

A holistic feasibility assessment of the South African coal to carbon industry

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ABSTRACT

The coal-to-carbon industry converts beneficiated coal into high-value, non-energy carbon products. South Africa, a coal-dependent developing country, can leverage the coal-to-carbon industry to develop such products from coal or carbon precursors sourced from coal. The industry provides novel markets and alternative options for South Africa's current coal utilisation.

This study aimed to assess the feasibility of South Africa's coal-to-carbon industry by comprehensively exploring market, technical, economic, environmental, and operational feasibility factors. It explored the status of coal-to-carbon products and technologies in South Africa, identified barriers and enablers for developing valuable carbon products from coal, identified opportunities for new products, and developed a stakeholder's relationship for the coal-to-carbon industry. The study summarizes key feasibility factors to guide decisions on alternative coal utilization, inform policy development, and offer decision support.

The investigation employed a qualitative approach. Initially, a systematic literature review was conducted to discover and evaluate feasibility factors (barriers, enablers, and opportunities). Additionally, semi-structured interviews were carried out with experts specializing in coal conversion technologies and coal-based carbon products. Thematic analysis was then performed on the collected data to extract and analyse perspectives and opinions regarding the feasibility of the industry. SWOT-TOWS and Porter's five forces analyses were conducted to examine strengths, weaknesses, and internal and external factors affecting the industry, respectively, centred on a systematic literature review and the findings from the empirical investigation. These analytical tools provide a comprehensive view of the feasibility of the South African coal-to-carbon industry.

Results show that South Africa has the necessary resources and expertise for a viable industry, with a solid value chain. However, environmental challenges, particularly the significant greenhouse gas emissions from current carbon precursor production processes, and a general lack of carbon technologies for diverse carbon products, present notable barriers. To fill industry narrative gaps, collaboration recommendations were provided for key stakeholders. However, the study's limitations include potential oversight of some stakeholder perspectives, incomplete exploration of alternative scenarios or strategies, and reliance on assumptions in strategic analysis that may not align with real-world developments. The identification of future research opportunities aims to delve into various aspects and niches of the coal-to-carbon industry.

Keywords: Carbon, Coal, Coal-based products, Feasibility, South Africa

PREFACE

The following research paper emanates from this research and has been published in the *SAIIE33 The Industrials – marvellous world of IE conference* proceedings and is found in Appendix G:

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TABLE OF CONTENTS

| | |
|--|------------|
| ABSTRACT | I |
| PREFACE | II |
| ACKNOWLEDGEMENTS | III |
| 1 INTRODUCTION | 2 |
| 1.1 Background | 2 |
| 1.2 Research Problem | 3 |
| 1.3 Research Opportunity | 3 |
| 1.4 Research Aim | 4 |
| 1.5 Research Questions | 4 |
| 1.6 Research Objectives | 4 |
| 1.7 Significance of the Study | 4 |
| 1.8 Chapter Summary | 5 |
| 2 LITERATURE STUDY | 8 |
| 2.1 Introduction | 8 |
| 2.2 The Coal-to-Carbon Industry | 8 |
| 2.2.1 Industry Structure | 9 |
| 2.2.2 Types of Coal-to-Carbon Products | 11 |
| 2.2.3 Precursors from Coal | 14 |
| 2.2.4 Coal-to-Carbon Technologies | 14 |

| | | |
|----------|--|-----------|
| 2.2.5 | The Global Coal-to-Carbon Industry..... | 16 |
| 2.2.6 | African Industry..... | 18 |
| 2.2.7 | South African Industry..... | 19 |
| 2.2.8 | Current Practices and Operations in the South African Coal-to-Carbon Industry..... | 20 |
| 2.2.9 | Research and Development..... | 22 |
| 2.3 | Feasibility Types..... | 22 |
| 2.3.1 | Market..... | 22 |
| 2.3.2 | Technical..... | 23 |
| 2.3.3 | Economic..... | 23 |
| 2.3.4 | Environmental..... | 24 |
| 2.3.5 | Operational..... | 24 |
| 2.4 | Overview of Strategic Business Analysis Tools..... | 24 |
| 2.4.1 | SWOT Analysis..... | 26 |
| 2.4.2 | TOWS Framework..... | 27 |
| 2.4.3 | Pestel Framework..... | 29 |
| 2.4.4 | Porter’s Value Chain Analysis..... | 31 |
| 2.4.5 | Porter’s Five Forces Framework..... | 33 |
| 2.4.6 | Strategic Group Analysis..... | 36 |
| 2.4.7 | Industry Lifecycle..... | 37 |
| 2.4.8 | Core Advantages of Business Analysis Tools..... | 38 |
| 2.5 | Chapter Summary..... | 38 |
| 3 | RESEARCH DESIGN..... | 41 |
| 3.1 | Introduction..... | 41 |

| | | |
|----------|---|-----------|
| 3.2 | Research Approach | 41 |
| 3.3 | Qualitative Secondary Research | 41 |
| 3.3.1 | Systematic Literature Review (SLR)..... | 42 |
| 3.3.2 | The SLR Method..... | 43 |
| 3.3.3 | Research Protocol | 43 |
| 3.3.4 | Search Strategy | 46 |
| 3.3.5 | Narrative Synthesis of the SLR..... | 48 |
| 3.4 | Empirical Research Methodology | 49 |
| 3.4.1 | Semi-Structured Interviews..... | 49 |
| 3.4.2 | Primary Data | 50 |
| 3.4.3 | Research Instrument | 50 |
| 3.4.4 | Design of Interview Questions and Protocol..... | 51 |
| 3.4.5 | Data Collection and Sampling | 54 |
| 3.4.6 | Data Transcription..... | 55 |
| 3.4.7 | Thematic Analysis of Interview Data..... | 55 |
| 3.5 | Integration of SWOT and Porter's Five Forces Analyses: Insights from SLR and In-Depth Interviews..... | 57 |
| 3.6 | Reliability, Rigor, and Validity | 58 |
| 3.7 | Ethical Considerations | 59 |
| 3.8 | Chapter Summary | 60 |
| 4 | SYSTEMATIC LITERATURE REVIEW ON THE COAL-TO-CARBON INDUSTRY (FEASIBILITY- BARRIERS AND ENABLERS AND OPPORTUNITIES) | 63 |
| 4.1 | Introduction..... | 63 |

| | | |
|----------|---------------------------------|----------|
| 4.2 | Data Summary..... | 63 |
| 4.3 | Data Extraction..... | 66 |
| 4.4 | Reflection on SLR Results..... | 69 |
| 4.5 | Coding and Categorization..... | 70 |
| 4.6 | The Summary of Themes..... | 71 |
| 4.6.1 | Resource Availability..... | 71 |
| 4.6.2 | Production Processes..... | 72 |
| 4.6.3 | Technology Readiness..... | 73 |
| 4.6.4 | Advanced Markets..... | 73 |
| 4.6.5 | Value Chain Transformation..... | 73 |
| 4.6.6 | Pollution Challenges..... | 74 |
| 4.7 | Chapter Summary..... | 74 |
| 5 | INTERVIEWS..... | 1 |
| 5.1 | Introduction..... | 1 |
| 5.2 | Data Summary..... | 1 |
| 5.3 | Themes and Sub themes..... | 1 |
| 5.3.1 | Enablers..... | 1 |
| 5.3.2 | Challenges..... | 3 |
| 5.3.3 | Competition..... | 4 |
| 5.3.4 | Industry Gaps..... | 4 |
| 5.3.5 | Coal Utilisation..... | 5 |
| 5.4 | Convergence of Themes..... | 6 |
| 5.5 | Chapter Summary..... | 7 |

| | | |
|----------|---|-----------|
| 6 | STRATEGIC ANALYSIS..... | 9 |
| 6.1 | Introduction..... | 9 |
| 6.2 | The Porter’s Five Forces Analysis | 9 |
| 6.2.1 | Bargaining Power of Buyers (Competition, Resource Availability)..... | 10 |
| 6.2.2 | Threats of New Entrants (Enablers, Challenges) | 12 |
| 6.2.3 | Bargaining Power of sSuppliers (Industry gaps, Coal utilisation)..... | 13 |
| 6.2.4 | Threats of Substitute Products (Value Chain Transformation)..... | 13 |
| 6.2.5 | Rivalry Among Existing Firms (Competition, Industry Gaps) | 14 |
| 6.3 | The SWOT Analysis | 14 |
| 6.4 | The Tows Matrix | 19 |
| 6.5 | Chapter Summary | 20 |
| 7 | DISCUSSION | 22 |
| 7.1 | Introduction..... | 22 |
| 7.2 | Feasibility Discussion | 22 |
| 7.2.1 | Market..... | 22 |
| 7.2.2 | Technical..... | 23 |
| 7.2.3 | Economic | 25 |
| 7.2.4 | Environmental..... | 26 |
| 7.2.5 | Operational | 28 |
| 7.3 | Consolidated Feasibility Factors | 29 |
| 7.3.1 | The Feasibility Factors Determining the Prospects..... | 29 |
| 7.4 | The Industry Stakeholder’s Relationships..... | 31 |
| 7.5 | Reliability of the Findings..... | 32 |

| | | |
|----------|---|-----------|
| 7.6 | Implications | 32 |
| 7.7 | Chapter Summary | 34 |
| 8 | CONCLUSIONS AND RECOMMENDATIONS..... | 36 |
| 8.1 | Research Study | 36 |
| 8.2 | Research Contribution | 36 |
| 8.3 | Limitations and Future Recommendations..... | 37 |
| 8.4 | Concluding Remarks | 37 |
| 9 | REFERENCES | 39 |
| | APPENDIX A: ETHICS APPROVAL LETTER OF STUDY | 45 |
| | APPENDIX B: INFORMED CONSENT FORM..... | 47 |
| | APPENDIX C: SAMPLE CODES AND CODES GROUPS | 1 |
| | APPENDIX D: SAMPLE PRESCRIBED NOTES | 2 |
| | APPENDIX E: THEMATICALLY ANALYSED TRANSCRIPT..... | 4 |
| | APPENDIX F: SLR FILTERING PROCESS VERIFICATION CHECKLIST..... | 11 |
| | APPENDIX G: INTERVIEWS WITH EXPERTS OF THE SOUTH AFRICAN COAL-TO-CARBON INDUSTRY | 14 |
| | APPENDIX H: AMENDED TITLE | 28 |

LIST OF TABLES

Table 1 Coal-to-Carbon Industry Structure 10

Table 2 Research Protocol 44

Table 3 Six Step Interview Process (Rabionet, 2011) 51

Table 4 The Interview Protocol 52

Table 5 Literature Source Table 64

Table 6 Data Extraction Form 66

Table 7 Codes and Categories 70

Table 8 A List of Themes and Sub-Themes 1

Table 9 The Coal-to-Carbon Industry's SWOT Analysis 14

Table 10 Consolidated Feasibility Factors 30

LIST OF FIGURES

| | |
|--|----|
| Figure 1 Atlas of Economic Complexity - South Africa | 5 |
| Figure 2 Theme Analysis..... | 8 |
| Figure 3 CTC Industry Value Chain Adapted from (Atkins et al., 2019; Luo et al., 2017) | 12 |
| Figure 4 Products from Coal Pyrolysis Adapted from (Malumbazo, 2016) | 16 |
| Figure 5 South African Coalfields (adapted from Snyman (1998) | 20 |
| Figure 6 Process Flow to Produce Coal Tar. | 21 |
| Figure 7 The SWOT Framework Developed from (Gürel, 2017; Porter, 1980; Serpa <i>et al.</i> , 2020)..... | 27 |
| Figure 8 The TOWS Matrix Developed from (Escalona <i>et al.</i> , 2022; Wehrich, 1982) | 28 |
| Figure 9 The PESTEL framework (redrawn from Rothaermel (2017))..... | 30 |
| Figure 10 Value Chain Analysis Matrix Adapted from (Porter, 1985) | 32 |
| Figure 11 Porter’s Five Forces Framework (Redrawn from (Grundy, 2006))..... | 34 |
| Figure 12 Industry Lifecycle Stages (Developed from Sabol <i>et al.</i> (2013))..... | 37 |
| Figure 13 Visualisation of a Research Approach. | 42 |
| Figure 14 Three Phase SLR Process (Albliwi <i>et al.</i> , 2014) | 43 |
| Figure 15 Selection Process Chart | 63 |
| Figure 16 Network Diagram Depicting Availability of CTC Industry Enablers..... | 1 |
| Figure 17 Network Diagram Depicting Opportunities in the CTC industry..... | 2 |
| Figure 18 Network Diagram Depicting Challenges in the CTC industry. | 3 |
| Figure 19 Coal-to-Carbon Industry's Porter's Five Forces Analysis | 10 |
| Figure 20 The Industry Stakeholders' Relationships | 31 |

LIST OF ABBREVIATIONS

| Abbreviation | Term |
|---------------------|--|
| AI | Artificial intelligence |
| CCS | Carbon capture and sequestration |
| CF | Carbon fibre |
| CTC | Coal-to-carbon |
| CTL | Coal to Liquid |
| CNT | Carbon nanotube |
| CNF | Carbon nanofiber |
| CO | Carbon monoxide |
| COP | Conference of parties |
| CO ₂ | Carbon dioxide |
| DC | Direct current |
| EAF | Electric arc furnace |
| EIA | Environmental Impact Assessment |
| ESG | Environmental, social and governance |
| FTS | Fisher-Tropsch |
| GDP | Gross domestic product |
| GHG | Greenhouse gas |
| H ₂ S | Hydrogen sulphide |
| IoT | Internet of things |
| Kt | Kilo tonnes |
| LCA | Lifecycle Assessment |
| MWCNT | Multi-walled carbon nanotube |
| NWU | North-West University |
| PAN | Polyacrylonitrile |
| PESTEL | Political, Economic, Social, Technological, Environment, and Legal |
| UNFCCC | United Nations Framework Convention on Climate Change |
| REC | Research Ethics Committee |
| R&D | Research and development |
| SDGs | Sustainable Development Goals |
| SLR | Systematic literature review |
| SWOT | Strengths, Weaknesses, Opportunities, and Threats |
| SWCNT | Single-walled carbon nanotube |

Chapter 1

INTRODUCTION

The chapter opens with an introduction to the research project, outlining its background and context. This sets the stage for identifying the research problem and opportunity that the study aims to address. The chapter further presents the research questions and research objectives that guide the investigation. Additionally, the significance of the study is highlighted, emphasizing its potential contributions and importance in the field of Industrial Engineering.

1 Introduction

1.1 Background

Coal is an abundant resource in South Africa (Eskom, 2021; Van Dyk *et al.*, 2006). The South African coal industry, according to Rademeyer (2021), is comprised of mainly four markets, the export market for international coal consumers, and three local markets: synthetic fuel producers, energy producers, and small industrial domestic consumers. Kalkuhi *et al.* (2019) point out that coal as a feedstock, not only constitutes a well-established, reliable technology for power generation, but it is also strongly interlinked with steel and cement production and has wider implications for industrial development.

It is universally known and widely acknowledged that coal consumption significantly contributes negatively to climate change. The combustion of coal accounts for about 50% of carbon dioxide emissions worldwide, which is a major greenhouse gas (GHG). As the world advocates for measures to mitigate the effects of GHG, the South African coal industry, much like the rest of the global coal industries, has been hampered by financial, and political pressures since the signing of the Paris agreement in 2015 (Parra *et al.*, 2021).

Rademeyer (2021) discusses the impacts of a global shift away from coal fuel and highlights the potential for subsequent deterioration in international coal trade on South Africa's coal market and economy. This is against the background of discussions on the role of coal in the future global energy mix. In a study by Rademeyer (2021) on the outcome for South African coal supply to the domestic market when faced with declining demand for exported coal, the result showed that the supply of coal for local power stations would decline when faced with a persistent decline in export demand. This is due to decreasing profits for mines, leading to the eventual closure of higher-cost mines. This result suggests that the global phasing out of coal could have significant implications for South Africa's energy security, as well as for coal mining sector employment.

