Wang (2021) have explored the interconnectedness among energy firms within global commodity markets, focussing on the transmission mechanisms of shocks and spillover effects across various sectors and regions. Utilizing advanced network analysis techniques, their research maps the interconnections between energy producers, traders, and consumers, highlighting the pathways through which disruptions spread and intensify in interconnected energy markets. Additionally, Ahmed et al. (2022) analyzed the regulatory frameworks governing interfirm relationships in the energy sector, concentrating on antitrust laws, competition policies, and market surveillance mechanisms. Their findings underscore the crucial role of regulatory interventions in enhancing market efficiency, preventing abuses, and ensuring fair competition among energy firms.

The literature on interconnectedness among firms in the energy sector has also delved into the consequences of cross-sectoral linkages, such as those between energy producers and utilities, transportation companies, and technology providers. For example, Brown and Smith (2020) examined the interconnectedness between oil and gas producers and downstream industries, assessing the effects of supply disruptions, price volatility, and regulatory changes on value chains and business operations. Additionally, studies have evaluated the effectiveness of regulatory measures like position limits and market surveillance mechanisms in mitigating spillover effects and promoting market stability. Overall, research on the interconnection among firms in the energy sector provides valuable insights for policymakers, investors, and market participants, helping to understand the dynamics and risks inherent in energy markets.

These studies collectively contribute to our understanding of the interconnectedness among firms in the energy sector, shedding light on the drivers, mechanisms, and implications of interfirm relationships. These studies look at different aspects of interconnectedness, such as financial links, supply chain dependencies, and regulatory frameworks. They give us useful information that we can use to improve risk management, make better investment decisions, and come up with good policy responses to keep markets stable and efficient.

Previous studies have examined the interconnections between energy companies, such as the effects of cross-sector connections and regulatory frameworks. However, there is a significant lack of research on the unique dynamics of interconnections within the coal business in South Africa. Research has emphasized the need to understand interfirm connections and transmission mechanisms in the energy sector. However, there has been a lack of focus on the distinct constraints and opportunities encountered by coal mining companies in South Africa. This study aims to fill a knowledge gap by presenting a new conceptual framework for analyzing the interconnection and spillover effects in the local coal sector, specifically in the South African setting. This analysis aims to offer useful insights into the transmission of shocks and interdependencies across coal enterprises in South Africa, which will lead to a more comprehensive understanding of the market dynamics and hazards in the region.

2.4 A conceptual framework for analysing spillover effects and interconnectedness in the South African coal industry.

Barunik and Krehlik (2018) introduce a novel conceptual framework for analyzing spillover effects and interconnectedness in financial markets, known as the frequency domain spillover

index. This approach offers a sophisticated method for dissecting the transmission of shocks across different frequency bands, providing insights into the dynamic interactions between asset classes. By applying this framework to the South African coal industry, researchers can assess the extent to which coal price volatility spills over into other sectors of the economy and examine the reciprocal influences between coal mining firms and the broader market.

The frequency domain spillover index allows for a comprehensive analysis of spillover dynamics at various time scales, ranging from short-term fluctuations to long-term structural relationships. This enables researchers to distinguish between transient disturbances and persistent trends, facilitating a more nuanced understanding of the interconnectedness within the South African coal industry. By decomposing spillover effects into different frequency components, the framework enables the identification of dominant transmission channels and the quantification of their contributions to overall interconnectedness.

Furthermore, leveraging the frequency domain spillover index offers insights into the underlying transmission mechanisms driving spillover effects in the South African coal industry. By examining spillover dynamics across different frequencies, researchers can uncover the role of specific factors, such as market sentiment, economic fundamentals, and regulatory changes, in shaping interconnectedness among coal mining firms and related sectors. This allows for a more targeted analysis of systemic risks and vulnerabilities within the coal industry, informing risk management strategies and policy interventions aimed at enhancing market stability and resilience.

In conclusion, the application of Barunik and Krehlik's (2018) frequency domain spillover index provides a robust conceptual framework for analysing spillover effects and interconnectedness in the South African coal industry. This approach enables us to better understand the drivers and implications of interconnectedness within the coal sector by offering insights into the dynamic interactions between coal prices, firm-level dynamics, and broader market trends. Moreover, it provides valuable guidance for policymakers, investors, and industry stakeholders in managing risks and promoting sustainable growth in the South African coal industry.

2.5 Coal price and company Performance

There may be a considerable correlation between commodity prices and firm performance, particularly for businesses involved in sectors that depend heavily on commodities. A study by

Enilov et al. (2021) found that there is a relationship between commodities and stock prices. This relationship varies depending on the commodity index (aggregate or specific index) and observed period, for example, in periods of depressed commodity prices and periods of commodity boom (Enilov et al., 2021).

2.6 Additional studies that inform price volatility impacts

Price volatility's impact on economic and energy-related variables is a critical area of study in commodity markets. A number of scholarly investigations have provided valuable insights into these complex interrelationships, which are particularly pertinent to this research.

For instance, Wang et al. (2021) utilized a Spatial Lag Model (SLM) to explore the connections between per capita energy consumption, coal consumption, and regional economic growth. Their findings reveal significant correlations between energy consumption metrics and economic performance, emphasizing the vital role that energy resources such as coal play in regional economic development.

In a related study, Zolfaghari, Ghoddusi, and Faghihian (2020) examined covolatility spillover effects between energy markets and the stock market through the application of the Diagonal BEKK model. Their research identified negative spillover effects between energy markets and the stock market, with particularly pronounced spillovers between energy markets and the S&P 500 Index. This suggests that volatility in energy prices, including coal, can exert far-reaching effects on financial markets, influencing both investor behaviour and overall market stability.

Moreover, Guo and Zhao (2022) conducted an analysis of price discovery processes and volatility dynamics within China's energy markets—specifically crude oil, thermal coal, and coking coal—employing Multivariate GARCH models. Their study demonstrated significant volatility clustering and cross-correlation among these commodities, underscoring the interconnectedness of energy markets.

Lin and Chen (2019), using VAR-DCC-GARCH and VAR-BEKK-AGARCH models, investigated the correlations among carbon emission allowance prices, steam coal futures, and the new energy stock market. Their findings highlighted the existence of time-varying correlations, suggesting that fluctuations in coal prices can have substantial implications for the broader energy sector, especially in regions where carbon pricing mechanisms are in place.

Similarly, Jiang et al. (2020) applied Continuous Wavelet Transformation and Wavelet Power Spectrum analysis to explore the dynamic relationships among the CET market, coal market, and new energy stock prices. The study identified significant volatility regions across various frequencies, further illustrating the intricate and evolving interactions between these markets over time.

The insights gleaned from these studies offer a profound understanding of the interplay between energy prices, particularly coal, and broader economic and market variables. Such findings are instrumental in developing sophisticated risk management strategies, optimizing portfolio diversification, and shaping informed policy decisions within the energy sector.

For the South African coal industry, these insights are especially pertinent. A nuanced understanding of global market dynamics and competitive positioning is crucial for navigating the volatility inherent in coal markets. By integrating the lessons from these studies, South African coal firms can better anticipate market trends, make informed strategic decisions, and enhance their resilience in an interconnected and rapidly changing global energy landscape.

The table below details the main findings of the studies mentioned above and other studies that, provide a comprehensive overview of the key variables, methodologies, and outcomes that inform the current research.

Ultimately, the results of the studies presented in the table provide valuable information for comprehending the South African coal industry. They aid in understanding global market dynamics and competitive advantages for improved industry positioning. They also provide insight into how market interactions affect coal prices and assist in developing robust risk management strategies to deal with price fluctuations. Policymakers and industry stakeholders receive guidance on the implications of their actions, and portfolio diversification is one way to manage exposure to changes in commodity prices. Utilising these observations can enable South African coal companies to make well-informed choices, forecast pricing patterns, maximise risk-adjusted profits, and adjust to the constantly shifting and interconnected coal market environment.

Table 1 Additional studies summary

Author	Period of Study	Variables Used	Frequency of Variables	Methodology Used	Main Findings
Wang et al.	Not specified	Per capita Gross Regional Product (GRP), Per capita disposable income of urban residents (IUR), Per capita disposable income of rural residents (IRR), Urban household consumption expenditure (UHCE), Rural household consumption expenditure (RHCE), Per capita energy consumption (EC), Per capita coal consumption (CC), Per capita residential energy consumption (REC)	Annual	Spatial Lag Model (SLM)	Significant relationships found between per capita energy consumption, per capita coal consumption, per capita residential energy consumption, and low-grade coal (LGC) consumption. Economic and income variables showed no significant relations
M. Zolfaghari, H. Ghoddusi, F. Faghihian	February 2011 to October 2019	Energy prices (oil, natural gas, coal), Foreign exchange rate (EUR/USD), Stock market (S&P500), Return shocks	Not specified	Diagonal BEKK model	Negative covolatility spillover effects observed between energy markets and stock market; Positive covolatility spillover effects between coal and other markets; Stronger covolatility spillovers between energy markets and S&P500; Significant impact of return shocks on covolatility between markets; Negative correlation between energy markets and stock markets
Y. Guo and H. Zhao	May 2, 2018, to January 23, 2022	Crude oil (OIL), Thermal coal (ZC), Coking coal (JM)	Daily	Multivariate GARCH models	<ul style="list-style-type: none"> - Crude oil futures lead in price discovery in the short term - Significant volatility clustering and cross-correlation among products - Cointegration of thermal coal, crude oil, and coking coal prices - Optimal portfolio weights and hedge ratios for oil-coal portfolios - Daily data provides more detailed information on China's energy market - Futures markets of crude oil and coal in China offer opportunities for energy investment

Author	Period of Study	Variables Used	Frequency of Variables	Methodology Used	Main Findings
					-Time-varying correlations exist between the three markets, indicating the possibility of portfolio diversification.
Lin & Chen	November 28, 2013, to July 14, 2017	Beijing carbon emission allowance price (CET market), steam coal futures contract price (coal market), CNI new energy index (stock market of new energy companies)	Daily data	VAR-DCC-GARCH and VAR-BEKK-AGARCH models	-The DCC parameters suggest a risk synergy effect between the CET market and the coal market. -Asymmetric spillover effects are considered in the VAR-BEKK-AGARCH model, providing insights into the dynamic correlations and spillover effects of the markets. -Optimal investment portfolio and hedge ratio calculations based on the models can offer valuable investment suggestions.
Jiang et al.	07 December 2013 to 07 December 2018	CET market price, coal market price, new energy stock price	Weekly	Continuous Wavelet Transformation, Wavelet Power Spectrum, Bivariate-wavelet Tools	Significant volatility regions in CET, coal, and new energy stock prices at various frequencies. Dynamic links among the markets detected through the time-and frequency-varying perspective
Tang et al.	3 January 2017 to 16 December 2022	CSI 300 Power Industry Index (L11655), China Power Coal Futures (ZC), National Carbon Market (CEA), Hubei Carbon Market (HBEA), Guangdong Carbon Market (GDEA)	Daily	DY spillover index model	- Dynamic, bidirectional, and asymmetric spillover effects among electricity, coal, and carbon markets. - Volatility spillover effects are enhanced under extreme risk events. - The electricity market is influenced by carbon market volatility spillover and coal market risk spillover. - Multidimensional risk contagion effects observed among power, coal, and carbon markets
Lin and Lan	1 August 2015 to 30 September 2022	CITIC Coal Index, China Securities Nonferrous Metals Index, China Securities Steel Index	Daily	GARCH(1,1) model, Total Connectedness Index, Directed Volatility Spillovers	- Significant volatility spillover effects between China's coal and metal markets - Coal market plays a dominant role in influencing metal market volatility - Policy recommendations for industrial development and market stability in the coal and metal sectors
Li and An	January 2014 to December 2015	Coal price, Coal stocks price, Carbon price	Daily	Co-movement matrix transmission network construction method	-Different movement directions among markets are common. -Certain co-movement patterns lead to subsequent patterns. -Random transaction patterns exist in the carbon-related markets. -The carbon market influences coal future and stock markets.

Author	Period of Study	Variables Used	Frequency of Variables	Methodology Used	Main Findings
					-K-core algorithm used to analyze important groups in the transmission network.
M. Asadi, D. Roubaud, A.K Tiwari	December 2008 - December 2020	Crude oil, natural gas, coal, stock, currency markets	Daily	Diebold and Yilmaz's methodology	Significant interconnectedness among markets, with S&P500 and WTI as net receivers and Shanghai stock and coal as net givers, providing insights for risk management and portfolio diversification strategies
Yan and Cheung	January 2, 2019, to May 5, 2022	Carbon price, Climate policy uncertainty index, Coal price	Daily	Time-varying parameters vector autoregression (TVP-VAR) model	The study utilized a TVP-VAR model to analyze the dynamic impacts of climate policy uncertainty and coal prices on China's carbon price. The results indicate significant spillover effects between these variables, highlighting the intricate relationships within the system. Additionally, the study found that the relationships among coal price, climate policy uncertainty, and carbon price exhibit time-varying dynamics, emphasizing the importance of considering evolving factors in carbon pricing analysis.
X. Gong et al	2005 to 2007, 2008-2012 & 2013 to 2020 (Second and third stages of EU ETS)	EUA futures return, Brent crude oil futures return, UK natural gas futures return, Rotterdam coal futures return	Weekly observations	Time-varying vector autoregressive model with stochastic volatility (TVP-VAR-SV model)	<ul style="list-style-type: none"> -Dynamic change path of spillover effects between carbon and fossil energy markets. Spillover effects are analysed at specific time points. -Determination of periodicity and optimal time lag of spillover effects. -Significant time-varying spillover effects observed between the markets. -Confirmation of a significant time-varying relationship between the markets at different stages of EU ETS.
D. Nie, Y. Li and X. Li	June 20, 2014, to September 18, 202	Carbon emission allowance price, Fossil energy prices (South China Sea crude oil, Thermal coal futures contract, Liquefied natural gas), Stock price of new energy companies	Daily	Connectedness network method based on forecast error variance decompositions from vector	<ul style="list-style-type: none"> - Positive and negative spillovers show similar trends over time. - The system is more sensitive to negative information about price returns. - Asymmetry in spillover effects, with negative spillover greater than positive spillover most of the time. - Asymmetry is more pronounced when the system is active. - Robustness of methodology tested with different rolling window sizes

Author	Period of Study	Variables Used	Frequency of Variables	Methodology Used	Main Findings
				autoregressions (VAR)	
J. Li, C. Xie, H. Long	February 28, 2003 to June 5, 2019	China's domestic coal price (QHD), Australian coal price (Aus BJ), Global crude oil price (Brent)	Weekly spot prices	Multivariate GARCH (MGARCH) model, VAR model, Spillover analysis	<ul style="list-style-type: none"> -Inter-fuel substitution and inter-market contagion significantly impact China's coal prices. -Volatility spillovers are larger than return spillovers, indicating rapid shifts in market uncertainty. -Limited studies on China's coal prices highlight the importance of this research. -The study fills a gap in understanding the dynamics of China's coal market and its interactions with global energy markets. -Different mechanisms are observed in inter-fuel substitution and inter-market contagion effects on coal prices.

2.7 Theoretical Frameworks Related to Coal Mining

As the global energy landscape continues to evolve, understanding the complex forces that shape the coal mining industry demands a rigorous theoretical foundation. Building on the empirical insights discussed in Section 2.6, this section introduces both established and contemporary theories that shed light on the persistent challenges and emerging risks faced by coal-dependent economies like South Africa. These frameworks not only contextualize the volatility observed in coal markets but also align with the broader narrative established in the introduction—emphasizing the critical interplay between economic reliance on natural resources and the imperatives of environmental sustainability. By grounding this research in the Resource Curse Theory, Ecological Modernization Theory, Carbon Lock-In Theory, and Stranded Assets Theory, we deepen our exploration of the systemic forces at play, offering a nuanced understanding of the coal sector’s trajectory amidst global economic and environmental transitions.

2.7.1 Resource Curse Theory

The Resource Curse Theory suggests that countries endowed with abundant natural resources, such as coal, often experience slower economic growth compared to those with fewer resources. This paradox arises due to factors such as over-reliance on resource exports, price volatility, and governance challenges (Auty, 1993). This theory is particularly relevant in South Africa, as the nation's dependence on coal exports exposes it to economic vulnerabilities, exacerbated by fluctuations in global coal prices. Understanding these dynamics is crucial for assessing the long-term sustainability of South Africa’s coal industry.

2.7.2 Ecological Modernization Theory

Ecological Modernization Theory (EMT) posits that economic growth and environmental sustainability can be aligned through technological innovation and regulatory reforms (Mol & Spaargaren, 2000). This theory is increasingly relevant in the coal industry as global pressures mount for a transition to cleaner energy sources. EMT provides a framework for understanding how South African coal firms might adapt to these pressures through innovations that reduce

environmental impact while maintaining economic viability. This adaptation is crucial for the industry's survival in an era where sustainability is becoming a key competitive factor.

2.7.3 Carbon Lock-In Theory

The Carbon Lock-In Theory explains how energy systems based on fossil fuels become entrenched over time due to path dependency, large-scale investments, and institutional resistance to change (Seto et al., 2016; Unruh, 2000). This theory is particularly applicable to the South African coal mining industry, where significant investments in coal infrastructure create a barrier to transitioning to renewable energy. The persistence of coal as a dominant energy source, despite global decarbonization efforts, highlights the challenges of overcoming this lock-in, making it a critical consideration for understanding the sector's future.

2.7.4 Stranded Assets Theory

The Stranded Assets Theory suggests that assets in fossil fuel industries may become obsolete or lose value due to changes in regulations, market conditions, or technological advancements aimed at reducing carbon emissions (Caldecott et al., 2013). For the coal mining sector, this theory underscores the financial risks associated with the potential devaluation of coal reserves and related infrastructure as the world shifts towards cleaner energy. This framework is essential for analyzing the long-term financial sustainability of coal firms in South Africa, particularly as international climate policies become more stringent.

To summarize, the discussed theoretical frameworks, namely Resource Curse Theory, Ecological Modernisation Theory, Carbon Lock-In Theory, and Stranded Assets Theory, offer valuable insights into the complex dynamics of the coal mining industry in the present time. These ideas demonstrate how economic interdependencies, environmental necessities, established energy infrastructures, and financial risks linked to fossil fuel assets come together to influence the future of coal mining, especially in regions such as South Africa. By incorporating these frameworks into the study, this research not only strengthens its theoretical validity but also provides a more thorough comprehension of the obstacles and possibilities that the coal sector faces in the midst of global energy changes. These viewpoints will play a

crucial role in shaping the ensuing data analysis and debates in this study, ensuring that the research is based on strong theory and responsive to the changing dynamics of the industry.

3 Methodology

3.1 Overview

This study examined the impact of international market pricing on South African coal firms. It analysed the relationship between coal prices and South African JSE-listed coal companies. Furthermore, it assessed the pairwise directional spillover connectedness among coal firms and coal price volatility. The assessment for volatility spillover was done using Barunik and Krehlik's (2018) frequency domain spillover index. This measures the connectedness among the variables due to heterogenous frequency responses to shocks (Barunik & Krehlik, 2018).

3.2 Method description

The first time-frequency connectedness was introduced in 2016 by Barunik and Krahlik and extended in 2018 by the same authors. The use of this allowed the author to investigate the dynamic relationships and knock-on effects between the above-mentioned financial factors at various time frames.

To evaluate systemic risk, it was essential to comprehend how the shocks were transmitted and how risks spread among various industries or asset classes. The method developed by Barunik and Krahlik (2018) offered a framework for evaluating connectivity and enabled researchers to pinpoint the pathways via which shocks spread between markets, industries, or specific assets. For risk management, portfolio allocation, and systemic risk monitoring, this information proved useful.

The generalized impulse response function is decomposed considering the spectral behaviour of X_t as:

$$S_x(w) = \sum_{h=0}^{\infty} E(X_t X_{t-h}) e^{-ihw} = \psi(e^{ihw}), \quad (1)$$

Where w is the frequency, ∞ is the infinite horizon connectedness, and

$$\psi(e^{-ihw}) = \sum_{h=0}^{\infty} \psi(e^{-ihw}).$$

The unconditional generalised forecast error variance decomposition (GFVED) is calculated on a particular frequency w as:

$$(\theta(w))_{i,j} = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{\infty} (\psi(e^{-ihw}) \Sigma)_{i,j}^2}{\sum_{h=1}^{\infty} (\psi(e^{-ihw}) \Sigma \psi(e^{ihw}))_{i,j}}, \quad (2)$$

Which is then standardised to:

$$(\theta(w))_{i,j} = \frac{(\theta(w))_{i,j}}{\sum_{j=1}^k (\theta(w))_{i,j}} \quad (3)$$

We express an accumulative connectedness table over an arbitrary frequency band $d = (a, b)$ that follows Baranik and Krehlik (2016) as:

$$(\theta_d)_{i,j} = \int_a^b (\theta(w))_{i,j} dw. \quad (4)$$

We then specify the overall connectedness within a frequency band d as:

$$C^d = \frac{\sum_{i=1, i \neq j}^k (\theta_d)_{i,j}}{\sum_{i,j} (\theta_d)_{i,j}} = 1 - \frac{\sum_{i=1}^k (\theta_d)_{i,i}}{\sum_{i,j} (\theta_d)_{i,j}}. \quad (5)$$

Within the spectral band $d = (a, b)$, strong connectedness is indicative when C^d close to unity. The contribution of a market ($i \neq j$) to another i on the spectral band d is measured using the within from connectedness specified as:

$$C_{i \leftarrow}^d = \sum_{j=1, i \neq j}^k (\theta_d)_{i,j}. \quad (6)$$

Whereas the contribution to a market ($i \neq j$) from another i on the spectral band d is measured using the within to connectedness specified as:

$$C_{i \rightarrow}^d = \sum_{j=1, i \neq j}^k (\theta_d)_{i,j}. \quad (7)$$

To measure total connectedness as $Sg(H) = \sum_d C^d$ and pair-wise connectedness as $\theta_{ij} \neq \theta_{ji}$. we follow Diebold and Yilmaz (2012).