The existing trends and market effects negatively affecting the coal sector are reinforced by the current pandemic. Parra *et al.* (2021) insist that the economic crisis following the COVID-19 pandemic will most likely result in a slow death of the coal industry unless national subsidies and public financing support are provided to this sector. Well-calculated and sustainable interventions should be sought out and implemented to avoid adverse effects on the industry.

The 26th conference of parties (COP 26) to the United Nations Framework Convention on Climate Change (UNFCCC) held in Glasgow adopted a commitment to limiting the carbon footprint without necessarily phasing out coal. New goals were set for countries to reduce further the use of coal

in applications that produces greenhouse gas emissions without carbon capture and sequestration (CCS) equipment. The COP 26 agreement to reduce coal power, or phase down use of unabated coal, coal burning without some form of carbon capture and storage, complicates the South African coal industry's energy mix even more.

Kalkuhi *et al.* (2019) observe that a major challenge for the developing world is to follow a feasible model of continued economic development that involves the abandonment of the use of coal. South Africa needs to ensure sustainable economic development despite the obligation to shift away from coal for energy generation. Developing countries heavily dependent on coal resources can explore new markets for coal in manufacturing carbon products of higher value (Andrews *et al.*, 2021). Understanding the status of the South African coal-to-carbon sector, through a qualitative study, could assist researchers, academia, industrialists, and policymakers with strategic decision making that can result in positive contributions to the economy.

Amidst all these challenges facing the coal industry, a market exists to obtain more value from coal by extracting the carbon and producing carbon-based products (Atkins *et al.*, 2019). The coal-to-carbon industry presents many opportunities in advanced markets for coal-derived products. The global market for coal to solid carbon products is currently estimated to consume between 300 and 400 million tons of coal per year, with chemicals, and fertilizers being the primary applications. Coal offers opportunities for both reducing the cost of manufacturing carbon products and, in many instances, providing a superior quality carbon feedstock. Coal is also less expensive (\$12-\$50/ton) in many advanced market applications than traditional feedstocks such as petroleum (\$400-\$500/ton) (Atkins *et al.*, 2019).

1.2 Research Problem

The coal industry is under significant challenges and pressures and is experiencing a decline of traditional coal markets, with current markets proving to be unsustainable. Interventions in the form of new, innovative markets for the coal industry are therefore required to revitalize and transform the industry. This poses a pressing challenge for stakeholders as they grapple with the prospect of a declining industry that has historically been a cornerstone of economic development for South Africa.

1.3 Research Opportunity

The novel markets offered by the coal-to-carbon industry offer an alternative solution. The opportunities presented by these markets are compelling, and therefore there is a need for a structured exploration of these opportunities. This study focuses on South Africa, a coal-

dependent developing country. The South African context is of interest as it has an excellent coal resource and a coal industry that has thrived or flourished previously.

1.4 Research Aim

This research aims to assess the feasibility of the coal-to-carbon industry in South Africa by exploring the market, technical, economic, environmental, and operational factors.

1.5 Research Questions

The research proposes to answer the following questions.

1. What is the current status of the South African coal-to-carbon industry?
2. What are the holistic feasibility barriers and enablers of the coal-to-carbon industry in South Africa?
3. What are the opportunities offered by the coal-to-carbon industry in South Africa?

1.6 Research Objectives

To achieve the study's aim and answer the research questions, the following objectives have been formulated.

1. To explore the status of coal-to-carbon products and technologies in South Africa.
2. To discover the feasibility barriers and enablers in developing valuable coal-based carbon products in South Africa.
3. To determine the opportunities for new products in the coal-to-carbon industry in South Africa.
4. To provide a summary of the feasibility factors and develop a stakeholder relationship diagram.

1.7 Significance of the Study

The coal industry holds a pivotal position in the South African economy. It makes a significant contribution to the country's gross domestic product (GDP), serves as a primary source of energy, and supports various sectors across South Africa. The diverse functions that coal fulfils within South Africa add significant value, and discontinuing its use could lead to adverse consequences. Consequently, conducting a study that focuses on this industry holds great economic importance not only for the industry itself but also for the broader national economy. To further substantiate the value of coal, Figure 1 depicts the market value in the South African export basket.

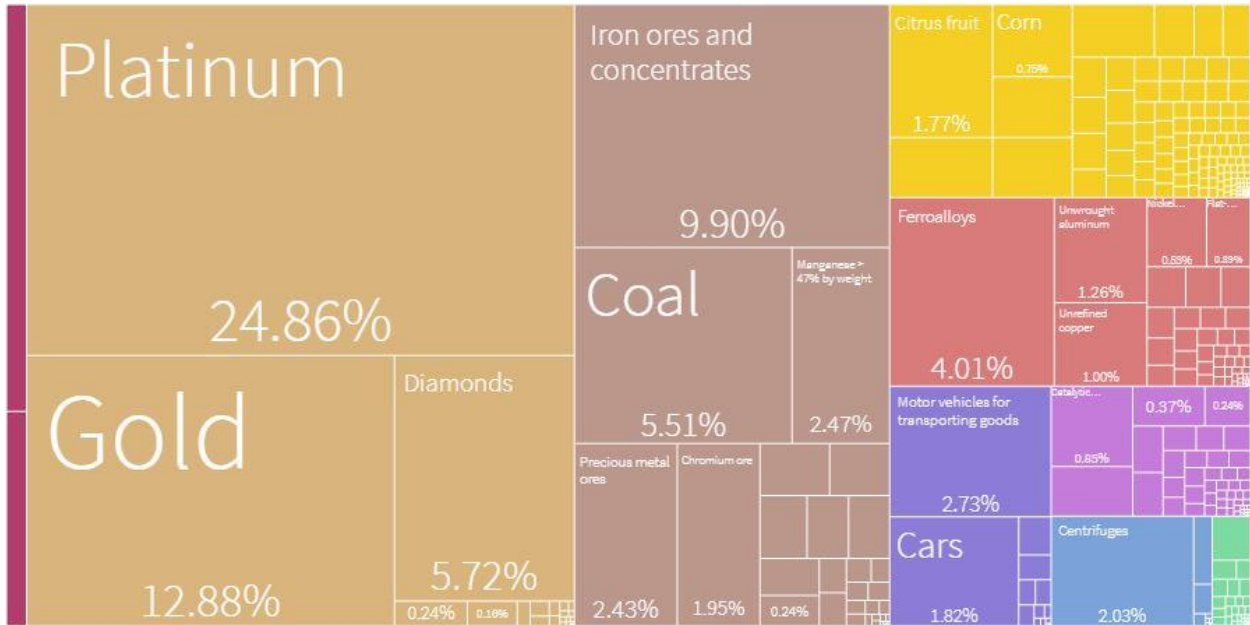


Figure 1 Atlas of Economic Complexity - South Africa

In addition, there are challenges currently facing the coal industry. These include global activities to tackle climate change, suggesting the phaseout of the use of unabated coal by leading coal-consuming countries. The coal industry suffers because of the advocacy for measures to combat the adverse impacts of climate change. At a time when the utilization of coal is under the spotlight globally, it would be worthwhile to look at solutions that can solve the challenges affecting the industry.

The new markets offered by the coal-to-carbon (CTC) industry provide novel opportunities for the coal industry. The coal-to-carbon industry has the potential for high margins on high-value products. The opportunities can create business opportunities, new jobs, and new industries related to the CTC industry. Therefore, by exploring these opportunities, the study will open a wide area of interest to industrialists, researchers, and policymakers.

1.8 Chapter Summary

The study refers to the "coal-to-carbon industry" as the conversion of coal or its precursors into high-value non energy carbon products. The focus of the study (unit of analysis) is the CTC industry in South Africa. The study focuses on high-value carbon products from coal within the carbon material groups. It also explores and discusses the technologies used in the manufacturing of these carbon products. The study is limited to the conversion capabilities and not necessarily the sourcing of coal or preparation and beneficiation of raw coal.

Against the background presented in this chapter, the purpose of this study is to explore the feasibility of the South African CTC industry. The present chapter has introduced and outlined the scope of the study. To provide additional context, the subsequent chapter will review pertinent literature pertaining to the subject matter of this investigation.

Chapter 2

LITERATURE STUDY

This chapter provides a synopsis of the current state of scholarship on the coal-to-carbon industry, aiming to provide a thorough grasp of the topic. It surveys various feasibility types and explores the strategic business analysis tools, explaining the rationale behind the selection and application of those utilised in this study. The inclusion of these tools broadens the study's context and scope, thereby enriching the depth and breadth of the research inquiry.

2 Literature Study

2.1 Introduction

The literature review provides an overview of the coal-to-carbon industry. The review complements the context of the study. All pertinent topics covered in this chapter are compartmentalized using the theme analysis encapsulated in Figure 2.

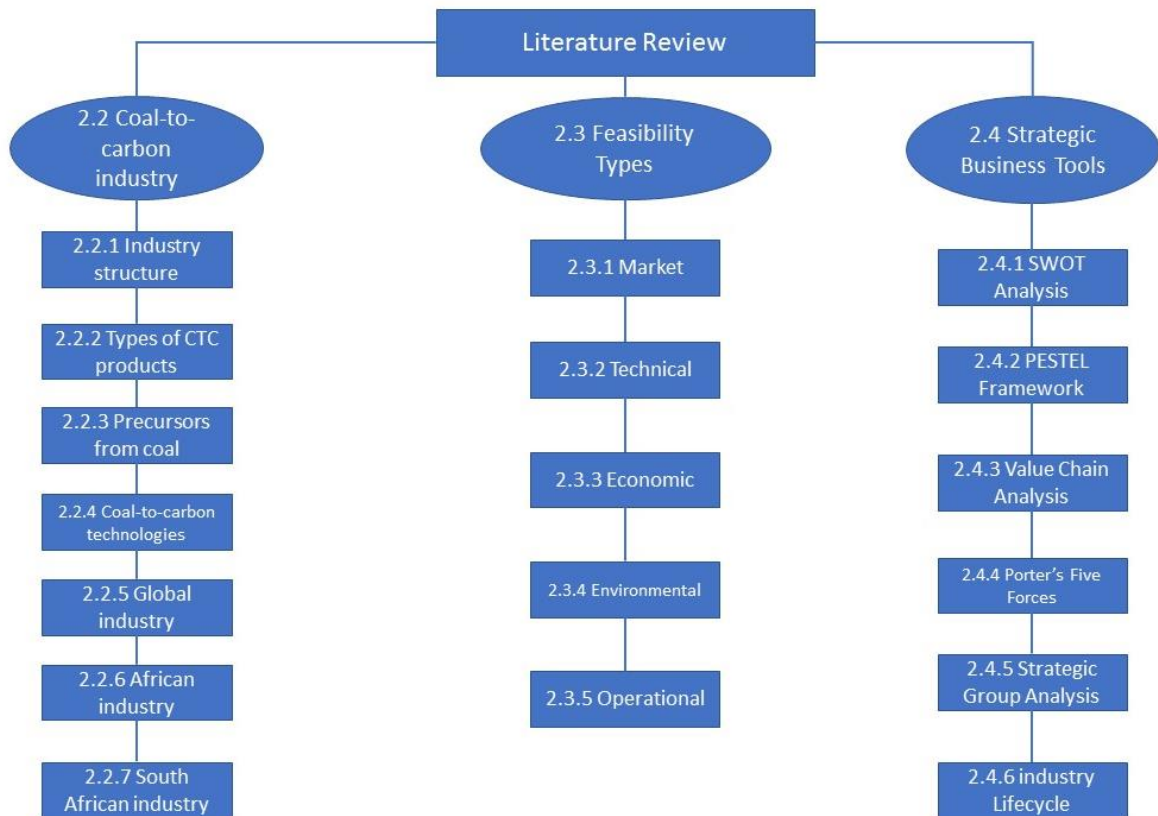


Figure 2 Theme Analysis

Initially, the relevant subject matter is introduced. The coal-to-carbon industry is discussed leading to the feasibility types and strategic business analysis tools.

2.2 The Coal-to-Carbon Industry

The coal-to-carbon industry is a subsector of the coal chemical industry. Regarding the coal conversion industry, a report by Reid (2021) indicates that there is a significant and increasing global interest in researching valuable and innovative products within this sector. The sector focuses on non-energy products from coal. Reid (2021) points out that the most significant and commercially valuable products from coal include carbon fibres, activated carbon, electrode

materials, pitch and chemicals from gasification processes, rare earth elements, and carbon nanomaterials.

The coal-to-carbon (CTC) industry converts coal or coal precursors into useful and valuable carbon products. The secondary sector (conversion of beneficiated coal into final products) is a niche sector, as it is still developing or under feasibility phase globally (Atkins *et al.*, 2019).

The industry is relatively new, with several technologies currently undergoing development and testing. Nonetheless, certain technologies, such as the production of the carbon precursors, constitute a mature industry, but the technologies for the production of the final carbon products are still emerging (Reid, 2018). The sector utilizes diverse methods to generate value-added carbon products from coal, integrating a range of technologies to produce these carbon-based products.

2.2.1 Industry Structure

The industry structure for coal-to-carbon can vary depending on the specific product being produced and the region in which the production takes place. Coal is the major building block of a chain of high-value carbon products (Savon & Zhaglovskaya, 2019). It also plays a significant role as a contributor to the carbon product value chain.

Some of the common components of the industry structure are:

1. Coal mining
2. Coal processing
3. Carbon conversion
4. Production manufacturing
5. Distribution and sales

The high value carbon products find themselves in different industries in various applications. Table 1 depicts each carbon product, as well as the industries and applications in which it is found.

Table 1 Coal-to-Carbon Industry Structure

| Product | Industry | Applications | Reference |
|------------------------------------|--------------------------------|--|---|
| Activated carbons | Chemical/ Pharmaceutical | Purify solutions of organic molecules Extract pharmaceuticals | (Campbell <i>et al.</i> , 2012; Sevilla & Mokaya, 2014; Suzuki, 1994) |
| | Petrochemical | Solid adsorbent, catalyst support | |
| | Food & beverages | Decolourization Removing dissolved organic compounds | |
| | Mining | Precious metal recovery | |
| | Automotive industries | Control emissions, Remove volatile organic compounds | |
| | Water treatment | Filtration Removing organic chemicals | |
| Carbon fibre and composites | Medical and optical industries | Tactical ladders Drones Construction materials | (Inagaki, 2000; Prashanth <i>et al.</i> , 2017) |
| | Manufacturing | Robotics Sporting goods Automotive body parts | |
| Carbon nanomaterials | Electronics & Semiconductors | Energy storage Device modelling Automotive components Marine vessel structures Athletic equipment Filtration systems Coatings Electromagnetic shields | (Atkins <i>et al.</i> , 2019; Reid, 2018; Speranza, 2021) |
| | Energy & Storage | Energy storage systems | |
| | Chemical Material & Polymers | Cosmetics Electrochemical sensing systems | |
| | Medical | Biomedical imaging Biosensors | |
| | | | |

| Product | Industry | Applications | Reference |
|--------------------------|------------------------------------|--|------------------------------|
| | Structural Composites Applications | Tissue engineering Cancer therapy | |
| Carbon black | Manufacturing | Manufacturing tires Plastics Mechanical rubber goods, Printing inks, and toners Insulating wires and cables Adhesives, and paints | (Kühner & Voll, 1993) |
| Carbon electrodes | Metallurgy | Electric arc furnaces | (Jones <i>et al.</i> , 2011; |
| | Chemical industry | Electrodes for batteries | McCreery & Cline, 2018) |
| | Electrochemistry | Electrodes for electrolysis | |
| Carbon foams | Military | Stealth technology | (Inagaki <i>et al.</i> , |
| | Aerospace | Aircraft and ship insulation | 2015) |
| | Commercial industries | Wall panels | |

2.2.2 Types of Coal-to-Carbon Products

Coal is well suited to produce various high-value carbon products because of its inherent carbon content. Examples of high-value carbon products include activated carbon, carbon fibre and composites, carbon black, carbon foam, and carbon nanomaterials such as fullerenes, carbon nanotubes (CNTs) including single-walled (SWCNTs) and multi-walled (MWCNTs), graphene and its derivatives like graphene oxide, nano diamonds, carbon quantum dots, crystalline diamond, and diamond-like carbon. Additionally, carbon and graphite electrodes are also considered high-value carbon products (Atkins *et al.*, 2019; Hoang *et al.*, 2018; Reid, 2021).