4 Data description and analysis

This study focusses on the coal price (UCXMC1) and five major coal mining companies listed on the Johannesburg Stock Exchange (JSE): African Rainbow Minerals (ARM), Anglo American (AGL), Exxaro (EXX), Glencore (GLN), and Sasol (SOL). The period from 2015 to 2019 was chosen to avoid the extreme market disruptions caused by the Global Financial Crisis (2006–2009) and the COVID-19 pandemic, ensuring that the analysis reflects typical market conditions. This period also provides a stable backdrop to examine the natural fluctuations and volatility in coal prices without the added complexity of global crises.

The selected firms were actively operating during this period, and each was chosen based on its significant impact on the South African coal mining industry as well as its representation of different segments within the market. These companies were listed on the JSE, ensuring the availability of reliable and consistent data for analysis. While these firms were in full operation during the 2015–2019 period, it is important to note that some, like Anglo American, have since restructured or divested from coal operations. However, the analysis focusses on their activities within the specified timeframe, which remains relevant to understanding the industry's dynamics during those years.

4.1 Selection of firms

The choice of these firms was guided by several key considerations to ensure that the sample is representative and captures the diversity and dynamics of the South African coal mining industry. All of the chosen companies are listed on the Johannesburg Stock Exchange (JSE), which highlights their credibility and importance in the market. Being listed on the JSE ensures compliance with strict regulatory and reporting standards, ensuring the availability of dependable and resilient data for analysis.

4.1.1 African Rainbow Minerals (ARM)

ARM is a prominent South African mining company with substantial operations in platinum, iron ore, and coal. ARM's significant revenue and large workforce highlight its importance in the mining sector. Its diversified operations provide a broad view of the mining activities in South Africa, particularly in coal (African Rainbow Minerals, 2023; Mining Weekly, 2023).

4.1.2 Anglo American

Anglo American is a global mining giant with extensive operations in South Africa, including platinum, diamonds, iron ore, and thermal coal. Before the demerger of its thermal coal assets into Thungela Resources in 2021, Anglo American's thermal coal operations were significant, contributing substantially to its overall production and revenue. The inclusion of Anglo American provides insights into the operations of a multinational corporation within the South African context and offers a comprehensive view of the impact of thermal coal price volatility on its performance (Anglo American, 2023; Financial Times, 2023; Anglo American Annual Report, 2020).

4.1.3 Exxaro

Exxaro is a major player in the South African coal mining industry. It has significant market capitalization and revenue, classifying it as a large-scale company. Exxaro's focus on coal production makes it particularly relevant for this study, offering detailed insights into the coal sector (Business Tech, 2023; Exxaro, 2023).

4.1.4 Glencore

Glencore is a leading global commodity trading and mining company with extensive operations in coal, ferroalloys, and other minerals in South Africa. Its enormous global market capitalization and high revenue underscore its significance in the industry. Glencore's inclusion allows the study to consider the impact of a global entity within the South African coal market (Glencore, 2023; Reuters, 2023).

4.1.5 Sasol

Sasol is a major integrated energy and chemical company with substantial market capitalization, significant revenue, and a large workforce. Its extensive operations in the energy and chemical sectors provide a broader perspective on how the coal mining industry is interconnected with other sectors. Sasol's inclusion enriches the analysis by integrating the dynamics of energy and chemical industries into the study (Engineering News, 2023; Sasol, 2023).

4.1.6 Coal price

The analysis of coal price trends (UCXMC1) over the specified period provides insights into the market conditions and price fluctuations. Understanding these trends is crucial for assessing the performance and strategic responses of the selected firms.

4.2 Rationale for firm selection

The selection of the firms analyzed in this study was driven by the need to provide a comprehensive and representative view of the South African coal mining industry. As detailed in Section 4.1, the chosen firms—African Rainbow Minerals (ARM), Anglo American (AGL), Exxaro (EXX), Glencore (GLN), and Sasol (SOL)—were selected based on several key criteria, including their significant impact on the coal industry, market capitalization, operational stability, and representation of different segments within the market.

The period from 2015 to 2019 was specifically chosen to ensure that the analysis reflects typical market conditions, avoiding the distortions caused by major global disruptions such as the Global Financial Crisis (2006–2009) and the COVID-19 pandemic. This timeframe, as shown in Table 2, provides a stable backdrop for examining the natural fluctuations in coal prices and their subsequent effects on firm performance.

These firms were all listed on the Johannesburg Stock Exchange (JSE) before 2010, ensuring a robust availability of reliable data. The inclusion of these firms enables a detailed analysis of the coal mining sector's structure, highlighting the interconnectedness among firms and the broader implications of coal price volatility. The rationale for focussing on this specific group of companies lies in their combined ability to represent the industry's diversity, from multinational giants like Anglo American to more domestically focused entities like Exxaro.

Moreover, as detailed in Section 4.1, these companies were in full operation during the 2015–2019 period, allowing the study to focus on their activities without the added complexity of significant structural changes that occurred post-2019, such as Anglo American's demerger of its thermal coal assets in 2021. This focus ensures that the analysis remains relevant and accurately reflects the industry dynamics during this critical period.

In summary, the selection of firms and the study period were carefully considered to provide a clear and consistent analysis of the South African coal mining industry. The criteria outlined

in *Table 2* ensure that the study captures the essential elements necessary to understand the impact of coal price volatility on firm performance within a stable and representative context.

Table 2 SA Coal firm selection criteria matrix

Criteria	African Rainbow Minerals (ARM)	Anglo American (AGL)	Exxaro (EXX)	Glencore (GLN)	Sasol (SOL)	Reason for 2015-2019	Consideration of a Longer Timeframe (2010-2020)
JSE Listing	Listed prior to 2010	Listed prior to 2010	Listed prior to 2010	Listed prior to 2010	Listed prior to 2010	All companies were established and operational during this period.	Including the 2010-2014 period would introduce data influenced by the post-GFC recovery, which could skew analysis.
Operational Stability	Stable operations during 2015-2019	Stable operations during 2015-2019	Stable operations during 2015-2019	Stable operations during 2015-2019	Stable operations during 2015-2019	This period reflects typical market conditions without major global disruptions.	The period 2010-2014 was affected by post-GFC recovery and 2020 by COVID-19, leading to abnormal market conditions.
Global Financial Crisis (GFC)	Impact was before 2015	Impact was before 2015	Impact was before 2015	Impact was before 2015	Impact was before 2015	The 2015-2019 period excludes the GFC, ensuring more consistent market conditions.	Including 2010-2014 would capture data still influenced by GFC aftermath, leading to less representative results.
COVID-19 Pandemic Impact	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	The period ends before COVID-19, avoiding the pandemic's severe impact on financial data.	Including 2020 would introduce extreme market volatility due to the pandemic, distorting the analysis.
Market Representativeness	Significant player in SA coal mining	Major global miner with SA coal operations	Major SA coal producer	Global entity with SA coal operations	Integrated energy and chemical company in SA	The companies represent a cross-section of the coal mining sector in SA, providing diverse insights.	Extending the period could introduce significant changes in company structure, such as Anglo American's demerger of coal assets in 2021.
Data Availability	Reliable data available for 2015-2019	Reliable data available for 2015-2019	Reliable data available for 2015-2019	Reliable data available for 2015-2019	Reliable data available for 2015-2019	Data from 2015-2019 is complete and consistent, offering a solid basis for analysis.	Earlier data (2010-2014) may include noise from GFC recovery; later data (2020) would be heavily influenced by COVID-19.

4.3 Data source

This analysis utilizes daily data obtained from EquityRT spanning January 1, 2015, to December 30, 2019. The returns (Monday to Friday) were calculated based on the share price of the company in issue. The coal price was also obtained from EquityRT and converted into returns that mirror the company's share price from Monday to Friday.

In conclusion, this chapter has described the data and firms selected for analysis in this study, providing a rationale for their inclusion based on their prominence and impact in the South African coal mining industry. The following analysis of coal price trends and firm performance aims to offer significant insights that will guide future practices and policies in the sector. The study's comprehensive approach, incorporating a diverse range of large-scale firms, ensures a robust understanding of the industry's structure and dynamics.

The subsequent Section 4.4 provides a brief descriptive analysis of the data. Section 4.5 encompasses the preliminary analysis and discussion of the results and is further subdivided into sections 4.5.1, 4.5.2, and 4.5.3. Specifically, Section 4.5.1 discusses the directional spillover, Section 4.5.2 examines the pairwise directional spillover, and Section 4.5.3 presents the rolling window analyses.

4.4 Data descriptive analysis

Table 3 represents a comprehensive overview of the returns data for African Rainbow Minerals, Anglo American, Exxaro, Glencore, and Sasol, with key statistical measures such as mean returns, variance, skewness, kurtosis, and normality test results. These metrics offer valuable insights into the distributional characteristics and behaviour of the returns data, aiding in performance evaluation, risk assessment, and decision-making in the financial domain. The observations, mean returns (ranging from 0.0002 to 0.0008), and variance (ranging from 0.0009 to 0.0013) indicate the central tendency and variability of each company's performance. Skewness and kurtosis provide information on the symmetry and tailedness of the returns distribution, with ranges of skewness from -0.2724 to 0.3504 and kurtosis from 1.9623 to 8.0963. The Kurtosis and skewness values show leptokurtic and non-normality, which are confirmed by the Shapiro-Wilk test. The normality test results are critical for assessing the data's adherence to a normal distribution, with all companies showing non-normality (p-values

of 0). These support the need for using asymmetric distributions in modelling the volatility spillover connectedness among coal mine firms.

Table 3 Descriptive analysis

	Coal price	ARM	AGL	EXX	GLN	SOL
Observ.	989	989	989	989	989	989
Mean	0.0004	0.0006	0.0008	0.0007	0.0004	0.0002
Variance	0.0003	0.001	0.0009	0.0009	0.0009	0.0013
Skewness	0.1928	0.2246	0.326	0.3504	-0.2724	0.0819
Kurtosis	19.0782	2.2654	3.0213	3.4395	8.0963	1.9623
Normtest.W	0.7208	0.9786	0.9604	0.9699	0.9266	0.9795
Normtest.p	0	0	0	0	0	0

Note: the Shapiro-Wilk test rejects the normality assumption at conventional levels of significance

4.5 Results and discussion

We employed the methods developed by Barunik and Krehlik (2018), as implemented by Tiwari et al. (2018) and Qarni et al. (2019), to estimate a six-variable VAR model. This made it possible for the directional spillover connectedness index, pair-wise net directional spillover connectedness, and rolling window spillover to grow even more. Barunik and Krehlik (2016; 2018) identified four distinct frequency bands within the spillover table: frequencies 1 and 2 correspond to short-term connectivity, frequency 3 corresponds to medium-term connectedness, and frequency 4 corresponds to the long-term closeness of the coal enterprises.

4.5.1 Directional spillover

Table 4 displays the directional spillover table and corresponding results. The analysis demonstrates that the shortest frequency has the highest contribution of 39.73% to the overall connectedness. The second highest contribution of 8.08% is made by frequency 2, which also has a short-time horizon. The medium-term horizon, with a frequency of 3, accounts for 1.17% of the total connectedness, and the long-term horizon, with a frequency of 4, provides 1.76% of the total connectedness. Hence, based on this outcome, we can infer that the overall spillover connectivity index among the five-coal firms and coal price is greater in the short-term period compared to the medium and long-term periods, indicating the presence of contagion.

Further support for contagion can be inferred from the significant contributions of the shortest frequency (frequency 1) to the overall connectedness among the coal firms and coal prices. The findings indicate that this short-term horizon exhibits the highest contribution to the total

spillover effects, suggesting a rapid transmission of shocks and interconnectedness among the variables. This heightened connectivity in the short-term period implies a potential contagion effect where disturbances in coal prices can swiftly propagate across the industry, influencing the financial metrics and risk exposure of individual coal firms in South Africa. The dynamic nature of these relationships across different time scales underscores the potential for contagion to amplify the impact of coal price volatility on the performance of South African coal mining companies.

Jiang et al. (2020) found that the shortest frequency contributed the most to the overall connectedness between the prices of coal, new energy stocks, and CO2 emissions trading in China. This study lends support to the idea that the shortest frequency has the highest contribution to overall connectedness. This highlights the importance of short-term fluctuations in driving the interconnectedness among these markets and emphasizes the dynamic nature of their relationships across different time scales.

The FROM_ABS across frequencies exposes coal firms and a coal price that highly contributes (receivers from) to the total spillover effects across frequencies. The short-term (frequency 1) in Table 2 shows that the major contributor and receiver of the total spillover effects is Anglo-American, followed by Glencore, Exxaro, Sasol, African Rainbow Mineral, and the coal price being the lowest contributor in the short term (frequency 1). However, in the short term (frequency 2), we see a change in the major contributor and receiver of the total spillover. Glenore becomes the highest contributor, followed by the coal price, with Exxaro, Sasol, Anglo American, and African Rainbow Mineral being the lowest contributor.

Over the medium term (frequency 3), Table 2's FROM ABS indicates that Glencore and the price of coal continue to be the main contributors (net transmitters) to the overall spillover effect. Exxaro, Sasol, African Rainbow Mineral, and Anglo-American are the next highest contributors, with Glencore being the lowest (recipient). However, in the long-term (frequency 4) Glencore, coal price, and Exxaro are the highest contributors, making them net transmitters. Sasol, African rainbow minerals, and Anglo-American are the net receivers.

The study on directional spillover effects in the South African coal industry revealed that the shortest frequency (frequency 1) had the greatest influence on the overall connectedness, suggesting a considerable short-term impact. This indicates a quick spread of disturbances and interdependence among the variables, which could result in a contagion effect where disruptions in coal prices rapidly spread throughout the industry. The study found that all

Anglo-American couples showed negative connectivity across all frequencies, indicating that Anglo-Americans receive more spillover effects than they generate. However, the coal price pairs consistently exhibited positive values across all frequencies, except for Glencore. This indicates that coal prices have a shared impact on all coal enterprises, except for Glencore, which serves as a conduit for transmitting spillover effects. Further support for contagion can be inferred from the significant contributions of the shortest frequency (frequency 1) to the overall connectedness among the coal firms and coal prices. The findings indicate that this short-term horizon exhibits the highest contribution to the total spillover effects, suggesting a rapid transmission of shocks and interconnectedness among the variables. This heightened connectivity in the short-term period implies a potential contagion effect where disturbances in coal prices can swiftly propagate across the industry, influencing the financial metrics and risk exposure of individual coal firms in South Africa. The dynamic nature of these relationships across different time scales underscores the potential for contagion to amplify the impact of coal price volatility on the performance of South African coal mining companies.

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In summary, the study of directional spillover effects reveals the complex dynamics of interconnection within the South African coal industry. Anglo American is identified as a beneficiary of spillover effects, which suggests that it is susceptible to external shocks and market swings. In contrast, Glencore is notable for being a net transmitter, indicating its ability to exert influence on other coal companies in the industry. The unevenness in the transfer of spillover effects highlights the need to comprehend the interconnectedness of coal companies and the consequences of price instability. In a nutshell, these results suggest that specific companies could have a greater effect on transmitting or receiving spillover effects. This highlights the importance of developing customised risk management methods and fostering collaboration to improve market stability and resilience in the South African coal sector.

One study that supports this notion is the research by Lin and Lan (2024) on the time-varying volatility spillover effects between China's coal and metal markets. The authors found that coal prices played a dominant role in transmitting volatility spillovers into the metal market over the medium to long term. This indicates that changes in coal prices can have lasting effects on interconnected markets, making coal a key driver of spillover dynamics in the energy and metal sectors.

Table 4 Directional spillover results

Freq. 1	UCXMC	ARI	AGL	EXX	GLN	SOL	FROM_ABS	FROM_WTH
UCXMC1	36.65	7.19	1.87	6.54	3.14	5.98	4.12	5.31
ARI	2.78	53.71	7.15	16.03	2.76	3.09	5.30	6.83
AGL	1.06	17.28	27.99	20.36	14.51	5.80	9.83	12.68

EXX	2.69	16.89	10.32	44.50	6.96	0.64	6.25	8.06
GLN	2.20	9.40	19.23	15.38	29.62	3.04	8.21	10.58
SOL	5.78	12.83	9.93	2.63	4.95	34.37	6.02	7.76
TO_ABS	2.42	10.60	8.08	10.16	5.39	3.09	39.73	
TO_WTH	3.12	13.67	10.42	13.10	6.95	3.99		51.24
Freq. 2								
UCXMC1	18.35	0.45	1.01	0.41	0.92	6.56	1.56	9.47
ARI	1.88	4.52	1.01	1.66	0.78	0.95	1.05	6.37
AGL	0.94	0.27	3.21	0.30	2.72	2.21	1.07	6.52
EXX	2.06	1.18	2.51	4.75	2.22	0.78	1.46	8.87
GLN	2.25	0.41	3.48	0.38	5.94	3.13	1.61	9.78
SOL	3.97	0.71	2.39	0.59	0.37	13.44	1.34	8.13
TO_ABS	1.85	0.50	1.73	0.56	1.17	2.27	8.08	
TO_WTH	11.23	3.07	10.54	3.38	7.11	13.80		49.13
Freq. 3								
UCXMC1	2.96	0.01	0.16	0.01	0.11	1.10	0.23	9.60
ARI	0.31	0.54	0.15	0.19	0.11	0.17	0.16	6.47
AGL	0.15	0.02	0.45	0.00	0.36	0.36	0.15	6.21
EXX	0.34	0.10	0.37	0.56	0.30	0.13	0.21	8.67
GLN	0.37	0.03	0.50	0.01	0.79	0.51	0.24	9.93
SOL	0.62	0.07	0.34	0.08	0.03	2.07	0.19	7.94
TO_ABS	0.30	0.04	0.25	0.05	0.15	0.38	1.17	
TO_WTH	12.54	1.61	10.53	2.03	6.34	15.78		48.82
Freq. 4								
UCXMC1	4.50	0.01	0.24	0.00	0.16	1.67	0.35	9.61
ARI	0.47	0.80	0.23	0.28	0.16	0.26	0.23	6.48
AGL	0.23	0.02	0.68	0.00	0.53	0.55	0.22	6.18
EXX	0.53	0.14	0.55	0.82	0.45	0.20	0.31	8.64
GLN	0.57	0.05	0.76	0.00	1.17	0.78	0.36	9.94
SOL	0.95	0.10	0.51	0.12	0.05	3.12	0.29	7.93
TO_ABS	0.46	0.05	0.38	0.07	0.23	0.58	1.76	
TO_WTH	12.67	1.46	10.53	1.88	6.25	15.99		48.79

Note: Freq. 1& 2 = short-term (1 to 16 days), freq. 3 = medium-term (16 to 32 days), and freq. 4 = long-term (> 32 days) connectedness of the currencies. WTH and ABS = within and absolute in the estimated system respectively. UCXMC1, ARI, AGL, EXX, GLN and SOL denote coal price, African rainbow mineral, Anglo American, Exxaro, Glencore, and Sasol respectively.

4.5.2 Pair-wise directional spillover connectedness

Subsequently, we developed a net-pairwise directional spillover connectedness measure to conduct a more intricate study of the outcomes. *Table 5* displays the net-pairwise directional spillover effects between coal firms, which are quantified by subtracting the value of the second variable from the value of the first variable. A negative number indicates that the first coal firm is experiencing a net inflow (receiver) of spillover effects from the associated coal firm. A

positive number indicates that the first coal firm is a net emitter (transmitter) of the spillover effect to the related coal firm. Table 3 clearly shows that all Anglo-American couples (AGL-EXX, AGL-GLN, AGL-SOL, AGL-ARI, AGL-UCXMC1) demonstrate negative connectedness across all frequencies. Anglo American is indicated to be a receiver of the spillover effect. The coal price pairs (UCXMC1-ARI, UCXMC1-AGL, UCXMC1-EXX, UCXMC1-GLN, UCXMC1-SOL) consistently show positive values at all frequencies except with Glencore (only frequency 1 shows a positive value), indicating that it is a common factor affecting all coal enterprises (transmitter) except Glencore.

Other coal firms, such as African Rainbow Mineral, show positive values across frequencies 2 to 4, which suggests that it is a net transmitter at a medium- to long-term horizon. However, it is a receiver at a shorter interval (frequency 1) for Exxaro, Glencore, Sasol, and the coal price. Glencore seems to be a net receiver from Exxaro and Sasol coal firms but a net transmitter to Anglo-American coal firms. Interestingly, Glencore receives the coal price in the short horizon (frequency 1), but it also transmits the African Rainbow Mineral in the same short horizon (frequency 1). Therefore, Glencore is a transmitter of the coal price in the short to long-term horizon (frequency 2-4) and a receiver of African Rainbow Mineral in the short to long-term horizon (frequency 2-4).

When studying the transfer of influence between pairs of entities in the South African coal business, a closer investigation of the results uncovered intriguing patterns among the coal companies. The findings revealed that all Anglo-American couples consistently exhibited a negative level of connectivity across all frequencies. This suggests that Anglo American acts as a recipient of spillover effects from the affiliated coal enterprises. However, the coal price pairs consistently displayed positive values at all frequencies, except with Glencore. This suggests that the coal price is a shared factor that influences all coal enterprises, save Glencore, which functions as a conduit for transmitting spillover effects.