Carbon products may be manufactured from various sources of carbon, renewable and non-renewable, that include coal, oil, natural gas, and biomass materials (Bozell, 2008; Reid, 2018; Savon & Zhaglovskaya, 2019). This study focuses on coal as the source of carbon for the carbon products. With coal as the feedstock for carbon product manufacture, it is part of the value chain from coal mining, preparation, and transportation to chemical plants where there are various industrial processes. The section that follows will provide a review of the most common high value carbon products. Figure 3 shows the simplified coal-to-carbon industry value chain.

1. Carbon Fibre

Carbon fibre (CF) is an elongated and slender material, with a diameter of around 0.01 mm, primarily made up of carbon atoms (Reid, 2018). Carbon fibre stands out as a compelling material suitable for applications demanding elevated tensile strength and low weight, surpassing steel in these aspects. Additionally, it proves advantageous for applications requiring resistance to chemical action and high temperatures, demonstrating corrosion resistance along with proficient electrical and thermal conductivity (Gagarin *et al.*, 2020). CF has other advantages, chemical inertness, and thermal conductivity, that makes it durable and resistant to corrosion, and allows for effective heat management.

Carbon fibre can be classified according to properties (modulus, and strength), precursor fibre materials, and final heat treatment temperature (Bhatt & Goe, 2017). The study focuses on pitch based CFs which can either be isotropic or anisotropic (mesophase) pitch based CFs (Inagaki, 2000).

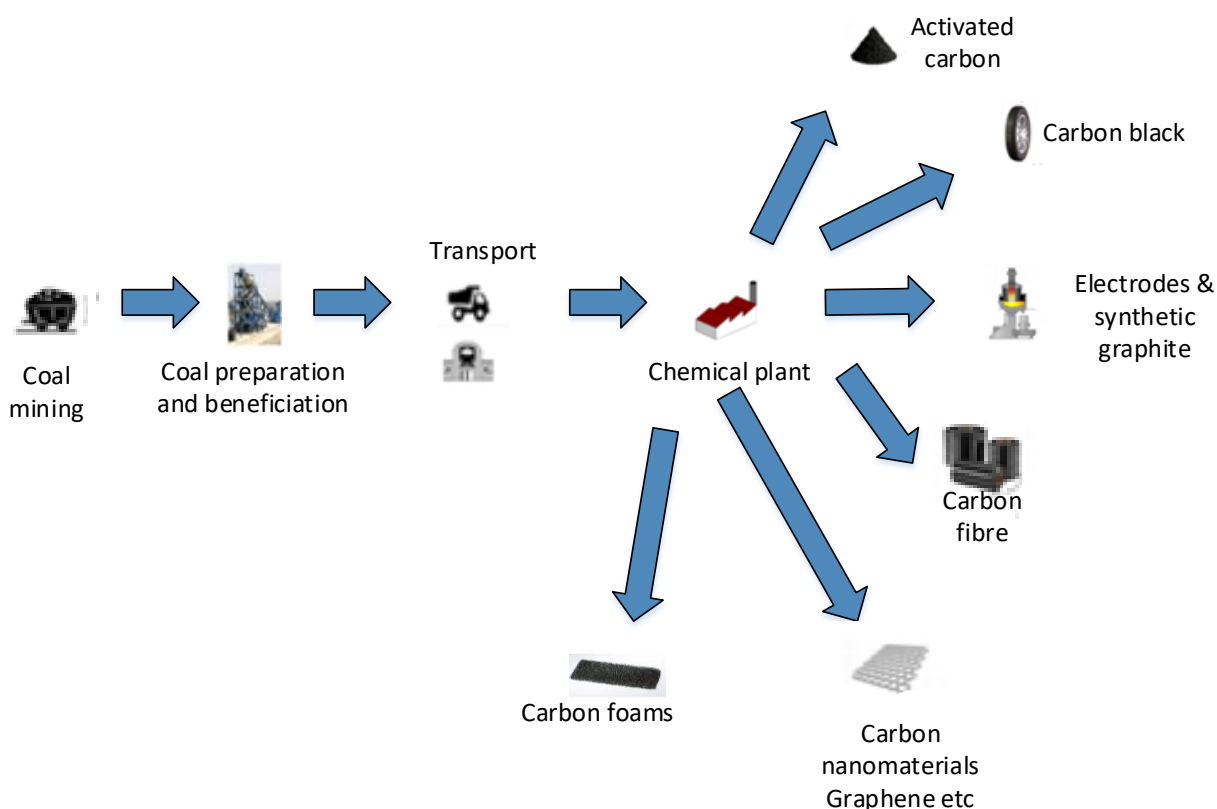


Figure 3 CTC Industry Value Chain Adapted from (Atkins *et al.*, 2019; Luo *et al.*, 2017)

2. Activated Carbon

Activated carbon is a variation of carbon characterized by a large surface area that allows for the physical adsorption of liquids and gases. It is also referred to as activated charcoal or activated

coal. Activated carbon finds applications in water purification and mercury adsorption in the precious metal extraction industry (Campbell *et al.*, 2012). It has more applications that include the elimination of impurities from the air, and flue gases treatment.

3. Carbon Black

Carbon black is a form of para-crystalline carbon characterized by a substantial ratio of surface area to volume. Its applications are mainly in tyre manufacturing as a reinforcement, as a pigment in black plastics, the ink industry, paint, lacquers, and enamels. Kühner and Voll (1993) differentiate carbon black from other carbon products because of its bulk density, which makes it difficult to transport.

4. Carbon Foam

Carbon foam is a transparent low-density graphite carbon material with open-pore construction with interconnected macro pores (Inagaki *et al.*, 2015). Carbon foam is used in ships for fireproofing, as the core material in a structural composite, in airplanes as a firewall, and in automobiles as energy absorbing structural components.

5. Carbon Nanomaterials

Carbon nanomaterials are a novel group of materials that includes fullerenes, carbon nanotubes (CNTs), graphene and its derivatives, graphene oxide, Nano diamonds, carbon quantum dots, crystalline diamond, and diamond-like carbon (Speranza, 2021). A CNT, or carbon nanotube, can be defined as a cylindrical structure formed by seamlessly rolling a sheet of graphene, exhibiting an exceptionally high length-to-diameter ratio (Moothi *et al.*, 2012). Applications for carbon nanomaterials include solar cells, displays, barrier materials, super capacitors, inks, advanced filtering, and silicon alternatives for memory chips (Atkins *et al.*, 2019; Reid, 2018).

6. Carbon Electrodes

Carbon electrodes are electrical conductors made from carbon. They are used in aluminium smelting as anodes and cathodes, and in electric arc furnace (EAF) steelmaking as electrodes. There are also classified as amorphous and graphite furnace electrodes used in metallurgical applications (Thethwayo & Steenkamp, 2020). In South Africa, a major application of carbon and/or graphite electrodes is in direct current (DC) arc furnaces (Jones *et al.*, 2011). The DC arc furnaces find applications in various metallurgical systems, in steel scrap melting, in reductive smelting of ore fines and other specialised industrial smelting applications.

2.2.3 Precursors from Coal

There are precursors derived from coal that are starting materials to produce carbon products. They include:

1. Coal tar pitch
2. Coke/chars
3. Hydrocarbons
4. Oil distillates

Derived from coal through the carbonization process in the manufacturing of metallurgical coke, pitch serves as a valuable by-product. It stands as a crucial source of aromatic hydrocarbons, essential as a raw material in the production of several carbon-based materials.

Coal tar pitch is a precursor employed in the production of advanced carbon materials (carbon fibres and composites, resins, carbon black, and nano carbons); char produces activated carbon; and volatile coal gases produce hydrocarbons, nano products and carbon materials (Reid, 2021). The tar from the carbonization process is presently employed in the manufacturing of electrodes or synthetic carbon materials as well as in carbon composites technology (Mikociak *et al.*, 2014).

Considerable research has delved into utilizing coal as a primary source for generating carbon nanotubes, as highlighted by Moothi *et al.* (2012). Moothi *et al.* (2012) point out heavy hydrocarbons, tars, chars, and coke as secondary products from coal used in the synthesis of carbon nanotubes. Coal tar pitch (pitch process) is believed to be a more economical route to carbon fibre than other precursors, e.g., PAN (Reid, 2018).

Coal tar is a complex mixture, rich in creosote and nitrogen-containing compounds, particularly in its lighter oil fraction. This mixture is a source of carbon precursor derived from the distillation and extraction of coal tar (Huang *et al.*, 2021). Anthracene oil, another component of coal tar obtained by distillation has been used as raw material to produce carbon precursors (González *et al.*, 2021).

2.2.4 Coal-to-Carbon Technologies

The main coal utilization technologies used worldwide in the production of precursors for coal based carbon products are carbonization and coal-liquefaction technologies (Keboletse *et al.*, 2021). Coal conversion technologies are well positioned to produce both activated carbon and pitch carbon fibre, which are crucial primary high-value carbon products for a CTC products industry (Reid, 2018).

1. Coal Liquefaction

The coal liquefaction process transforms coal into liquids through two distinct paths.

Direct liquefaction, also referred to as hydrogenation, entails the direct production of liquid fuels from coal using a hydrogen donor solvent (Speight, 2013). The process mainly produces fuels, but it is also able to produce pitches and coke precursors (Dadyburjor *et al.*, 2004)

The indirect liquefaction process involves liquefying coal through the Fischer–Tropsch (FTS) process. In this method, the synthesis gas produced from the gasification process is utilized to convert into liquid hydrocarbons (Speight, 2013).

2. Coal Gasification

The process involves coal reactions with air, oxygen, steam, or their mixtures resulting in the production of a combustible gaseous fuel termed "synthesis gas" (Speight, 2013). The process has revolutionized the production of high-quality liquids and gases. The primary chemical reactions break and oxidize hydrocarbons to give a product gas of carbon monoxide CO, carbon dioxide CO₂, hydrogen H₂, and water. Other significant parts are hydrogen sulphide (H₂S), various compounds of sulphur and carbon, ammonia, light hydrocarbons, and heavy hydrocarbons (tars).

Dried coal breaks down into volatile compounds such as ash, charcoal, moisture, and tar during the pyrolysis reaction. The quantity and makeup of volatiles generated are determined by the volatile characteristics of the coal, as well as the temperature and pressure of the pyrolysis reaction. Methane, ethane, carbon monoxide, carbon dioxide, hydrogen, ammonia, and hydrogen sulphide are the primary components of these volatiles (Otoshi *et al.*, 2021).

3. Carbonization

Carbonization is the commercial scale thermal degradation of coal at high temperatures up to 1500°C (Speight, 2013). Carbonization is a term used for the pyrolysis of coal in the production of coke (Dadyburjor *et al.*, 2004). Coal tar, a by-product of metallurgical coke making, is used to make pitch. The coal tar pitch is the major constituent in the manufacture of various high value carbon materials used in different industries (Kuznetsov *et al.*, 2015). Carbonization is principally the process of producing carbon-containing residues by the thermal break down of organic matter with the concurrent removal of distillates. The products of pyrolysis are tar, light gases, and char (Malumbazo, 2016). Figure 4 shows products from coal pyrolysis.

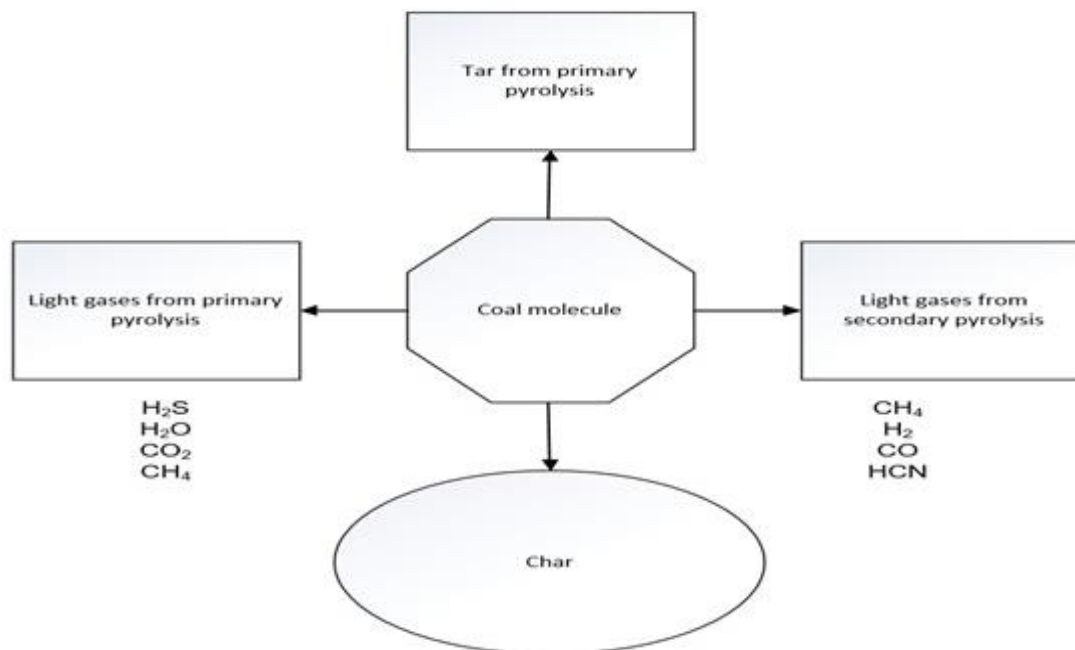
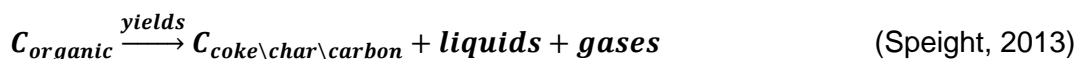


Figure 4 Products from Coal Pyrolysis Adapted from (Malumbazo, 2016)

The following chemical equation shows the reaction that happens when a coal molecule breakdown.



2.2.5 The Global Coal-to-Carbon Industry

Globally the CTC industry is a rapidly growing industry (Reid, 2021), it is expanding in research and development, as companies seek to create new and innovative ways to utilize coal as a feedstock for high-value carbon products. The leaders in this industry include China, which has vast coal resources, and the United States (US) which has invested significantly in the development of this industry.

China has been a dominant player in the coal industry for many years, and its coal-to-carbon industry involves various processes to convert coal into different carbon-based products. One of the primary products from this industry is metallurgical coke, which is crucial for the manufacture of iron and steel. The coal-to-carbon industry in China also produces carbon products like activated carbon, carbon black, and have invested in the production of carbon fibres utilized in a variety of applications, including automotive, aerospace, and electronics (Chen, 2016; Park, 2015).

China's coal-to-carbon industry has faced challenges in terms of environmental impact, as coal-based processes are associated with higher greenhouse gas emissions and air pollution. However, the Chinese government has been investing in research and development to improve the efficiency and environmental sustainability of these processes (Ma *et al.*, 2022).

The United States has historically been a major coal-producing nation, and its coal-to-carbon industry has played a vital role in various sectors. While coal consumption has declined in recent years due to increasing concerns about environmental impacts and a shift toward cleaner energy sources, some coal-based carbon industries continue to operate (Gagarin *et al.*, 2020).

In the United States, coal is used to produce metallurgical coke for the steel industry (Babich & Senk, 2019; Diez *et al.*, 2002). Additionally, coal-derived carbon products are employed in areas such as activated carbon for water purification and air filtration, carbon black for rubber and tire manufacturing, and carbon fibres used in aerospace, automotive, and sports equipment (Andrews *et al.*, 2021).

Like China, the coal-to-carbon industry in the United States has faced pressure to reduce its environmental footprint and transition toward cleaner technologies. As the country emphasizes a move toward sustainable energy and reducing carbon emissions, there has been increasing interest in carbon capture and utilization technologies to mitigate the environmental impact of coal-related industries.

Australia is another major producer and exporter of coal, and the country has also been exploring coal-to-carbon technology as a way to diversify its coal industry (De Beer *et al.*, 1998). The country has excellent coal resources and infrastructure, but there is a lack of carbon manufacturing industries. Most of the country's coal is exported to other countries. Much like South Africa, it has carbon precursor producing facilities like coal tar and carbon black feedstocks, but it lacks advanced manufacturing capability (Stanger, 2019).

There has been interest in producing high-value carbon fibres, which can be used in a range of high-tech applications. In recent years, several Australian companies have begun to develop coal-to-carbon technology, including the use of pyrolysis to produce high-quality carbon products (Uddin *et al.*, 2018). However, the industry is in its early stages, and there are concerns about the environmental impact of the process.

Japan is another major importer of coal, and the country has been exploring the use of coal-to-carbon technology to produce high-quality carbon products for use in electronics and other industries.

Global literature provides insights into the barriers, enablers, and opportunities in the coal-to-carbon industry. Comparative studies highlight best practices, technological advancements, and policy frameworks adopted by countries including the United States, China, and Australia. These examples can inform South Africa's approach to addressing barriers, leveraging enablers, and capitalizing on opportunities.

2.2.6 African Industry

There are potential opportunities for the development of the CTC industry in Africa, particularly in the production of advanced materials for high-tech industries. With the right infrastructure and regulatory framework in place, African countries could potentially leverage their coal reserves to create new economic opportunities and reduce their dependence on imported carbon products.

Coal conversion into valuable carbon products is still a concept to be adopted in Africa at large. African countries with coal reserves, such as Botswana and Mozambique have invested in the production of diesel and gasoline fuels from coal using the coal to liquid (CTL) technology (Reid, 2021) which can also be useful in the CTC industry. Zimbabwe has the potential to take up the CTC industry as it produces carbon precursors, but it will need to invest in the technologies needed to produce the carbon products.

Some African countries, such as South Africa, Zimbabwe, and Botswana, have significant coal reserves and have already established coal industries. These countries are also starting to explore opportunities in the CTC industry, particularly to produce carbon fibres and other advanced materials.

Coal tar pitch a precursor in the manufacture of valuable carbon products is produced in African countries. The production and processing capacity of tar in the various countries according to (Stompel, 2018) are as follows. In Egypt, the production of tar amounts to 5 kilo tonnes (kt), but the real processing capacity has not been specified. However, the tar processing capacity in Egypt is reported to be 50 kilo tonnes (kt). Moving to South Africa, the country produces 95 kilo tonnes (kt) of tar, with a tar processing capacity of 200 kilo tonnes (kt) by ArcelorMittal. The actual processing in South Africa is reported to match its production, standing at 95 kilo tonnes (kt). For Zimbabwe, the production of tar has not been specified, and the tar processing capacity is reported to be 50 kilo tonnes (kt) by ZimChem. However, the real processing capacity in Zimbabwe has not been provided (Stompel, 2018).

However, there are some challenges that need to be addressed in developing the CTC industry in Africa. These include:

1. Lack of infrastructure: Many African countries lack the infrastructure needed to support the establishment and growth of a CTC industry, such as access to reliable sources of electricity and water.
2. Environmental concerns: The coal-to-carbon process can be energy-intensive and produce significant amounts of greenhouse gas emissions, which can have negative environmental impacts.
3. Regulatory barriers: Some African countries may not have a favourable regulatory environment for the establishment and growth of a CTC industry, which could make it difficult for companies to invest in the sector.

2.2.7 South African Industry

South Africa has large proven coal reserves and resources (Eskom, 2021; Van Dyk *et al.*, 2006). However, the South African coal is generally regarded as low-grade by international standards. The typical coal produced in South Africa has an ash content of between 20% and 30% while high grade bituminous coal has a low ash content of less than 7% (Obeng-Odoom, 2017).

Coal produced in South Africa consists mainly of bituminous steam coal found in the Mpumalanga and Northern Provinces which exists in seams up to several metres thick, and with only 1.2% anthracitic coal found in KwaZulu-Natal with deposits in relatively thinner seams (Cairncross, 2001). The best quality coals are found in the central highveld basin.

Most of the South African coalfields have undergone considerable exploration and exploitation, while the remaining 70% of the coal reserves are in Limpopo (Hancox & Götz, 2014). The study is interested in coking coal coalfields, and the Limpopo coalfields stands out as they contain large amounts of coking coal that can be used to make carbon-based products.

South Africa's coking coal resources include the Limpopo (Tuli) coalfield, the Waterberg Coalfield, and the Vryheid Coking Seam in Utrecht, which produces semi-soft coking coal suitable for use in metallurgy and carbon products (Jeffrey, 2005). The Klip River Coalfield, Utrecht Coalfield, and Vryheid Coalfield in KwaZulu-Natal, as well as the Soutpansberg Coalfield in central Witbank are sources of coking coal. Waterberg coals and the Soutpansberg Coalfield, with the Tshikondeni currently exploiting the resources in the area, are among the remaining coalfields that produce coking coal, as is the Vryheid Coalfield. Figure 5 depicts the 19 coalfields designated by South Africa in its various areas.

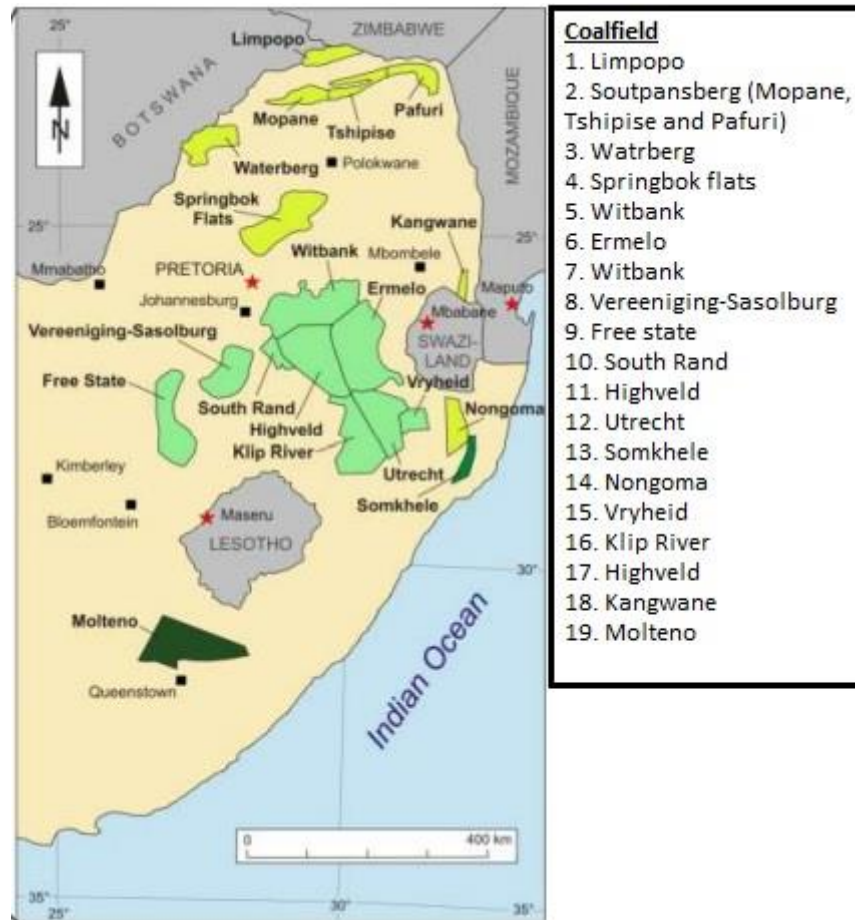


Figure 5 South African Coalfields (adapted from Snyman (1998))

2.2.8 Current Practices and Operations in the South African Coal-to-Carbon Industry

The coal processing industry in South Africa involves several stages, including exploration, mining, processing, and transportation. The goal of coal processing is to remove impurities and prepare the coal for use in various applications. The largest coal mining companies in South Africa include Anglo American, BHP Billiton, Exxaro Resources, Glencore, and Sasol.

South Africa converts processed coal into various forms of carbon using different methods. The exact conversion process will depend on the specific product being produced. In South Africa, ArcelorMittal has been involved in the production and utilization of coal tar. Coal tar or bituminous coal tar is a by-product of the coking process used in the production of coke, which is a crucial ingredient in steelmaking. During the coking process, coal is heated in the absence of oxygen to produce coke and various by-products, including coal tar. Coal tar can be used in various applications, such as road construction, roofing materials, surface coatings, and as a feedstock to produce chemicals. The specific utilization and value-added products derived from coal tar in ArcelorMittal's operations in South Africa varies. Figure 6 shows a basic process flow to produce coal tar.

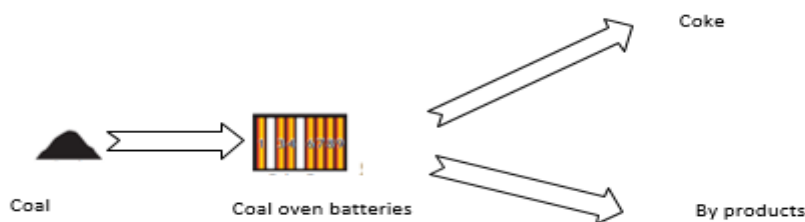


Figure 6 Process Flow to Produce Coal Tar.

ArcelorMittal operates DR Otto twin flue under jet type batteries. ArcelorMittal South Africa Newcastle Works has four batteries of coke ovens, each with 50 ovens in a battery (Arcelormittal, 2021). Dr. Otto's gas purification and by-product factory generates crude tar, crude benzol, ammonium sulphate, and sulfuric acid. The crude tar produced can be processed in a tar refining plant to produce a variety of oils and pitch a precursor in high value carbon products.

The carbonization plants produce coal tar pitch a by-product in the production of metallurgical coke for steel industries. The use of the coal tar pitch produced requires a pre-processing to adapt its composition and characteristics for the different advanced carbon products that includes carbon fibres, carbon composites and carbon graphites (Mikociak *et al.*, 2014).

South Africa has been using the liquefaction technology since the 1950s, when Sasol established the Sasol plant in Sasol Burg. Sasol manufactures high quality carbon-based products using coal from their Carbo Tar Plant. The materials find their way into designated speciality markets that includes the manufacture of graphite electrodes, cathode blocks and feedstock to produce graphite artefacts (Sasol, 2021).

According to L. Sima (2013) the pitch from Sasol has the following characteristics

1. Extremely high oxygen content
2. Significant aliphatic content
3. Low polycyclic aromatic hydrocarbons (PAHs)

From the study they pointed Sasol pitch as a potential precursor of carbon materials for different energy storage systems that is Li-ion batteries or super capacitors. The production of carbon based high value-added materials, such as carbon fibres and composites, need commercial pitches pre-treated to enhance certain of their features, such as boosting carbon output while preserving a reasonably high fluidity (L. Sima, 2013).

South Africa also produces carbon black. Coal tar distillates are used in the production of carbon black in South Africa. A carbon black plant in Port Elizabeth produces carbon black through the furnace black process (Yuriy Lozynskyy, *et al.*, 2014). The furnace black process, which is continuous, uses the principle of oxidative decomposition. It is operated in closed reactors where highly turbulent flows prevail due to high flow velocities.

2.2.9 Research and Development

The literature survey reveals a robust environment of research and development in South Africa based on carbon nanotubes and other carbon nanomaterials. Many academic institutions, notably the University of Johannesburg, Tshwane University of Technology, the University of KwaZulu-Natal at Westville, and Vaal University of Technology, are actively involved in pioneering research in this sector. Furthermore, prestigious research institutes such as the Council for Scientific and Industrial Research's Centre for Nanostructured Materials and MINTEK make major contributions to the advancement of knowledge in this subject.

Coville *et al.* (2011) underscore the critical responsibilities that these institutions and research organizations play, further substantiating their involvement in cutting-edge research activities. Furthermore, Sabi Nano Pty Ltd, a well-known South African business specializing in the production of carbon nanotubes and other carbon nanomaterials, demonstrates the country's leadership in this field.

The literature continually underlines the importance of these research activities and the existence of a prominent manufacturer in South Africa's carbon nanotube and carbon nanomaterials ecosystem. This thriving ecosystem demonstrates the country's dedication to pushing the boundaries of innovation and technology in this crucial field of research.

2.3 Feasibility Types

Feasibility studies are conducted to ascertain the practicality and viability of a given project, plan, or business proposal. There are various types of feasibility studies, each of which focuses on a different component of a project. The existing literature on feasibility studies is scattered across different academic fields (McLeod, 2021). To provide a comprehensive assessment of the South African CTC industry, the following feasibility types are reviewed and applied to the study.

2.3.1 Market

Market feasibility plays a crucial role in establishing the viability of any project. This type of study evaluates whether there is a demand for the product or service in the target market. The market

feasibility key objectives are to have a full understanding of the market, market size, competitors, suppliers, barriers, opportunities and determine if enough demand exists to make the business successful (Winston *et al.*, 2013). It is a means for understanding the market environment and it helps identify opportunities.

2.3.2 Technical

Technical feasibility evaluates the practical aspects of implementing a project. It refers to the feasibility of a technological solution, considering practicality, technical resource availability, and skill accessibility. The aim of the technical feasibility phase is to validate the performance of the product and ensure that there are no hindrances in the production process.

Technical feasibility involves three critical aspects: technology assessment, resource availability, and infrastructure requirements. It is essential to evaluate the existing technologies and their suitability for the project, considering how technological advancements may influence feasibility. Ensuring the availability of essential resources, including raw materials and equipment, is a fundamental consideration. The assessment of infrastructure requirements is crucial, focusing on factors such as facilities and utilities, to ensure compatibility with the chosen technology.

2.3.3 Economic

Economic feasibility focuses on the financial viability of a project. A measure of the profitability of a project or solution. The economic feasibility step of business development is a company's cost cover finance based on all costs associated with developing a product from an idea to the market and generating enough sales to cover the debt or investment. The cost required and the value to be attained from the venture are leading criteria for a feasibility study.

The economic feasibility assessment will analyse sources, the production costs, the cost of implementing the system, annual costs of operation, and cost benefit analysis. The investment decisions criteria choices include the net present value, internal rate of return, benefit-cost ratio and net terminal value (Mishan & Quah, 2020).

Environmental, social and governance (ESG) reports, and carbon tax aspects are closely tied to a company's economic performance, as they influence compliance costs, operational efficiency, access to capital, risk management, and market positioning. By addressing their environmental impacts and sustainability practices, companies can mitigate economic risks and leverage economic opportunities, ultimately contributing to both their financial health and environmental responsibility.

2.3.4 Environmental

Environmental feasibility involves examining the project's impact on the natural environment. The environmental viability of the business is pivotal to the success of the (CTC) industry. The analysis of the viability of the industry from an environmental perspective, categorising potential issues and threats to the running of the business. It investigates solutions and mitigative measures to the environmental issues. It examines the potential environmental impact of the project and whether it complies with environmental regulations and sustainability goals.