Overall, the research on pair-wise directional spillover connectedness offers unique insights into the precise links and pathways via which coal enterprises in South Africa influence each other. The findings emphasise the diverse functions of different enterprises in terms of generating or receiving spillover effects within the industry. Anglo-American emerges as a significant recipient of spillover effects, while Glencore stands out as a key transmitter of such effects. The presence of directional spillover effects highlights the intricate interconnection and interdependencies among coal companies in the South African industry. Comprehending these

dynamics is essential for stakeholders to properly manage risks and execute focused measures to reduce the impact of external shocks on individual enterprises and the industry as a whole. In short, the results highlight the significance of taking proactive measures to control risks, fostering teamwork, and engaging in strategic planning to strengthen the resilience and stability of the South African coal industry in the face of price fluctuations and market uncertainty.

Table 5 Pair-wise directional spillover connectedness results

Currencies	Freq. 1	Freq. 2	Freq.3	Freq.4
UCXMC1-ARI	0.00092	0.00174	0.00026	0.00039
UCXMC1-AGL	0.03972	0.01753	0.00272	0.00411
UCXMC1-EXX	0.01334	0.00844	0.00128	0.00193
UCXMC1-GLN	0.03293	-0.00063	-0.00008	-0.00012
UCXMC1-SOL	0.03033	0.02163	0.00325	0.00490
ARI - AGL	0.01020	0.36728	0.05739	0.08678
ARI - EXX	-0.29578	0.07237	0.01266	0.01933
ARI - GLN	-0.09942	0.22924	0.03611	0.05464
ARI - SOL	-0.30851	0.03769	0.00725	0.01114
AGL - EXX	-0.23931	-0.19162	-0.02908	-0.04386
AGL - GLN	-0.26889	-0.06805	-0.00982	-0.01474
AGL - SOL	-0.45640	-0.13710	-0.01968	-0.02953
EXX - GLN	0.07241	0.12520	0.01918	0.02896
EXX - SOL	-0.17844	0.02550	0.00466	0.00713
GLN - SOL	-0.33456	-0.09348	-0.09348	-0.02002

Note: Freq. 1& 2 = short-term (1 to 16 days), freq. 3 = medium-term (16 to 64 days), and freq. 4 = long-term (32 to inf days) connectedness of the coal firms & coal price.

4.5.3 Rolling window analysis

We provide an insightful analysis regarding net pairwise connectedness among the coal firms and the coal price. We capture the time-varying net-pairwise directional and overall spillover connectedness among the coal firms and coal prices using the rolling window approach. The horizontal axis of the graphs depicts the period of analysis where 200, 400, 600, and 800 represent connectedness in 2015/2016, 2016/2017, 2017/2018, and 2018/2019, respectively, which corresponds to our period of analysis. The vertical axis indicates the system's level of connectedness.

Within bands 3.14 to 0.79, it can be observed in Figure 1 that the coal price exhibits an almost zero spillover effect, characterised by significant fluctuations in specific indices for African Rainbow Mineral, Anglo American, Exxaro, and Glencore. The coal firms described above exhibit a negative spillover effect at index 400. In addition, African Rainbow Mineral experiences a negative spillover effect at index 800, whereas Glencore faces a negative spillover effect at index 1050. Nevertheless, it appears that the price of coal exhibits a significant degree of volatility in its impact on Sasol.

Anglo-American, Exxaro, Glencore, and Sasol are significantly impacted by the fluctuating spillover effect of African Rainbow minerals. Anglo American encounters an initial period of volatility marked by a negative spillover effect at index 0, which is subsequently followed by further surges in volatility, encompassing both negative and positive values, at index 80, 200, and 400. The Exxaro stock has low volatility at a 0 index while displaying significant positive fluctuations at index 400 and 1000. Glencore initially encounters a negative spillover effect, then is accompanied by both negative and positive surges at index 80, 400, and 420. At index 0, Sasol shows a negative spillover impact, followed by a volatile spillover effect and a negative spike at index 1100. However, the spillover effect on Exxaro caused Anglo-American to first exhibit a positive spillover effect but subsequently maintain a negligible net spillover effect, with a significant positive surge observed at index 1200.

Hence, the analysis of Figure 1 demonstrates interesting discoveries regarding the spillovers between bands 3.14 and 0.79. Within this range, the coal price exhibits a minimal spillover effect, with notable swings observed in specific indices for African Rainbow Mineral, Anglo-American, Exxaro, Glencore, and Sasol. During this era, the influence of coal prices on these particular enterprises is modest or negligible, demonstrating a lack of significant interconnectivity or directional influence within this range.

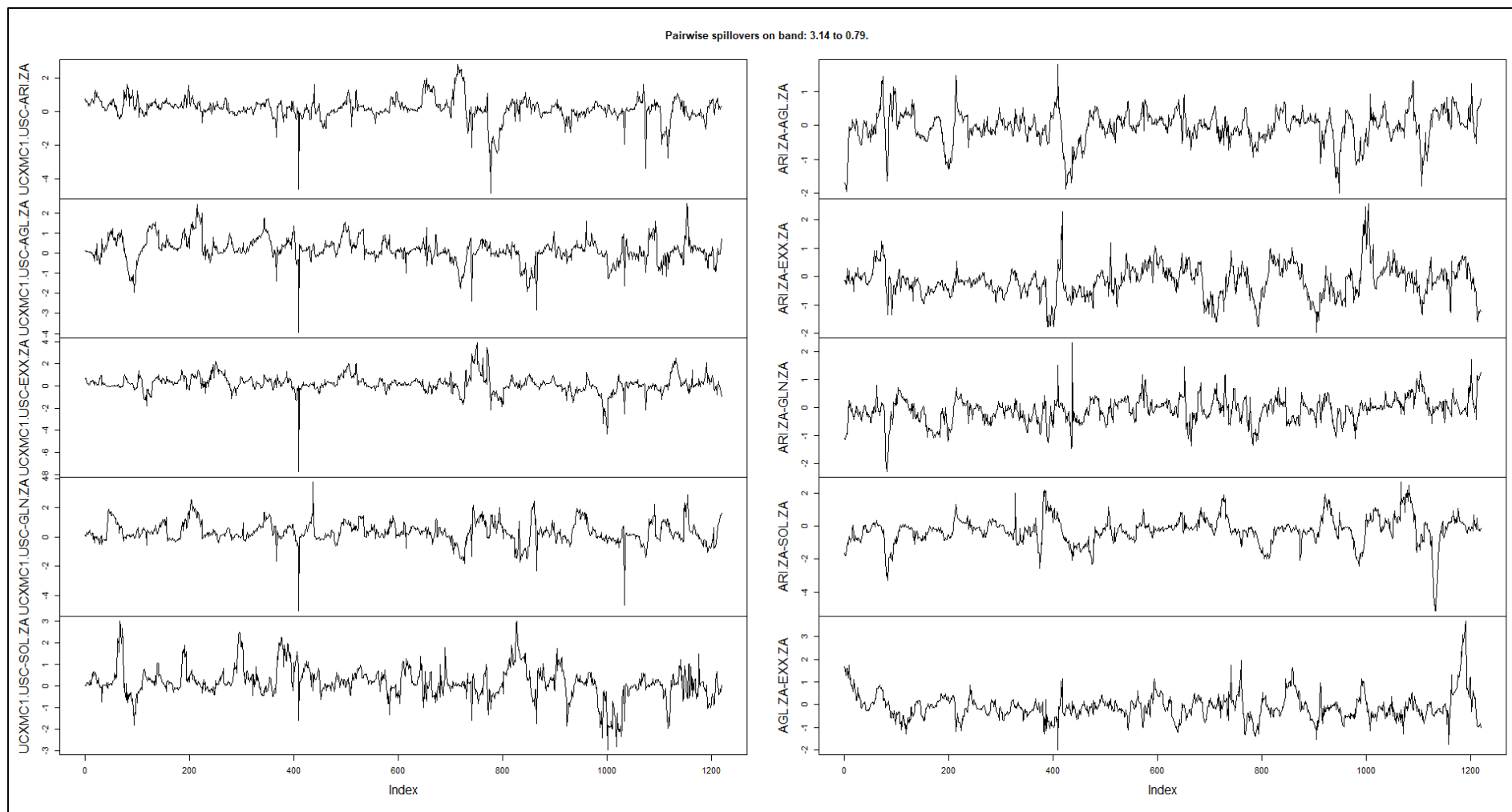


Figure 1 Pairwise spillover on band 3.14 to 0.7

Within band 0.10 to 0.00, as seen in Figure 2, the impact of the coal price on all coal companies is nearly negligible (almost zero spillover effect), but there are occasional fluctuations in some indexes, both positive and negative. African Rainbow Mineral has negative spikes at index 200 and 380. Positive spikes are observed on Anglo American at index 500. Exxaro initially encountered a high volatility spillover effect resulting from the coal prices at index 0 up until index 700. Subsequently, the spillover effect for the remaining indexes for Exxaro remains at almost zero. The spillover effect of coal prices on Glencore is minimal but has a positive spike observed at index 900. The coal price has a significant and positive spillover effect on Sasol, with negative spikes observed at index 860 and 1000.

The spillover effect of African Rainbow Mineral on Anglo-American, Exxaro, and Sasol seems to exhibit a high volatile spillover effect. However, the spillover effect on Glencore seems to be almost zero, with a positive spike at the 1100 index. The spillover effect of Anglo-American on Exxaro seems to be highly volatile but mostly fluctuates negatively, suggesting that Anglo-American has a high volatile negative spillover effect on Exxaro.

Figure 2 Figure 2 Pairwise spillover on band 0.10 to 0.00

Data demonstrate substantial variations in spillover effects within the depicted frequency range. The analysis emphasises the different levels of spillover effects on major stakeholders, including African Rainbow Mineral, Anglo-American, Exxaro, Glencore, and Sasol. The fluctuations seen during this precise period, which include both positive and negative spikes, highlight the volatility and interdependence of the coal market. The effect of African Rainbow Mineral on other companies seems to be highly unpredictable, with varying levels of influence reported throughout time. This highlights the complex and interwoven nature of spillover effects and how they impact the performance and behaviour of individual companies in the coal industry.

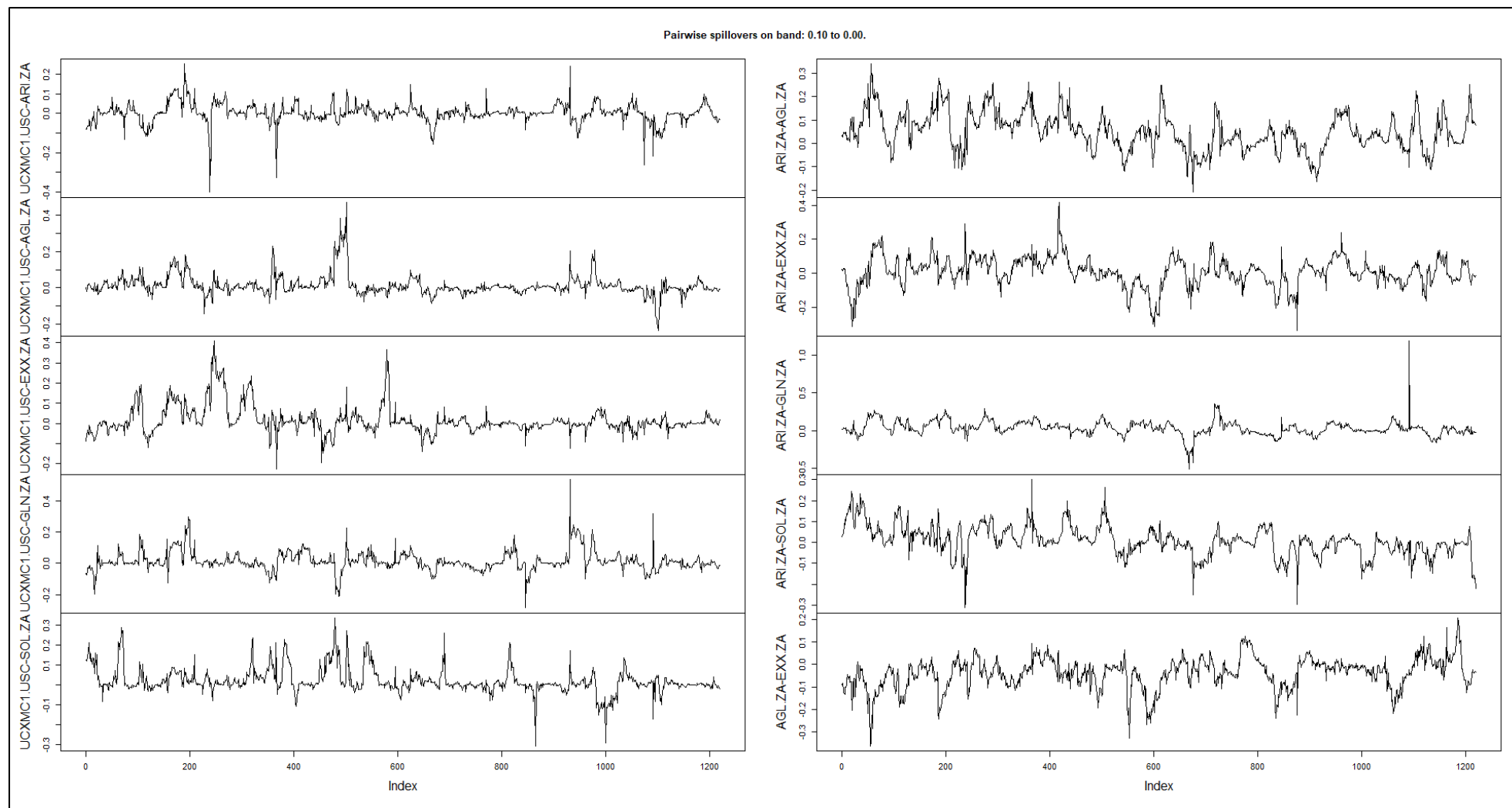


Figure 2 Pairwise spillover on band 0.10 to 0.00

The spillover effect of the coal price on all coal firms appears to be negligible (almost zero) for Anglo-American and African Rainbow Mineral within the band of 0.20 to 0.10 as observed in *Figure 3*. However, both positive and negative spikes were observed. African Rainbow Mineral exhibits negative spikes at index 200 and 380, followed by a sustained spillover impact of nearly zero. Anglo-American exhibits a positive spike at index 500; however, it consistently sustains a minimal spillover effect. The coal price has a high volatile spillover effect on Exxaro, resulting in a significant and unpredictable spillover effect from index 0 to index 600. Subsequently, the spillover effect becomes nearly negligible. Glencore experiences minimal coal price spillover effect, with a slight increase observed at index 900. Nevertheless, it appears that the price of coal has a favourable spillover impact on Sasol since it exhibits positive fluctuations except for a negative spike observed at index 850 and 1000.

The volatility spillover effect of African Rainbow Mineral on Anglo-American, Exxaro, and Sasol appears to be highly volatile. Nevertheless, the spillover effect on Glencore is minimal, with a notable positive spike observed around index 1100. Upon examination of the spillover impact between Anglo-American and Exxaro, it becomes evident that the spillover effect exhibits a significantly high volatility.

Concerning *Figure 3*, the results demonstrate substantial fluctuations in the transmission of effects over the examined timeframe. The volatility of coal prices affects major stakeholders such as African Rainbow Mineral, Anglo-American, Exxaro, Glencore, and Sasol, resulting in both favourable and unfavourable fluctuations. The price fluctuations highlight the coal market's interdependence and ever-changing nature during this particular period. The investigation uncovers the complex characteristics of spillover effects and their potential impact on the performance and behaviour of individual companies in the coal industry.

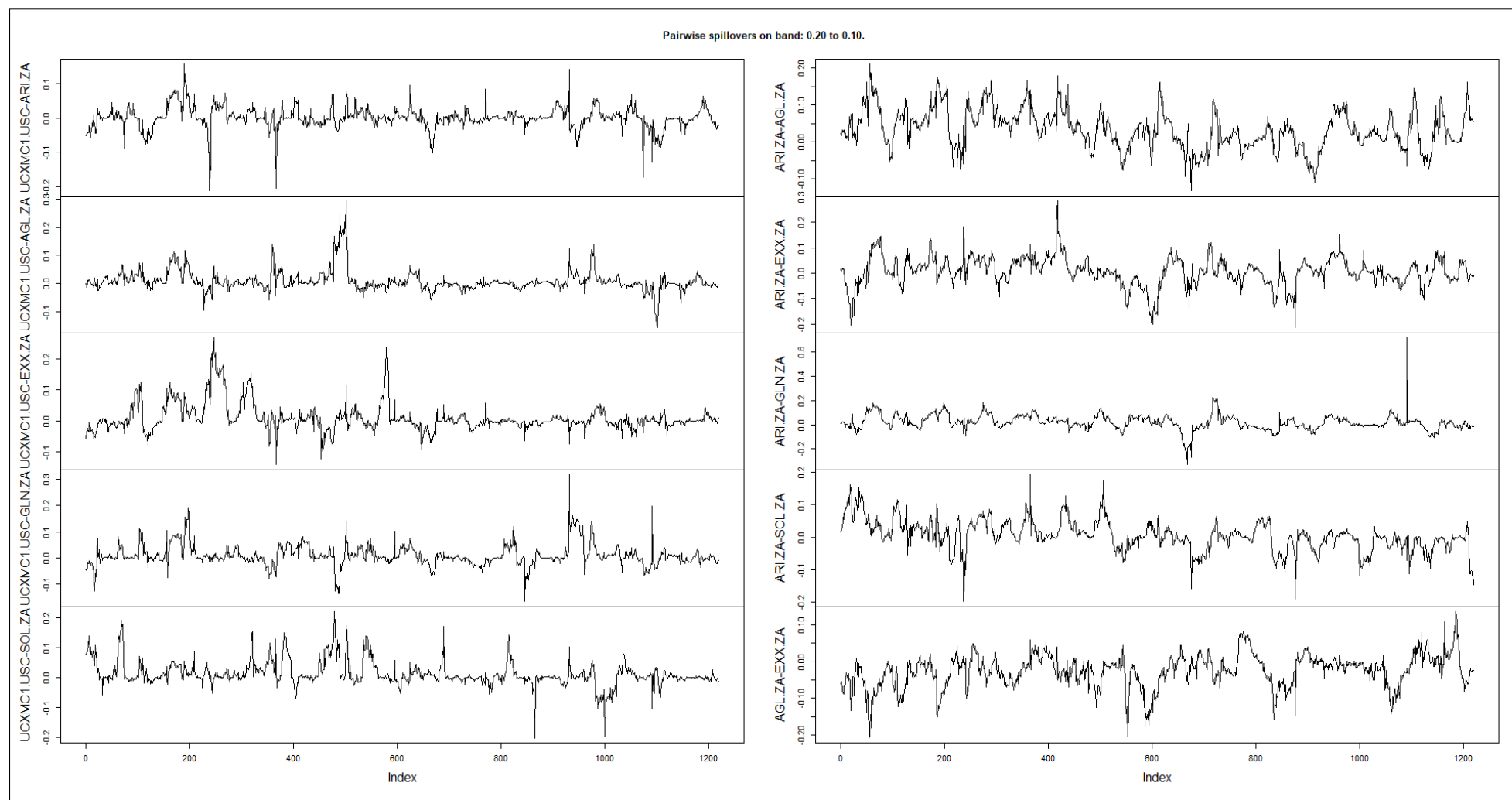


Figure 3 Pairwise spillover on band 0.20 to 0.10

The spillover effect of the coal price on African Rainbow Mineral and Glencore appears to exhibit significant volatility within the band of 0.79 to 0.20, as seen in *Figure 4*. The spillover effect on Anglo-American exhibits significant volatility until reaching the index 500, after which it continues to fluctuate to a level of almost zero. The spillover impact on Exxaro exhibits significant volatility until reaching an index of 700, after which it continues to vary at a level close to zero. However, the spillover impact for Sasol is nearly negligible, with negative spikes observed at index 880 and 1000.

The African Rainbow Mineral's impact on Anglo-Americans, Sasol, and Exxaro appears to be highly volatile. The impact on Glencore is unpredictable, although it remains close to zero, with a negative spike at index 700 and a positive spike at index 1100. Exxaro experiences a noticeable positive spike at index 400 due to the spillover effect. Examining the impact of Anglo American on Exxaro, it is evident that there is a significant and unpredictable spillover effect on Exxaro.