Key considerations include Environmental Impact Assessment (EIA), Sustainable Development Goals (SDGs), and Lifecycle Assessments (LCAs). Understanding and adhering to environmental regulations and standards is imperative. Local and national government publications and reports often provide information on these regulations.

2.3.5 Operational

Operational feasibility focuses on the practical aspects of running a project. This type of feasibility study focuses on the operational aspects of the project. It assesses whether the project can be effectively and efficiently managed and whether the organization has the necessary resources and expertise to carry it out. Managing the supply chain effectively is a key operational aspect as well ensuring access to skilled labour and managing the workforce is vital. Efficient logistics and distribution networks are crucial for operational success.

2.4 Overview of Strategic Business Analysis Tools

Strategic business analysis is a process of evaluating an organization's internal and external factors to understand its current state, identify opportunities and challenges, and develop strategies to achieve its goals. It involves examining various aspects of the business, including its resources, capabilities, market dynamics, competitive landscape, and industry trends (Fleisher & Bensoussan, 2003; Gürel, 2017).

Industry analysis, specifically, is a subset of strategic business analysis that focuses on understanding the dynamics and trends within a specific industry. It involves examining factors such as market size, growth rate, competition, customer preferences, regulatory environment, and technological advancements. Industry analysis provides insights into the competitive forces and market conditions that shape an industry's attractiveness and competitiveness (Ketchen Jr *et al.*, 2004).

There are several business theories and techniques that can be used to conduct an industry analysis. Some of the most used theories and techniques include SWOT Analysis, PESTEL Analysis, Value Chain Analysis, Porter's Five Forces, Strategic Group Analysis, and the Industry Life Cycle. The purpose of conducting strategic business analyses include but not limited to the following:

- **Market Analysis:** For the CTC industry; it is critical to understand the demand for carbon products, both domestically and internationally. Analyse market trends, growth potential, competitor landscapes, and customer preferences to assess whether products derived from coal-to-carbon processes have a viable market.
- **Financial viability:** Evaluate the project's financial components, such as launch costs, operational expenses, revenue predictions, and prospective profits. This analysis determines if the project can create positive cash flow and attain long-term profitability.
- **Technical Feasibility:** Assess the technical aspects of coal-to-carbon conversion. Examine the readiness, scalability, efficiency, and potential problems of the technology. This assessment verifies that the necessary technology is available and capable of satisfying production expectations.
- **Availability of Resources:** Examine the availability of coal resources, infrastructure, and skilled labour for the project. Consider aspects such as availability to coal reserves, transportation networks, electricity supply, and carbon conversion technology knowledge.
- **Regulatory and Environmental Compliance:** Investigate the regulatory environment and environmental consequences of coal-to-carbon processes. Consider permits, licenses, pollution laws, waste management, and sustainability standards. Compliance is critical for avoiding legal problems and public reaction.
- **Risk Assessment:** Identify potential risks and uncertainties that could jeopardize the success of the project. Financial, operational, technological, market-related, and geopolitical risks are all included. Create mitigation measures to address and mitigate these hazards.
- **Strategic Alignment:** Ensure that the coal-to-carbon industry aligns with the overall strategic aims and objectives of the firm. Examine how the project fits into the existing portfolio of the organization and how it contributes to long-term growth and sustainability.
- **Stakeholder Engagement:** Identify key stakeholders, such as government agencies, local governments, environmental organizations, and investors. Examine their interests, concerns,

and potential impact on project outcomes. Creating successful communication and engagement methods is critical for gaining support and reducing resistance.

- **Economic Impact:** Assess the economic impact of the CTC industry on the South African economy. This involves analysing job creation, municipal development, tax income, and overall economic growth contribution.
- **Lifecycle Analysis:** Consider the full coal-to-carbon process's lifecycle, from raw material extraction to end-product disposal. To guarantee that sustainable practices are implemented, assess the environmental, social, and economic repercussions at each stage.
- **Scenario Planning:** Create numerous scenarios that take into consideration changing market conditions, technology breakthroughs, and regulatory changes. This aids in the development of a resilient business model capable of adapting to changing conditions.
- **Feasibility Report:** In a detailed feasibility report, summarize the conclusions of the strategic business assessments. This study is intended to help stakeholders and investors make decisions by providing a comprehensive picture of the project's potential benefits, risks, and overall viability.

2.4.1 SWOT Analysis

SWOT analysis is a method for assessing a company's competitive situation and developing strategic plans, assessing the internal (strengths and weaknesses) and the external (opportunities and threats) factors, as well as current and future potential to a firm (Helms & Nixon, 2010; Leigh, 2009). SWOT stands for strengths, weaknesses, opportunities, and threats. Every SWOT analysis focuses on these factors shown in Figure 7.

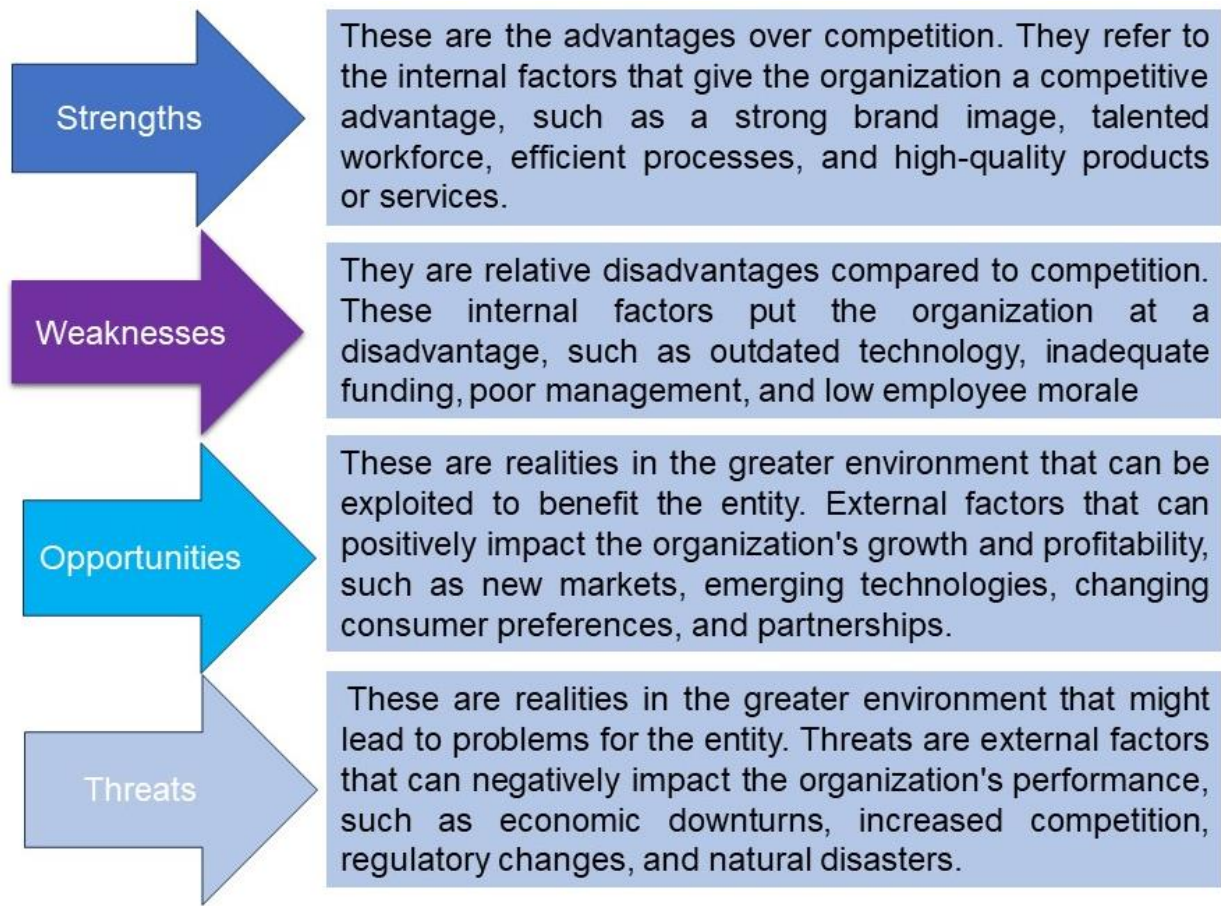


Figure 7 The SWOT Framework Developed from (Gürel, 2017; Porter, 1980; Serpa *et al.*, 2020)

By analysing these four factors, organizations can identify areas where they need to improve, as well as opportunities for growth and potential risks that they need to mitigate. SWOT analysis can help organizations make informed decisions and develop effective strategies to achieve their goals.

Kessler (2013) points out that it offers a systematic approach and support for decision making. The core advantage of SWOT matrix is that it assesses both internal and external elements of a firm or an industry. It identifies source of competitive advantage internally and makes use of the information a firm has about its external and internal environments and to formulate its strategies (Gürel, 2017).

2.4.2 TOWS Framework

The TOWS Matrix, sometimes sated as the TOWS Analysis, is a strategic planning tool that aids firms in determining and assessing both their internal strengths and weaknesses and their external opportunities and threats. To build practical strategies based on the insights from the

SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats), it is frequently used as a supplement. Heinz Wehrich created the TOWS Matrix as an expansion of the SWOT analysis in the 1980s. Figure 8 shows the TOWS Matrix.



Figure 8 The TOWS Matrix Developed from (Escalona *et al.*, 2022; Wehrich, 1982)

Identify Strengths (S): Start by identifying the internal strengths of your organization. These are the attributes, resources, and capabilities that give your organization a competitive advantage.

Identify Weaknesses (W): Next, identify the internal weaknesses of your organization. These are areas where your organization may be lacking or could improve.

Identify Opportunities (O): Examine external factors in the business environment that could create opportunities for your organization. These could be market trends, emerging technologies, changes in regulations, or shifts in customer preferences.

Identify Threats (T): Identify external factors that pose threats or challenges to your organization. These could include competitors, economic downturns, industry disruptions, or other external risks.

After identifying the strengths, weaknesses, opportunities, and threats, the TOWS Matrix can be employed to generate strategic insights and potential strategies (Wehrich, 1982).

SO, Strategies (Strengths-Opportunities): These strategies leverage an organization's strengths to capitalize on external opportunities. For example, if you have a strong research and development team (strength) and there's a growing demand for innovative products in the market (opportunity), you might develop new, cutting-edge products.

WO Strategies (Weaknesses-Opportunities): These strategies focus on improving internal weaknesses to exploit external opportunities. If your customer service is a weakness, but there's a growing demand for excellent customer support (opportunity), you might invest in training and resources to enhance your customer service capabilities.

ST Strategies (Strengths-Threats): ST strategies aim to use your organization's strengths to mitigate or defend against external threats. If you have a strong brand reputation (strength) and new competitors are entering the market (threat), you might reinforce your brand's value and loyalty to retain customers.

WT Strategies (Weaknesses-Threats): These strategies involve defensive actions to minimize weaknesses and protect against external threats. For example, if you have a weak supply chain (weakness) and there's a risk of supply chain disruptions due to geopolitical instability (threat), you might diversify your suppliers to reduce risk.

The TOWS Matrix challenges businesses to consider how they may develop effective strategies by balancing their strengths and weaknesses with external opportunities and threats. It aids in forming a more proactive and knowledgeable strategy for planning.

It's vital to remember that the TOWS Matrix is a flexible tool that may be used to strategize at several levels, from corporate to departmental to project-level. Additionally, it can be utilized on a regular basis to review and modify tactics in response to shifting internal and external factors (Escalona *et al.*, 2022).

2.4.3 Pestel Framework

The PESTEL framework is a tool used for analysing the macro-environmental factors that can affect an organization's operations and strategy (Nusantari, 2021). Organizations utilize this management framework to evaluate external factors affecting their operations, aiming to enhance their competitiveness in the market as well as to evaluate large supply chains. The PESTEL model categorizes factors in the broader business environment into six segments (Rothaermel, 2017).

These six areas encompass: Political, Economic, Social-Cultural, Technological, Legal, and Environmental/Ecological factors within the PESTEL model and these are shown in Figure 9.



Figure 9 The PESTEL framework (redrawn from Rothaermel (2017))

Political factors: These pertain to the influence of government policies and regulations on the organization. Examples encompass tax policies, trade restrictions, labour laws, and political stability (Rastogi & Trivedi, 2016; Yusop, 2018).

Economic factors: Economic factors encompass the influence of economic conditions on the organization, including aspects such as inflation, unemployment, interest rates, and exchange rates (Yusop, 2018).

Social factors: These factors refer to the influence of social and cultural trends on the company, such as demographics, lifestyle changes, and consumer attitudes and behaviours (Çitilci & Akbalık, 2020).

Technological factors encompass various aspects of technology that impact business operations. These factors include production techniques, information and communication resources, production, logistics, marketing, and e-commerce technologies (Johnson *et al.*, 2009). They also refer to the impact of technology and innovation on the organization, such as advances in

automation, the internet of things (IoT), artificial intelligence (AI) and other Industry 4.0 technologies (Ota & Knudsen, 2021).

Technological advancements play a significant role in shaping industries and influencing business strategies. They can provide opportunities for innovation, improved efficiency, and competitive advantage. Companies that effectively leverage technological factors can enhance their production processes, streamline communication, expand their market reach, and develop efficient e-commerce platforms.

Environmental factors: These elements pertain to the effect of environmental issues and sustainability on the organization, such as climate change, pollution, and resource scarcity (Çitilci & Akbalık, 2020; Dalirazar & Sabzi, 2023).

Legal factors: These factors refer to the impact of laws and regulations on the organization, such as health and safety regulations, consumer protection laws, and data privacy laws (Mazikana, 2023).

By analysing these six factors, organizations can identify opportunities and threats in their external environment and adjust their strategies accordingly. For example, a company might use the PESTEL framework to identify emerging technologies that could disrupt its industry, or to evaluate the potential impact of new regulations on its operations. The PESTEL framework can help organizations make informed decisions and prepare for future challenges and opportunities.

2.4.4 Porter's Value Chain Analysis

According to Porter (1985), value chain analysis is a crucial framework that enables organizations to comprehensively evaluate and recognize the various activities that generate value for their customers and stakeholders. It is a tool used to identify the key activities that create value for an organization and the costs associated with those activities. The value chain encompasses a sequence of activities executed by a company to produce and deliver a product or service to its customers. These activities can be divided into two primary categories: primary activities and support activities. Primary activities involve the direct creation and delivery of a product or service, including inbound logistics, operations, outbound logistics, marketing and sales, and customer service. On the other hand, support activities, such as procurement, technology development, human resource management, and infrastructure, are indirectly involved but play a pivotal role in the overall success of the organization. Figure 10 shows the value chain analysis.