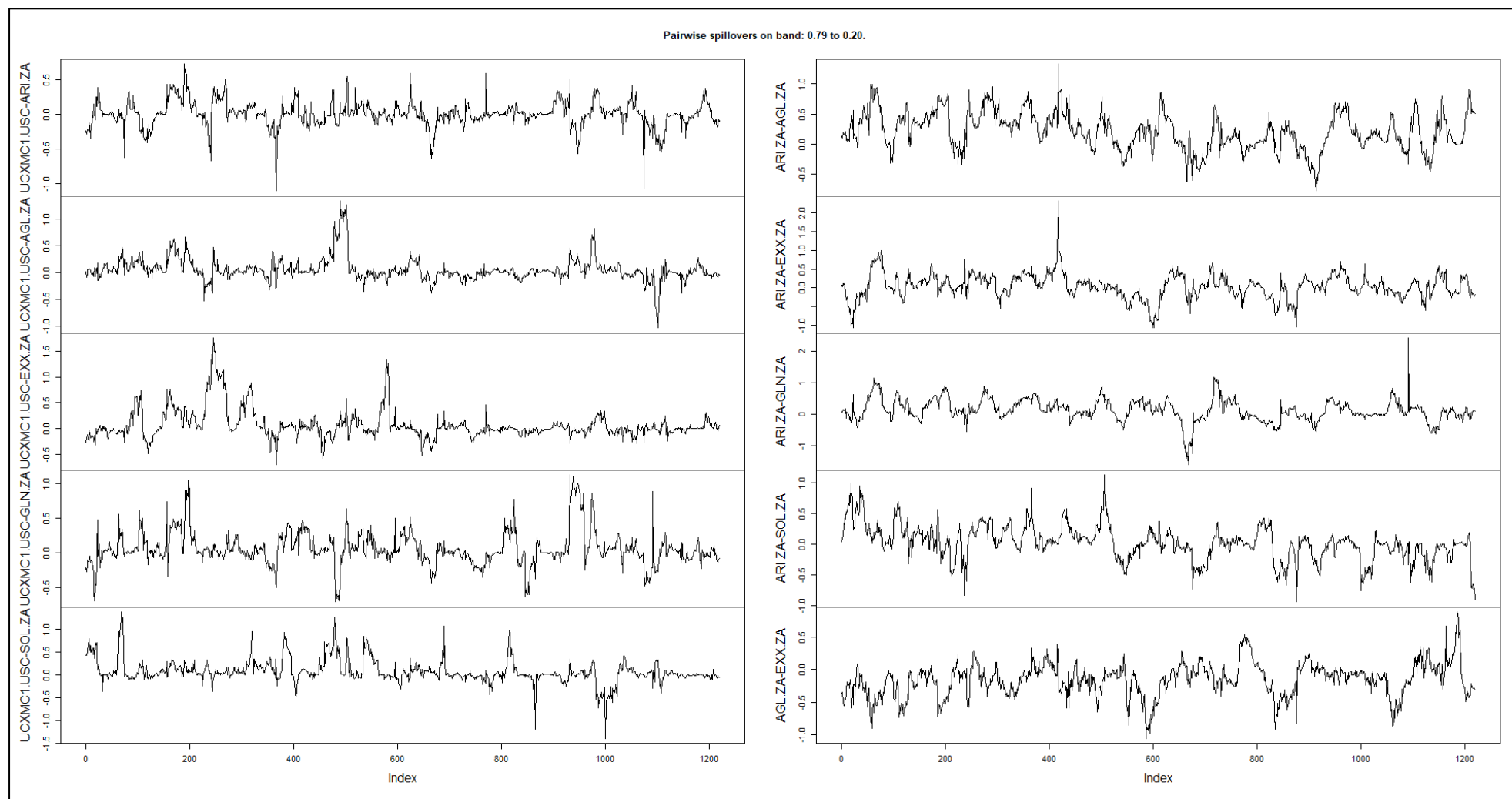


Figure 4 Pairwise spillover on band 0.79 to 0.20

In conclusion, the rolling window analysis provides valuable insights into the dynamic interrelationships and spillover effects among coal firms and coal prices. By employing a time-varying approach, the study captures the net-pairwise directional and overall spillover connectedness, shedding light on the complex interactions within the coal industry.

The findings highlight significant fluctuations in spillover effects at specific indices for key players such as African Rainbow Mineral, Anglo-American, Exxaro, Glencore, and Sasol. These fluctuations, characterized by both positive and negative spikes, underscore the volatility and interconnectedness of the coal market. The impact of the African Rainbow Mineral on other firms appears to be highly volatile, with varying degrees of influence observed over time.

Moreover, the analysis reveals the intricate nature of spillover effects and how they can influence the performance and behaviour of individual firms within the coal sector. Understanding these dynamics is crucial for stakeholders in making informed decisions and managing risks in a complex and interconnected market environment.

Overall, the study contributes to the existing literature on financial interconnectedness and spillover effects in the coal industry, offering valuable insights for researchers, policymakers, and industry practitioners. Further research in this area could explore additional factors influencing spillover effects and their implications for market stability and efficiency.

4.6 Key findings

The study examining the directional spillover effects between South African coal enterprises and coal prices revealed that the shortest frequency (Frequency 1) had the greatest influence on overall connectivity, accounting for 39.73% of the total. This indicates a substantial short-term impact. Frequency 2 contributes with 8.08%, which indicates its short-term significance. The overall connectedness was 1.117%, with medium-term connectivity having a frequency of 3. On the other hand, long-term closeness, with a frequency of 4, contributed 1.76%. These findings indicate that the impact of spillover connectivity is stronger in the immediate future, suggesting the possibility of contagion effects. This means that fluctuations in coal prices can quickly affect the entire industry, leading to changes in financial performance and risk exposure for individual coal firms. The results emphasize the ever-changing nature of relationships throughout various periods, as well as the possibility for the spread of influence to magnify the effect of fluctuations in coal prices on the success of South African coal mining firms. Additionally, the analysis revealed that Anglo-American coal firms were net receivers of spillover effects, while coal price pairs were net transmitters, except with Glencore, indicating a common factor affecting all coal enterprises.

The analysis of pair-wise directional spillover connectedness shows that all Anglo-American couples (AGL-EXX, AGL-GLN, AGL-SOL, AGL-ARI, and AGL-UCXMC1) display negative connectedness across all frequencies. This suggests that Anglo-American receives more spillover effects from the associated coal firms than it transmits. Conversely, the coal price pairs (UCXMC1-ARI, UCXMC1-AGL, UCXMC1-EXX, UCXMC1-GLN, UCXMC1-SOL) consistently exhibit positive values across all frequencies, except for Glencore, where only frequency 1 displays a positive value. This indicates that the coal price (UCXMC1) serves as a conduit for transmitting spillover effects to the other coal companies, except for Glencore, which is not greatly impacted by changes in the coal price.

The Rolling Window Analysis (4.5.3) offers valuable insights into the overall interconnectedness between coal enterprises and coal prices throughout various periods. The analysis demonstrates that the price of coal has different spillover effects on various coal firms within particular ranges. African Rainbow Minerals exhibits significant volatility in its influence on other companies, characterised by both positive and negative fluctuations. Anglo-American, Exxaro, and Sasol are significantly affected by changes in the price of coal, which may be noticed by swings in several indices. Contrarily, Glencore exhibits negligible spillover

effects, occasionally experiencing positive surges. The study emphasises the intricate linkages within the South African coal industry, highlighting the dynamic interrelationships and spillover effects among coal firms and coal prices.

5 Conclusion & Recommendations

5.1 Conclusion

In conclusion, this study provides insight into the complex dynamics of the South African coal sector by analysing the significant influence of fluctuations in coal prices on the performance of coal mining companies. Through a thorough analysis of the interconnections between markets, directional spillover effects, and pair-wise connectedness, we have obtained valuable information about the transmission of risks and opportunities within the industry. This study examines the consequences of price changes and the interconnections between coal companies. It not only improves our comprehension of market dynamics but also offers practical insights for investors, policymakers, and industry stakeholders.

This study emphasizes the significance of strategic risk management in reducing the negative impacts of price volatility, thereby enhancing coal firms' ability to navigate market disruptions and remain resilient. Furthermore, the recognition of net-pairwise directional spillover effects emphasises the interconnectedness between coal companies and the shared factors that impact their performance. Acquiring this knowledge can allow investors to make well-informed decisions and help companies adjust their plans efficiently in response to market conditions. This eventually improves competitiveness and sustainability in the South African coal sector.

This study enhances academic research and offers practical guidance to industry stakeholders in optimising profitability, mitigating weaknesses, and promoting growth in a dynamic market environment. It achieves this by providing empirical evidence on the impact of coal price volatility and interconnectedness among firms. Effective management of the complexity of the coal business requires understanding the consequences of price volatility and market interconnection. This understanding will help shape the future trajectory of the sector, making it more resilient and sustainable.

5.2 Recommendations

This research, as the first of its kind in South Africa, particularly within the coal industry, lays a solid foundation for future investigations delving into the intricate economics of the coal sector. Building on this foundation, the author advocates for future studies to delve into crucial areas such as

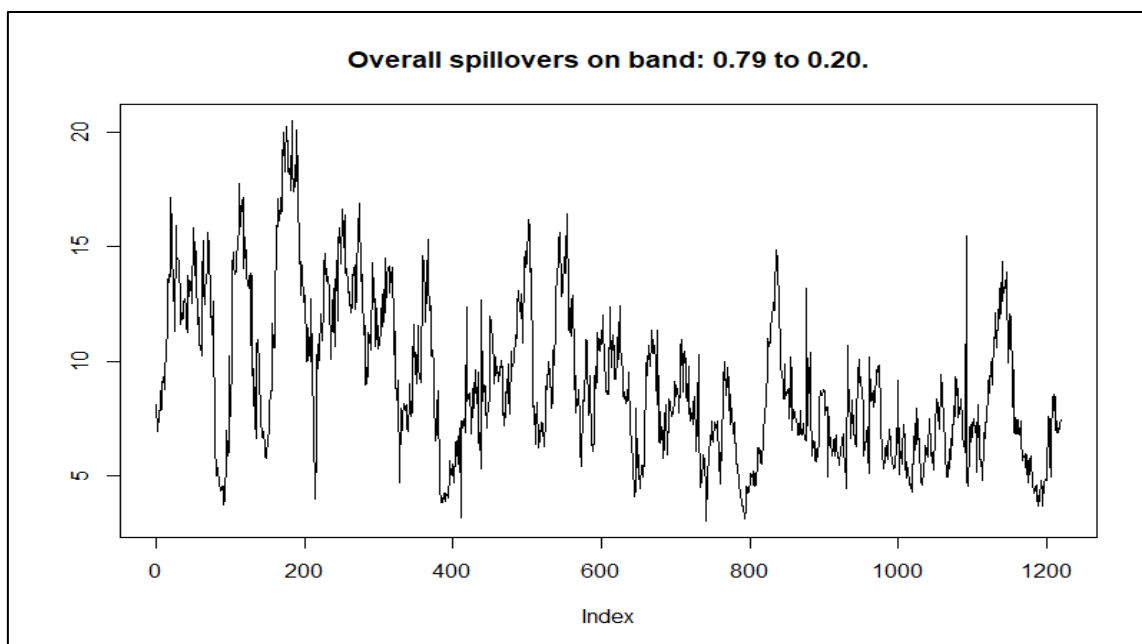
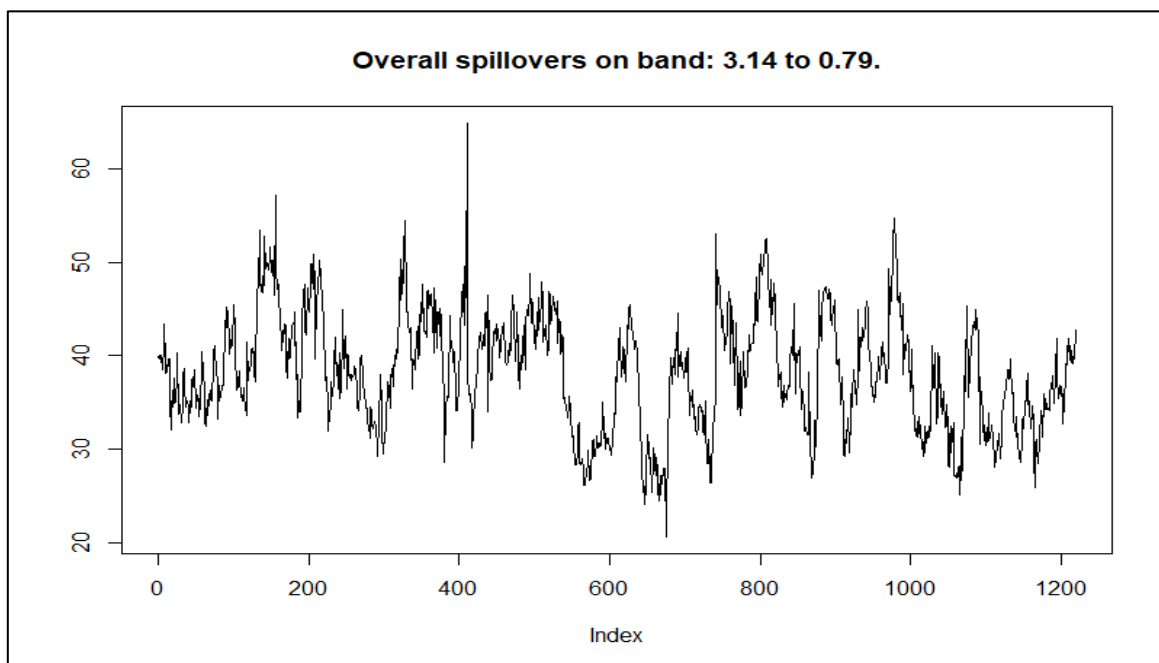
- Future funding sources for South African coal firms will evolve, taking into account changing market dynamics and sustainability imperatives.

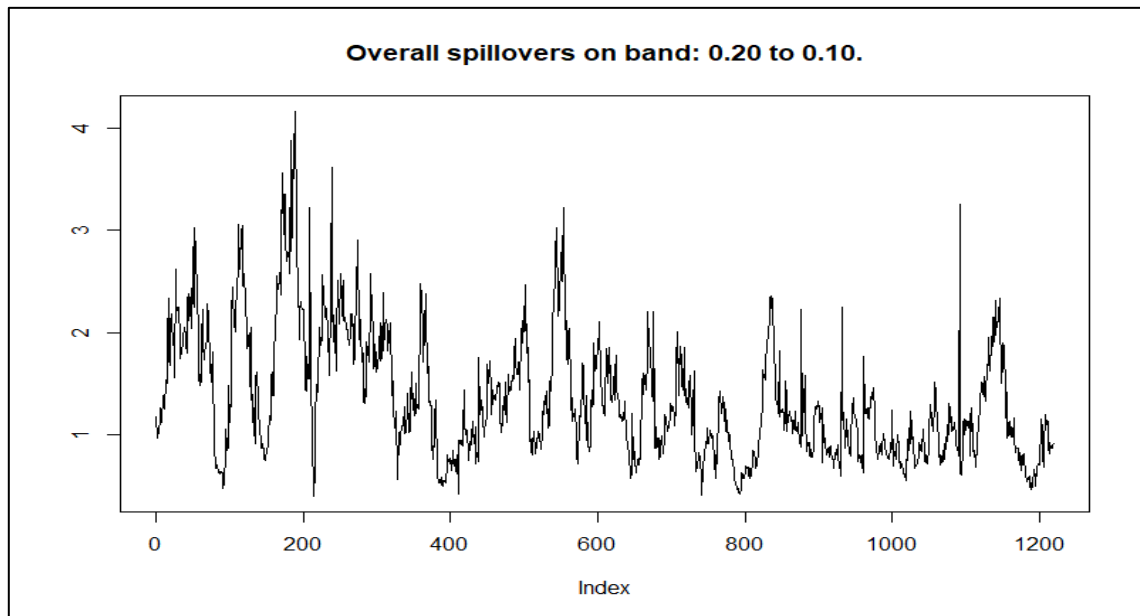
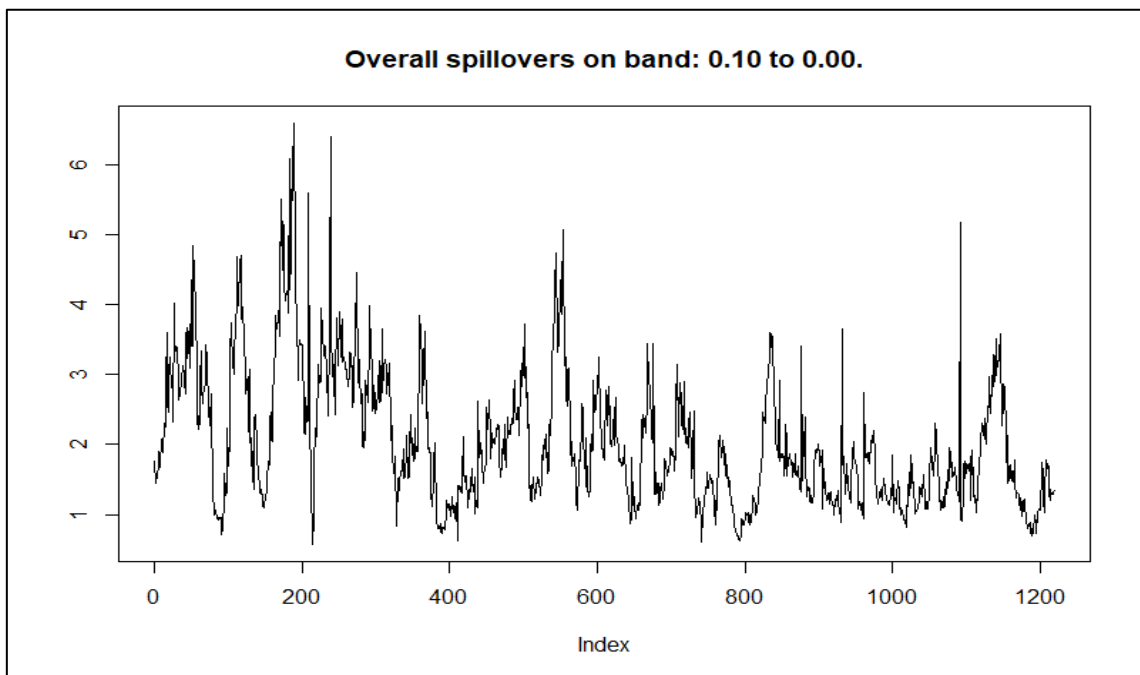
- Assessing the influence of Transnet on the operational performance and competitiveness of South African coal companies, highlighting the significance of transportation infrastructure.
- Investigating the repercussions of constrained funding from South African banks on the growth and resilience of coal enterprises, emphasizing the importance of financial support mechanisms.
- Exploring the spillover effects of price volatility on other commodity firms like gold and platinum, elucidating the interconnected nature of commodity markets and the broader economic landscape.

Future research endeavours can enhance our comprehension of the obstacles and prospects confronting the coal industry in South Africa by focussing on these crucial research domains. This will facilitate well-informed decision-making, strategic planning, and sustainable expansion in the ever-evolving energy industry.

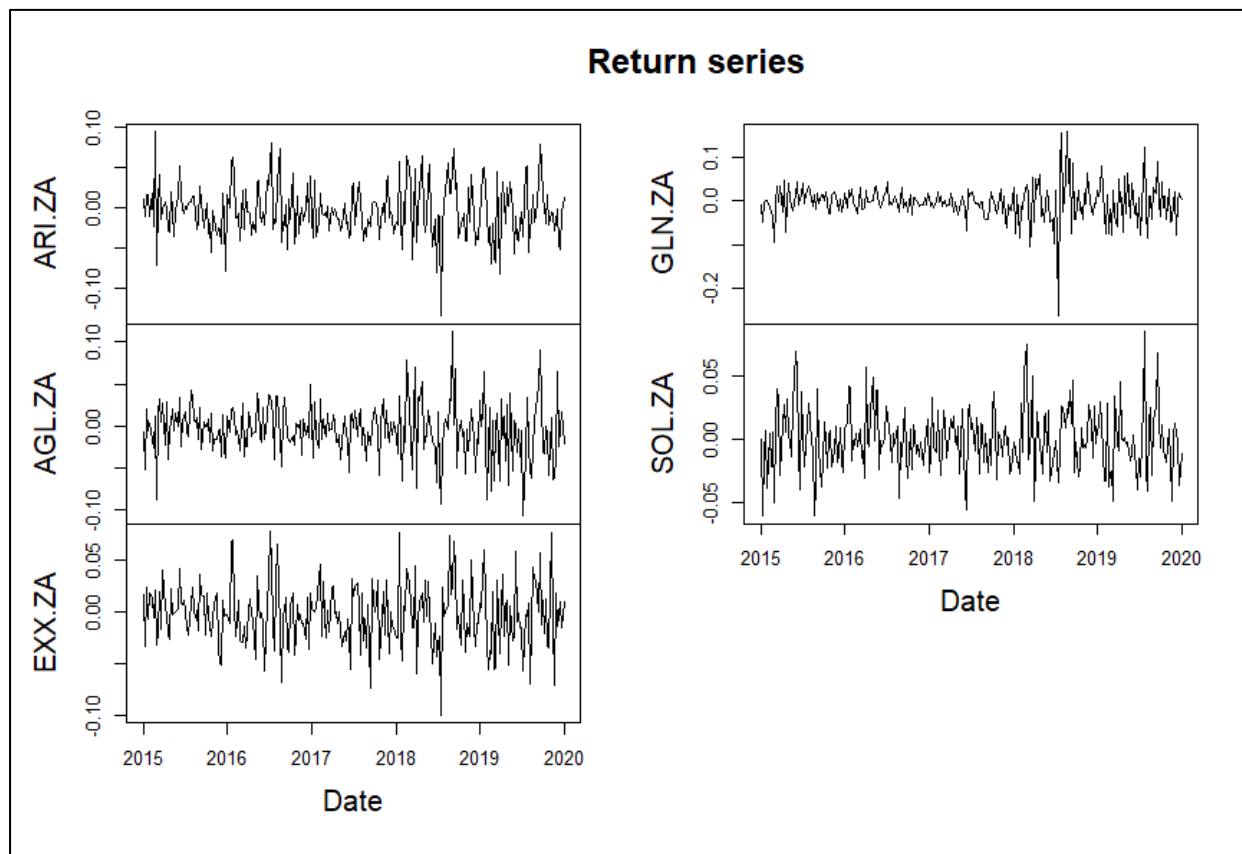
Appendix

Overall spillover results





Return Series



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