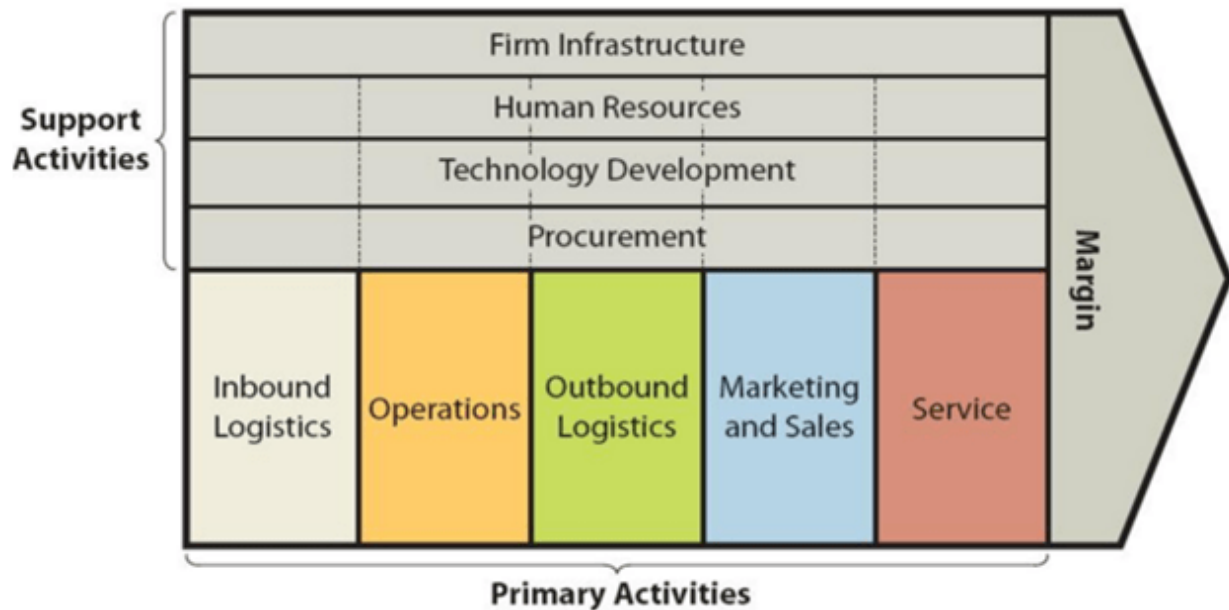


Figure 10 Value Chain Analysis Matrix Adapted from (Porter, 1985)

Conducting a value chain analysis entails identifying the costs associated with each activity and assessing their contributions to the organization's overall performance and competitive advantage. By scrutinizing the value chain, organizations gain insights into areas where costs can be reduced, efficiency can be enhanced, and customer value can be augmented. A notable advantage of value chain analysis lies in its ability to illuminate the interdependence of various activities and their collective impact on the organization's value proposition.

By comprehending the intricacies of the value chain, organizations can discern opportunities for differentiation, thereby generating additional value for their customers. Value chain analysis is versatile and applicable across multiple domains, including product development, supply chain management, and business process optimization. Its implementation empowers organizations to obtain a deeper understanding of their operations and make informed decisions regarding performance improvements, consequently creating greater value for their stakeholders (Porter, 1985).

Value chain analysis is a framework that assists organizations identify and evaluate the activities that produce value for their customers and stakeholders. The value chain is a set of operations carried out by a business to create and deliver a product or service to its customers. The activities are divided into two categories:

Primary activities include inbound logistics, operations, outbound logistics, marketing and sales, and customer service are examples of activities that are directly engaged in the manufacture and delivery of a product or service.

Support activities: These are activities that are not directly involved in the creation and delivery of a product or service but are essential to the overall success of the organization, such as procurement, technology development, human resource management, and infrastructure.

Value chain analysis involves identifying the costs associated with each activity and evaluating how well each activity contributes to the organization's overall performance and competitive advantage. By analysing the value chain, organizations can identify opportunities to reduce costs, improve efficiency, and create more value for their customers (Zamora, 2016).

One of the key benefits of value chain analysis is that it helps organisations understand the interdependence of different activities and how they contribute to the organisation's overall value proposition. By understanding the value chain, organizations can determine how they may set themselves apart from their opponents and create more value for their customers.

Value chain analysis is applicable in diverse contexts, including product development, supply chain management, and business process optimization. By applying value chain analysis, organizations can gain a deeper understanding of their operations and make more informed decisions about how to improve their performance and create more value for their stakeholders (Ensign, 2001).

2.4.5 Porter's Five Forces Framework

In 1980, Michael Porter released his influential publication "Competitive Strategy," a work that has significantly influenced the perspectives of academics, industrialists, and managers globally. The introduced framework in this work, known as the five forces model, can be applied to comprehend the strategic implications for individual firms operating within a particular industry.

Porter's Five Forces analysis is a framework used to analyse the competitive forces that affect an industry's profitability, attractiveness and shape an industry. The analysis focuses on five forces that shape competition within an industry. Porter's five forces are:

1. Rivalry among existing firms.
2. Threat of new entrants into the industry
3. Bargaining power of supplier
4. Bargaining power of buyers
5. Threat of substitute products or services

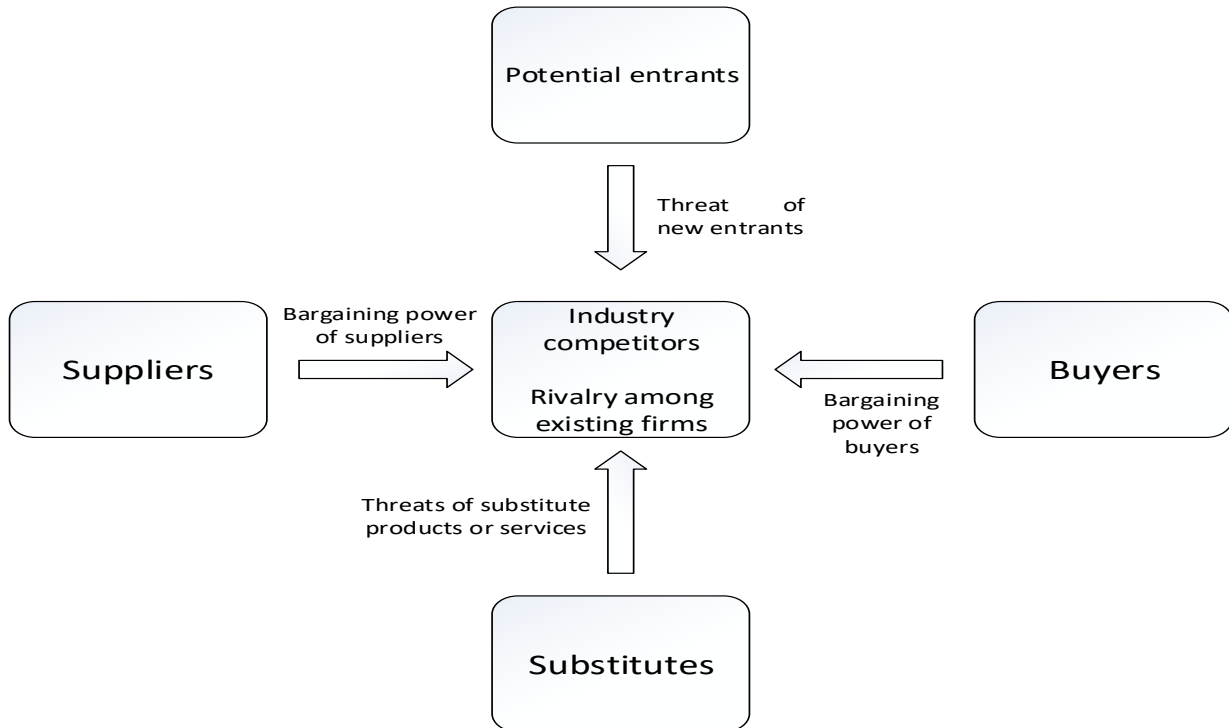


Figure 11 Porter's Five Forces Framework (Redrawn from (Grundy, 2006))

Threat of new entrants: This force measures how easy or difficult it is for new companies to enter the industry. If there are low barriers to entry, such as low capital requirements or low regulatory hurdles, then the threat of new entrants will be high, and competition will be more intense.

Bargaining power of suppliers: This force measures the degree of influence that suppliers possess in establishing prices and dictating terms to the industry. If suppliers hold substantial negotiating leverage, they can increase prices or reduce quality, which can reduce industry profitability.

Bargaining power of buyers: This force measures the extent of influence buyers wield in shaping prices and terms within the industry. If buyers possess substantial bargaining power, they can negotiate for lower prices or more favourable terms, thereby potentially diminishing industry profitability. High switching costs can increase the bargaining power of buyers. If customers have invested heavily in a particular supplier's products or services, they may have more leverage in negotiations, as the supplier stands to lose significant revenue if the customer switches.

Threat of substitutes: This force measures the extent to which alternative products or services can be utilized in lieu of those offered by the industry. If numerous substitutes are readily available, the industry's profitability may be reduced.

Rivalry among existing competitors: This is a gauge of the level of rivalry among existing companies in the industry. If there are many competitors, the industry may be highly competitive, and profitability may be reduced.

By analysing these five forces, companies can assess the competitive landscape of their industry and develop strategies to improve their position within it. For example, companies can focus on building barriers to entry, increasing their bargaining power with suppliers or buyers, differentiating their products or services, or collaborating with competitors to reduce rivalry.

The advantages offered by the Porter's five forces are that it focuses on external analysis which is important in firm's response to changes in the external environment (Goyal, 2020). The analytical power of Porter's five forces is limited in that it cannot quantify the overall competitive situation and the magnitude of each force. Another disadvantage of Porter's five forces is that it oversimplifies the industry value chains (Grundy, 2006) and the model also ignores complements focusing only on rivalry and citing the industry structure as the only factor influencing profitability of firms (Goyal, 2020).

Each of the five forces in the Porter's model consists of several features that are combined in order to determine the strength of each force and its influence on the degree of competition (Evans, 2013). The application of a strength rating to each of the forces, along with importance weight factor to each determinant, one can determine how fierce the competitive rivalry is in the industry.

There are three additional forces to the Porter's five forces to make Porter's Eight forces model which are, Complementary Products and Services, Relative Power of Other Stakeholders and Emerging Forces. Porter's Eight Forces model provides a more holistic view of the external and internal factors shaping an industry's competitive landscape. It encourages businesses to consider a broader range of influences when developing their strategies and assessing their competitive position. By analysing all eight forces, organizations can better understand the complexities and nuances of their industry and make more informed decisions.

Complementary Products and Services: This force considers the influence of complementary products or services on the industry. Complementary goods can affect demand for an industry's products.

Relative Power of Other Stakeholders: This force acknowledges that factors beyond suppliers, buyers, and competitors can influence an industry. It includes stakeholders such as regulators, trade associations, and influential interest groups.

Emerging Forces: This force accounts for emerging trends, technologies, and disruptors that may not be immediately apparent but could significantly impact the industry's future competitiveness. The Porter's Eight Forces model focuses more on digitalisation.

2.4.6 Strategic Group Analysis

According to Porter (1980) strategic group analysis is a valuable tool utilized by organizations to identify clusters of companies operating within an industry, sharing similar business strategies and competitive positions. This tool is used to categorize clusters of companies in an industry that share similar strategies and business models. Its purpose is to offer insights into the competitive dynamics of the industry and pinpoint opportunities for enhancing competitive advantage.

The strategic group analysis involves identifying the key dimensions that differentiate companies within an industry and mapping the positions of the companies on a graph based on these dimensions. The key dimensions could be factors such as product quality, price, distribution channels, marketing strategies, and customer segments.

Once the companies have been mapped on the graph, they can be grouped into strategic groups based on their position on the graph. Companies within the same strategic group are likely to face similar competitive forces and have similar strategic options.

The strategic group analysis can be useful for organizations in several ways:

- ❖ Identifying competitors: By mapping the positions of companies on the graph, organizations can identify their closest competitors and gain a better understanding of their competitive strengths and weaknesses.
- ❖ Identifying opportunities: By analysing the gaps in the market between different strategic groups, organizations can identify opportunities to differentiate themselves and create a unique value proposition for their customers.
- ❖ Evaluating performance: By comparing the performance of companies within the same strategic group, organizations can evaluate their own performance and identify areas for improvement.
- ❖ Planning strategic moves: By understanding the strategic options available to companies within each strategic group, organizations can plan their own strategic moves and anticipate the moves of their competitors.

Overall, strategic group analysis is a useful tool for organizations that want to enhance comprehension of their competitive environment and formulate effective strategies to improve their performance and competitive position (Porter, 1980).

2.4.7 Industry Lifecycle

The industry life cycle is a framework that describes the stages of development of an industry, from its inception to its decline. The industry life cycle is characterized by four stages as shown in Figure 12.

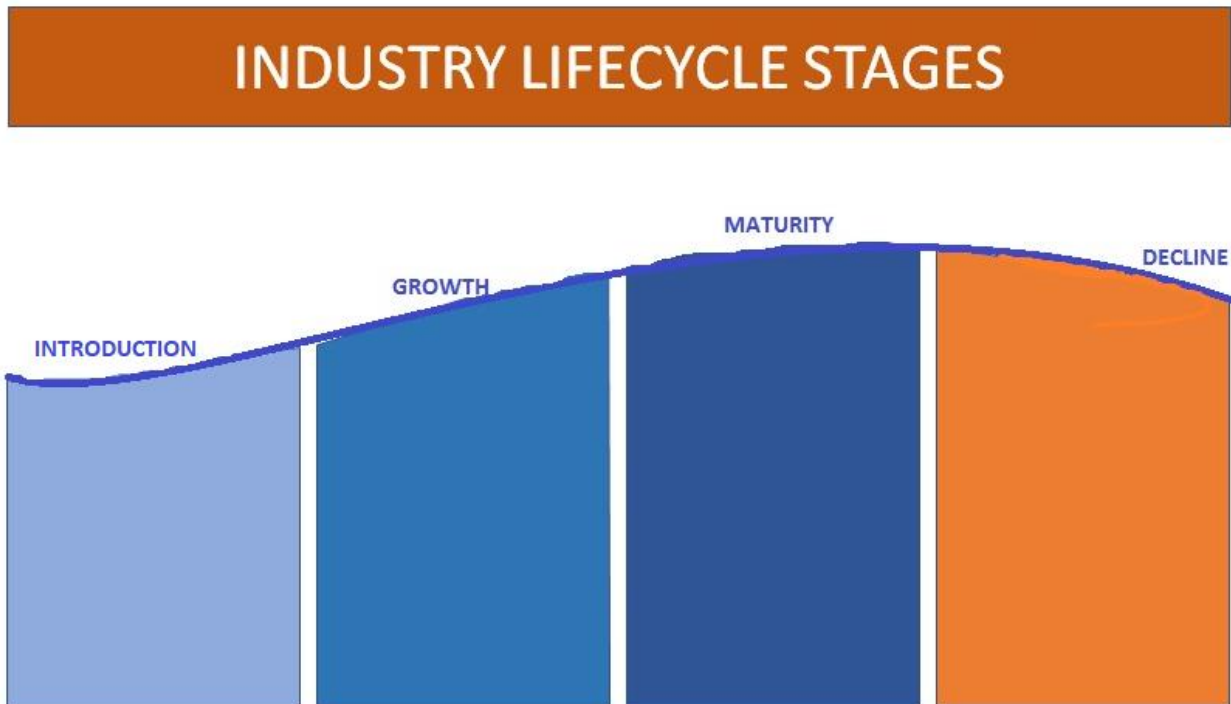


Figure 12 Industry Lifecycle Stages (Developed from Sabol *et al.* (2013))

Introduction: The introduction stage is characterized by low levels of demand, few competitors, and high levels of uncertainty. Products or services are new to the market, and customers are not yet familiar with them. The focus of companies during this stage is on product development and establishing a foothold in the market.

Growth: The growth stage is marked by increasing levels of demand, a growing number of competitors, and a decrease in uncertainty. Customers become more familiar with the products or services, and companies begin to focus on expanding their market share and improving their production efficiency.

Maturity: The maturity stage is characterized by stable levels of demand, many competitors, and a high level of saturation. Companies during this stage focus on cost control, differentiation, and maintaining market share.

Decline: The decline stage is characterized by decreasing levels of demand, a declining number of competitors, and a high level of uncertainty. Companies during this stage focus on either exiting the market or finding ways to rejuvenate their business.

The industry life cycle can have important implications for companies operating within an industry. Companies need to understand the stages of the industry life cycle to develop appropriate strategies. For example, companies in the introduction stage may need to focus on developing a strong brand identity and investing in research and development, while companies in the maturity stage may need to focus on cost control and process efficiency.

Overall, the industry life cycle facilitates life cycle thinking. By viewing industries or organisations in this way, it becomes a useful framework for understanding the dynamics of an industry and the challenges and opportunities that companies may face as the industry evolves over time.

2.4.8 Core Advantages of Business Analysis Tools

By using these theories and techniques, organizations can gain a better understanding of the competitive environment of their industry and develop strategies to improve their performance and competitive position. Industry analysis is an important component of strategic planning and can help organizations make informed decisions about investments, partnerships, and other business opportunities (Luftman, 2003).

Each strategic business analysis tool has its unique focus and purpose. SWOT Analysis provides a holistic view of internal and external factors Gürel (2017), while PESTEL Analysis focuses solely on external macro-environmental factors (de Sousa & Castañeda-Ayarza, 2022). Value Chain Analysis emphasizes internal processes, while Industry Life Cycle examines the broader industry development. Strategic Group Analysis helps identify key competitors, and Porter's Five Forces assess the overall industry competitiveness.

2.5 Chapter Summary

To explore the feasibility of the South African CTC industry, the Porter's five forces and the SWOT analysis are particularly useful. They provide a comprehensive view of the feasibility of a CTC industry, considering internal and external factors, as well as the competitive landscape. The tools aligned with objectives of the study and were suitable according to the available data were selected. The Porter's Five Forces framework and the SWOT analysis were integrated to analyse the findings from the data collected in the study. The SWOT analysis provides a resource-based view of the firm, and when integrated with the five forces framework, they can be viewed as complementary perspectives (Porter, 1980).

It is intended to allow for a realistic, data-driven analysis of an organization's, its projects', or its industry's strengths and shortcomings. The application of the SWOT framework has been extended from companies to industries and even to countries (Helms & Nixon, 2010). As an industry analysis tool, its application has been extending to even wider areas as researchers continue to find its far-reaching usefulness.

While Porter's Five Forces is a classic framework, it remains relevant in the digital age with the adaptation to consider the unique dynamics of digitalization. Analysing how digitalization influences each of the five forces can provide valuable insights for the coal-to-carbon industry.

The research focus is on the overall feasibility assessment, on economic, technical, market, operational and environmental feasibility, so the analysis is performed according to this overall approach. By using these tools, the study identified potential challenges and opportunities for the industry and developed strategies to overcome these challenges and leverage these opportunities.

Chapter 3

RESEARCH DESIGN

This chapter demonstrates the research approach used, delves into the research methodology and analysis processes used, and highlights the study's ethical considerations.

3 Research Design

3.1 Introduction

The research design for this dissertation combines qualitative secondary research with primary research. The purpose of this investigation is to explore the feasibility factors relevant to the coal-to-carbon (CTC) industry. Therefore, the adopted research design is aimed at comprehensively assessing the feasibility of the South African CTC industry.

3.2 Research Approach

The research approach for this study is qualitative, enabling a thorough exploration of the coal-to-carbon industry. Qualitative secondary research involves using already available data to address research questions (Largan & Morris, 2019), while primary research involves collecting data directly from the source to conduct an in-depth analysis. The study adopts a constructivist paradigm (Adom *et al.*, 2016; Fox, 2001), which posits that knowledge and understanding are socially constructed or invented. Considering that this study seeks to find feasible solutions to transform the coal-to-carbon industry, these solutions will be constructivist in nature and partially based on social constructs. Thus, the primary research in this study provides insights from participants' experiences and views.

As the CTC industry in South Africa has not yet been extensively explored, this study seeks to gather preliminary information to gain familiarity with the industry. The study uncovers new insights, areas of concern, barriers and enablers, and opportunities within the industry. Figure 13 shows the visualised research framework. The figure has been created to illustrate the investigation's research methodology. It encompasses the research objectives and questions, providing a representation of the study's approach. Additionally, the figure visually outlines the overall structure of the study, highlighting each chapter.

3.3 Qualitative Secondary Research

Secondary qualitative research is a methodical approach of exploiting existing data to give new or different understandings beyond the original intent of the data (Largan & Morris, 2019). In this study, the systematic literature review method is used to conduct qualitative secondary research. The feasibility assessment of the CTC industry is a multifaceted study, involving multiple factors and therefore qualitative secondary research can help explore these complexities as a complement to primary research by analysing existing data, and or reports. Secondary research also provides a historical perspective as to how the coal-to-carbon industry has evolved over time.

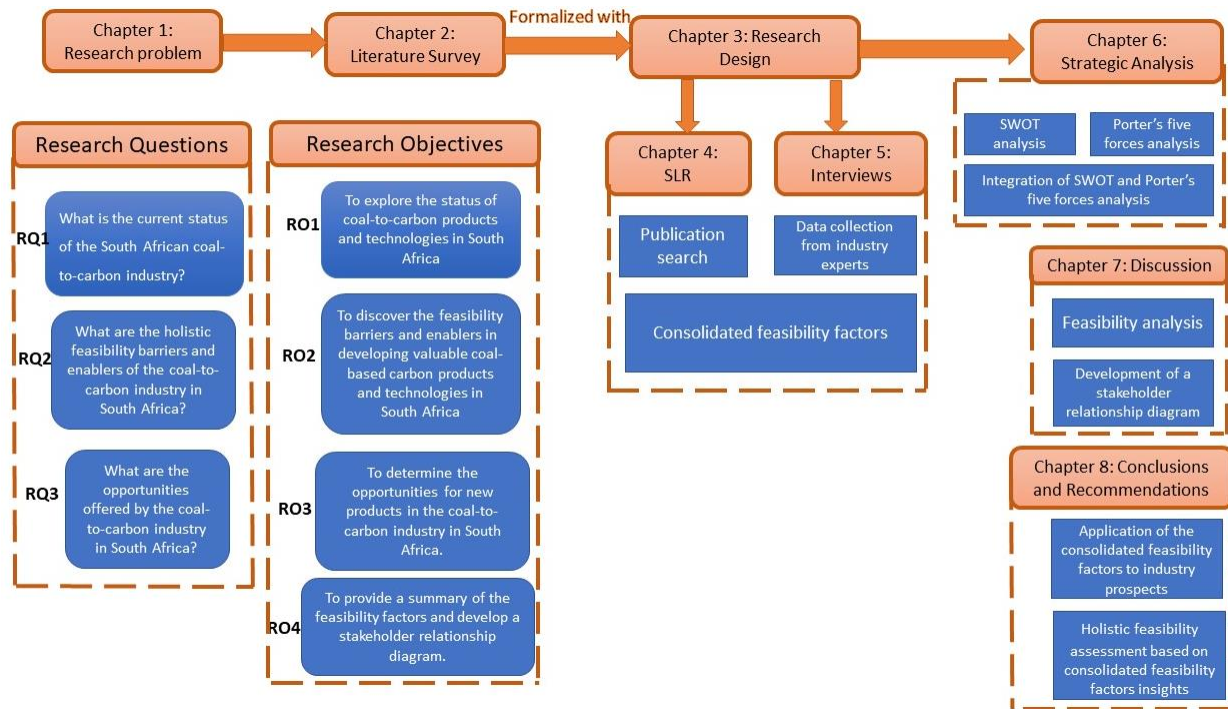


Figure 13 Visualisation of a Research Approach.

3.3.1 Systematic Literature Review (SLR)

A systematic literature review (SLR) is a rigorous and transparent method created by academics and practitioners to identify, evaluate, and synthesize existing sources of literature. Its primary goal aims to furnish information and evidence-based responses to research inquiries (Boland et al., 2017).

The outcomes of an SLR can provide a pathway for progression in a field or a combination of information and qualified judgment to enable justified decision-making. In this study, the literature was critically reviewed against predetermined criteria to identify the critical factors in the coal-to-carbon (CTC) industry's feasibility. The primary aim of this phase was to explore and analyse the feasibility barriers and enablers of developing valuable coal-based carbon products in South Africa, as well as identifying opportunities for new products in the CTC industry.

The rationale for this systematic literature review is to contribute to the existing knowledge base, fill research gaps, and provide valuable insights into the feasibility aspects, barriers, enablers, and opportunities associated with developing valuable coal-based carbon products in South Africa's CTC industry. This review aims to inform decision-making, policy formulation, and future research endeavours in this field.

3.3.2 The SLR Method

The methodology used in the SLR included the global coal-to-carbon industry, as it provides valuable insights into the South African industry. The study adhered to the Systematic Literature Review (SLR) method, as outlined by. The method has 3 phases with 10 stages which are shown in Figure 14.

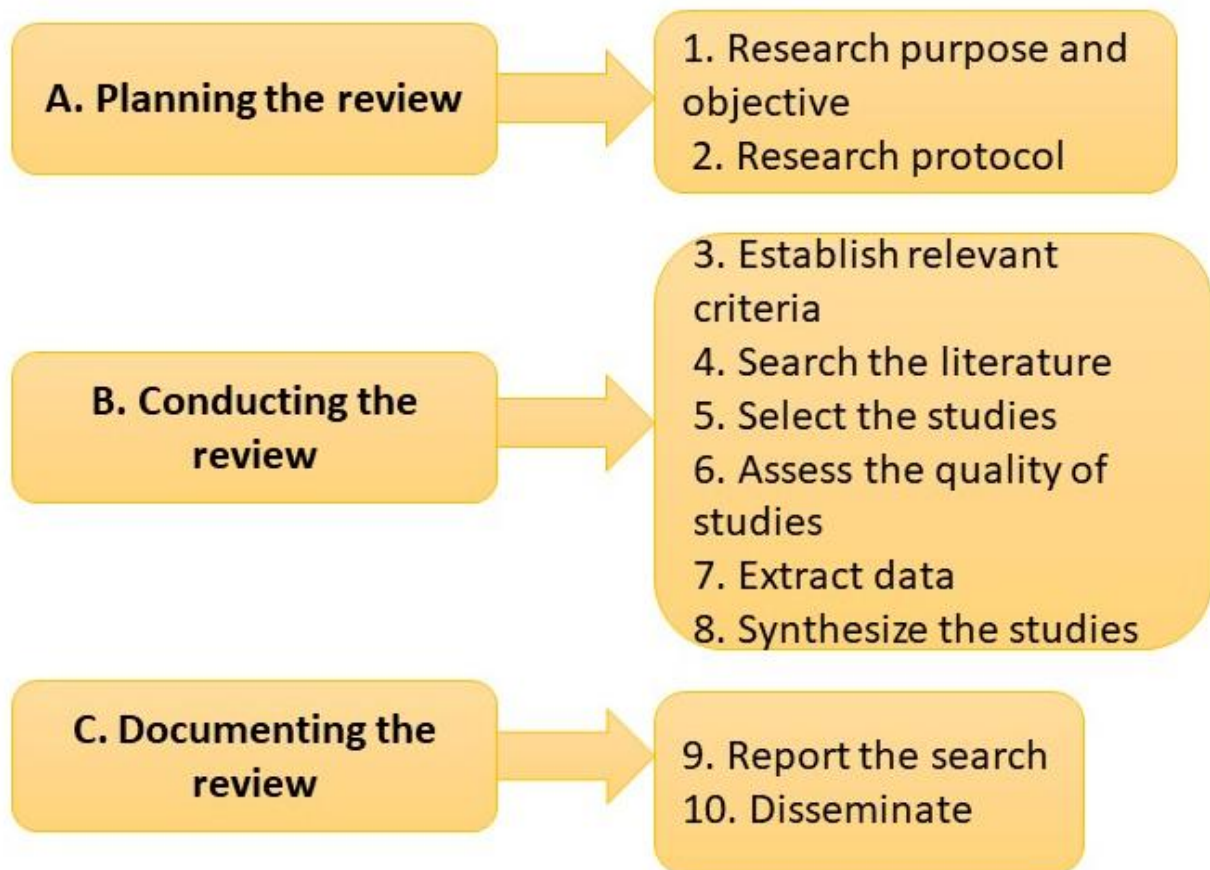


Figure 14 Three Phase SLR Process (Albliwi *et al.*, 2014)

The systematic literature review was conducted in three main phases: planning, execution, and documentation. These phases comprised a total of 10 stages. The purpose and objective of the SLR was to explore and analyse the feasibility barriers and enablers of developing valuable coal-based carbon products and technologies in South Africa, as well as identifying opportunities for new products in the CTC industry.

3.3.3 Research Protocol

The research protocol for this study is outlined in Table 2, which includes keywords, search strategy and the inclusion and exclusion criteria to eliminate researcher bias and increase repeatability. The selection of databases was based on their inclusion of relevant literature related

to the study's theme. The research protocol also includes keywords and quality assessment criteria to guide the search process and evaluate the quality of the findings. The research protocol was validated through iterative discussions and deliberations with a fellow researcher.

Table 2 formalised the research protocol, indicating the various components, selection, and rationale used. The search protocol was not limited to the publications on the South African industry as the initial literature survey showed that there are limited publications of this industry in South Africa. Publications on the global industry provided the information and evidence-based answers that illuminated the issues that also affects the South African industry.

Table 2 Research Protocol

| Component | Selection | Rationale |
|---------------------------|---|---|
| Keywords | Coal-based carbon products, value added products from coal, coal derived carbon products, feasibility, Carbon, South Africa, Technologies, barriers, enablers, | Key terms relevant to the purpose of the study |
| Platforms | Science Direct, Web of Science, Emerald Insight, Scopus, Google Scholar, IEEE Explore, and EBSCOhost (Academic search premier, Business source premier, E-journals, MasterFILE premier) | Researchers can access reputable platforms for high-quality journals and publications |
| Search strategy | ("Coal based carbon products" OR "Value added products from coal" OR "Coal derived carbon products") AND ("Feasibility" OR "Carbon" OR "South Africa" OR "Barriers" OR "Enablers" OR "Technologies") | Boolean expressions were used to generate search results that were more relevant to the purpose of this study |
| Inclusion criteria | <ul style="list-style-type: none"> • Review/Research articles or papers in English. • Related to the global coal-to-carbon industry. • Peer-reviewed journal and conference articles, government reports, industry publications, theses, and working papers. • Publications must address feasibility aspects. | Refine academic search results to identify publications that are most pertinent to the nature of this study. |

| Component | Selection | Rationale |
|------------------------------------|--|--|
| | <ul style="list-style-type: none"> Includes reports on industry expert perspectives | |
| Exclusion criteria | Focus on coal-based carbon products; specific to coal-to-carbon processes | Eliminate publications that are not relevant to the research questions or are outside the scope of the study |
| Quality assessment criteria | Eliminate any duplicated literature; assess the recovered literature for relevance. | Ensure that all literature included in the study is unique and relevant to the research questions |

The keywords for the systematic literature review were determined through a careful process that involved identifying relevant terms and concepts related to the research topic. The main concepts that need to be covered were identified from the research questions and the objectives of the study. By breaking down the research questions into key concepts, the concepts which are the building blocks of the literature review and a guide to keyword selection were identified. The key concept includes "feasibility" and "coal-based carbon products."

The process of keyword generation and refinement was systematically conducted to optimize the search for relevant literature. Initially, keywords were generated by extracting key terms directly from the research topic and questions. This foundational step laid the groundwork for subsequent actions.

To further enrich the keyword list, additional resources were explored. These included thorough examinations of existing literature reviews, relevant articles, textbooks, and databases specific to the research field. The purpose was to identify potential keywords that may have been overlooked initially.

The generated keyword list underwent a review and refinement process. Keywords deemed excessively broad, overly narrow, or unrelated to the research question were systematically eliminated. The utmost importance was placed on ensuring that the selected keywords accurately encapsulated the core elements of the research topic. Three iterations were used to filter the final search keywords used in the study.

Prior to commencing the actual search, a critical step involved testing the selected keywords within the chosen database or search engine. This served to enhance the reliability of the search process. Through this testing, the relevance and specificity of the initial search results were assessed. Before committing to the research protocol, a blitz review was done to iteratively update the table to ensure that the correct search strategy was ultimately used (Dobbins, 2017; Moons *et al.*, 2021).

3.3.4 Search Strategy

To formulate the search strategy, key terms relevant to the purpose of the study were identified first. These included "coal-based carbon products," "value added products from coal", coal derived carbon products" "feasibility," "carbon," "South Africa," "barriers", "enablers" and "technologies." These terms were chosen because they accurately reflect the focus of the study and likely to yield relevant results.

Next, a range of reputable platforms for high-quality journals and publications, including Science Direct, Web of Science, Emerald Insight, Scopus, Google Scholar, IEEE Explore, and EBSCOhost (Academic Search Premier, Business Source Premier, E-Journals, MasterFILE Premier) were identified. These platforms were chosen because they are widely used by academic researchers and are known to have strong collections of literature in the engineering field.

Using these key terms and platforms, a Boolean expression search strategy was developed. The strategy included the use of "AND" and "OR" expressions to generate search results that were more relevant to the purpose of the study. For example, the search strategy used the expression "Coal based carbon products" AND ("Feasibility" OR "Carbon" OR "South Africa" OR "Barriers", OR "Enablers", OR "Carbon product development" OR "Technologies") to ensure that only relevant literature was retrieved. The search included all publications from 2000 to date.

In addition to the search strategy, an inclusion and exclusion criteria was developed. The articles considered for inclusion must pertain to the global coal-to-carbon industry and meet certain criteria. These criteria include being peer-reviewed journal or conference articles, government reports, industry publications, theses, and working papers. Additionally, included reports should present industry expert perspectives, and publications must specifically address feasibility aspects. Furthermore, only articles or papers written in English will be reviewed. The exclusion criteria focused on articles that were not related to coal-based carbon products or did not conform to the timeframe of the study.

One of the key stages is the selection of the studies or publications. The step-by-step process followed was:

1. **Screening Based on titles and Abstracts:** In the initial phase, articles retrieved from the search underwent screening based on their titles and abstracts. This careful review led to the exclusion of articles that were evidently irrelevant or unrelated to the research question and objectives. Only those articles that exhibited potential relevance, as indicated by their titles and abstracts, were retained for further consideration.
2. **Full-Text Assessment:** Subsequently, full-text versions of the potentially relevant articles were procured and subjected to comprehensive examination. This involved an assessment to determine their alignment with the research question and objectives. Adherence to predefined inclusion and exclusion criteria played a pivotal role in evaluating whether these articles met the specified requirements for inclusion in the systematic literature review. Articles failing to meet the inclusion criteria or deemed unequivocally irrelevant were systematically excluded. Only those articles that satisfied the inclusion criteria and directly addressed the research question or objectives were incorporated into the review.
3. **Assessing Eligibility and Quality:** The next step involved a two-fold assessment: eligibility and quality. Eligibility was determined based on specific criteria, with a primary focus on articles concerning coal-based products and their relevance to the coal-to-carbon industry. Factors considered included publication type and language. Simultaneously, the quality and rigor of the selected articles were scrutinized, considering critical elements such as methodology, sample size, data collection procedures, and analysis techniques. Only articles aligning with eligibility criteria and demonstrating high-quality research were deemed suitable for inclusion.
4. **Cross-Checking References and Citations:** A vital component of the selection process involved a review of the reference lists of the selected articles. This endeavour aimed to identify additional pertinent studies that might not have surfaced in the initial search, thereby enhancing the comprehensiveness of the review.
5. **Iteration:** To ensure the exhaustive coverage of relevant literature, the selection process followed iterative rounds encompassing screening, full-text assessment, and eligibility evaluation. Notably, to maintain rigor and avoid duplication, all duplicate literature was removed from consideration.

This methodical and structured approach to article selection ensured that the research synthesis was based on a rigorous and comprehensive foundation of high-quality, pertinent literature. Data was extracted from the selected publications, extracting the study designs, research methods and the key findings.

3.3.5 Narrative Synthesis of the SLR

The data analysis of the selected publications from the systematic literature review followed a narrative synthesis. The steps followed in this process are described below.

Familiarize Yourself with the Material:

The researcher read and reviewed the collected sources.

Coding and Categorization:

The researcher began by coding the data, which involved labelling or tagging specific segments of text or data related to common concepts or ideas.

Following coding, the researcher categorized these codes based on their thematic relevance, grouping similar codes together to form preliminary themes.

Constant Comparison:

The researcher engaged in constant comparison while reviewing the data, continuously comparing new data or codes to previously identified ones to refine and modify categories and themes.

Iterative Process:

The researcher repeatedly reviewed and revised themes as they evolved and changed during the deeper understanding of the data.

Seek Patterns and Relationships:

The researcher actively sought patterns, relationships, and connections between the codes and themes, looking for recurring ideas or concepts and exploring possible hierarchy among themes.

Define and Name Themes:

The researcher clearly defined each theme with a brief description of what it represented. Descriptive names were assigned to each theme for ease of reference.

Write the Narrative Synthesis:

In this stage, the researcher organized the narrative synthesis, discussing each theme in detail and explaining its relationship to the research question or objective. Evidence and examples from

the data were provided to support each theme. The documentation of the review can be found in Chapter 4.

3.4 Empirical Research Methodology

After conducting the systematic literature review, the next phase of the study involved primary research. The purpose of the primary research was to gather first-hand data on the feasibility factors relevant to the (CTC) industry in South Africa.

This section presents the methodology used to conduct the primary research and the results obtained from the data collected. The section also discusses the analysis of the data and the conclusions drawn from the study.

The study collected and analysed primary data using semi-structured interviews with experts in the CTC industry in South Africa, as well as expert researchers in coal-based carbon products.

3.4.1 Semi-Structured Interviews

Interviews represent a widely employed method for collecting data in qualitative research. They entail purposeful conversations between researchers and participants aimed at acquiring the desired knowledge (Saunders et al., 2019). Interviews are particularly useful for exploring major themes or posing questions to experts in a study. However, due to the interactional nature of interviews, researchers must approach them with proper guidelines to ensure effective outcomes.

To this end, the following guidelines are recommended to ensure effective interviews:

- Begin with introductory questions.
- Keep questions clear and brief.
- Ensure that 90% of the talking is done by the participants.
- Ask one question at a time.
- Use open-ended questions, unless otherwise required.
- Refrain from posing sensitive questions unless they fall within the scope of the study.
- Avoid controversial questions at the start.
- Start with generic questions and then narrow down to specific ones.
- Avoid leading questions.

3.4.2 Primary Data

The primary data gathered from the coal-to-carbon industry experts and researchers in coal-based carbon products is essential in providing a detailed understanding of the industry in South Africa. The empirical evidence obtained through semi-structured interviews is key to identifying the critical factors that impact the feasibility of developing valuable coal-based carbon products in South Africa. These insights provide valuable information on the opportunities for new products in the coal-to-carbon industry, as well as the enablers and barriers that need to be addressed to ensure successful implementation.

By gathering primary data directly from experts in the industry, the study can avoid potential biases and errors that may arise from relying solely on secondary sources. The experts' experience and knowledge can provide a rich and nuanced understanding of the complex dynamics and challenges in the industry, which can help inform decision-making and policy formulation. The primary data obtained also provides an opportunity for the researchers to ask probing questions, clarify any ambiguities or uncertainties, and gain a deeper understanding of the experts' perspectives.

Furthermore, the use of semi-structured interviews ensures that the research remains flexible and open to new insights and perspectives that may emerge during the data collection process. The interviews are guided by a set of pre-determined questions, but the researchers have the flexibility to explore new themes or ask follow-up questions based on the experts' responses. This approach allows for a more in-depth exploration of the issues and enables the researchers to capture the complexity and diversity of perspectives within the industry.

3.4.3 Research Instrument

Semi-structured interviews with open-ended questions were used as the primary research instrument for collecting empirical data in this study. Semi-structured interviews are commonly used in qualitative analysis, allowing researchers to discuss major themes or pose questions to experts, in this case, the CTC industry.

To ensure effective interviews, the researcher adopted the six-step process developed by Rabionet (2011) These steps are as follows:

1. Selecting the type of interview
2. Establishing the ethical guidelines
3. Crafting the interview protocol
4. Conducting and recording the interview

5. Crafting the interview protocol
6. Report the findings.

The table 3 outlines how each step was applied in the study.

Table 3 Six Step Interview Process (Rabionet, 2011)

| Step | Step description | Application in the study |
|--|---|--|
| Selection of the type of interview | Deliberate on which interview structure to follow | Semi structured |
| Establishment of ethical guidelines | Consider confidentiality, informed consent, voluntary participation, privacy, compensation, and avoidance of harm | Ethical clearance approved by NWUREC (NWU-01083-21-A3) Appendix A |
| Crafting the interview protocol | Provide the interview context and develop questions and follow up probes | Section 3.4.4 The protocol can be found in Table 5 |
| Conducting interviews | Conduct interviews | Section 3.4.2 – 3.4.5 |
| Analysing interviews | Transcription, Coding, and recurring theme identification | Section 3.4.6 |
| Reporting the findings | Present the results from the interview data analysis | Chapter 5 |

3.4.4 Design of Interview Questions and Protocol

The interview protocol for this study was designed using Castillo-Montoya (2016) interview protocol refinement framework, which has four stages: (1) verifying that interview questions align with research inquiries, (2) creating a conversation based on inquiry, (3) obtaining feedback on the interview protocol, and (4) testing the interview protocol through a pilot phase.

To align the interview questions with the research questions and objectives, the researcher formulated open-ended questions that would facilitate data collection to answer the research questions. The interview questions were chosen based on the idea that the participants would

share their narratives to provide insights into how their experiences unfolded and the significance they attributed to these experiences could be found (Roberts, 2020). The questions were crafted to be easily understood and phrased in a way that would encourage participants to freely communicate (Brinkmann & Kvale, 2015).

The research questions were chosen based on the literature review, and they covered all the feasibility areas of the study: technical, economical, market, environmental, and operational. A set of interview questions was formulated under each research question, along with prompts to get clarifications and further explanations on the phenomena. This approach ensured that all aspects of the research questions were addressed during the interviews.

During the interview protocol refinement process, the researcher constructed an inquiry-based conversation that would allow for follow-up questions and further exploration of the participants' responses. Feedback on the interview protocol was received from colleagues and experts in the field to ensure that the questions were appropriate and relevant. Finally, the interview protocol underwent a pilot phase involving four participants to confirm the clarity of the questions and their ability to generate the intended responses. This pilot testing facilitated the refinement of question wording to enhance overall clarity.

Overall, the interview questions and protocol were carefully designed to collect rich and meaningful data to answer the research questions and explore the feasibility enablers and barriers of the CTC industry in South Africa. Table 5 shows the interview protocol with the interview questions.

Table 4 The Interview Protocol

| Interview Protocol for Coal Conversion Experts | | |
|--|---|--|
| Research Question 1 | Research Question 2 | Research Question 3 |
| What is the current status of the South African coal-to-carbon industry? | What are the holistic feasibility barriers and enablers of the coal-to-carbon industry in South Africa? | What are the opportunities offered by the coal-to-carbon industry in South Africa? |

| Interview Questions | Interview Questions | Interview Questions |
|--|---|--|
| <p>1. South Africa has abundant coal reserves and resources; do you think they are being utilized to their fullest? Why do you believe this is the case?</p> <p>2. In terms of coal conversion into useful products South Africa has excelled with its leading coal to liquid (CTL) industry, what do you think of the coal-to-carbon (CTC) industry?</p> <p>3. What do you believe are the coal-to-carbon (CTC) industry key success factors?</p> <p>4. How do you see the current size and growth potential of the market for coal-based products in South Africa?</p> <p>5. As an expert in the coal conversion industry, you may have witnessed or experienced some of the challenges currently facing this industry. Can you share some of these instances?</p> | <p>6. Would you like to share some thoughts on the feasibility of technologies in the production of valuable coal products?</p> <p>7. I would like us to consider the environment as we look at the feasibility of the CTC industry. From this perspective what do perceive as critical issues that may affect the CTC industry?</p> <p>8. Are there any operational issues on the feasibility of the coal-to-carbon industry that you might want to discuss?</p> <p>9. From studies done in other regions, the coal conversion industry is rapidly growing, what are your thoughts on South Africa’s competitiveness globally in production of valuable coal-based products?</p> <p>10. The coal conversion industry is capital intensive which makes it a high-risk business. In the current economic and political environment would you tell us reasons why you would either invest or not invest in this industry?</p> | <p>11. What do you think are the benefits of the coal-to-carbon industry to the South African economy?</p> <p>12. To what extent do you think the coal-to-carbon industry has potential to disrupt the coal conversion industry?</p> <p>13. According to you, how can the coal-to-carbon industry best realize its full potential in South Africa?</p> |

3.4.5 Data Collection and Sampling

The research aimed to collect empirical data on the views and opinions of experts in the coal conversion industry, specifically focusing on the CTC industry in South Africa. A purposive sampling method was used to select participants from the industry and academia, with snowball sampling employed to expand the sample size (Saunders *et al.*, 2019).

To qualify for participation, individuals were required to demonstrate their expertise and experience in carbon-based products derived from coal and the technologies involved in coal conversion. This demonstration could take the form of academic publications, industry reports published in widely recognized sources, as well as certifications or qualifications in the field.

Participants were required to have the necessary knowledge to provide relevant information for the study, ensuring their insights would contribute meaningfully to the research objectives. Therefore, for academic experts, it was required:

- Individuals with a research focus or a history of academic publications related to coal-based products or coal conversion were targeted for inclusion and/ or
- Those with records of active participation in conferences and workshops addressing topics related to coal or energy conversion.

For Industry Practitioners:

- Hands-on experience working with coal-based products and coal conversion technologies, emphasizing roles associated with recognized industry organizations such as the Southern African Coal Processing Society, the International Energy Agency, and similar entities and or
- A key qualifier was active participation in research projects, innovative initiatives, or the development of coal-based products, technologies, or processes.

LinkedIn was used to reach out to experts in coal-based carbon products and coal conversion technologies in the South African industry. The researcher made initial contact with participants to obtain consent to partake in this research. A copy of the informed consent form is in Appendix B. As previously mentioned, snowball sampling was employed to identify further individuals in the professional group who could provide relevant and useful information for the study.

3.4.6 Data Transcription

To ensure all participants' responses were accurately captured, the audio recordings of the interviews were transcribed verbatim. The only instances where elements were excluded from the transcriptions were when the participant hesitated or repeated words. The online platform used for the interviews was Zoom. The interview questions are in Table 4.

As an example, an anonymised sample of the transcribed notes from a participant is available in Appendix E. This sample provides an insight into the format of the notes taken during the interviews, which included capturing the participants' responses in full sentences, noting their tone and body language, and any other relevant details.

3.4.7 Thematic Analysis of Interview Data

The researcher utilised the interpretive data analytic process known as thematic analysis. Thematic analysis is an approach to systematically uncovering and organizing data, involving the examination of patterns and themes within a collection of data (Braun & Clarke, 2022). The aim in using an interpretative approach is to emerge with the meanings that are being constructed by the participants.

The coal-to-carbon industry is highly technical and therefore experiences, perspectives and meanings of participants who are experts in this industry can be well-captured using thematic analysis.

Thematic analysis involves submerging oneself in the data to identify multiple facets of an idea or concept or themes that develop based on the topic being studied and that correlate with the study's research questions (Braun & Clarke, 2016). ATLAS.ti 22.0.5.0 was utilised to analyse the data. Braun and Clarke (2006); (2022) suggested different phases in the thematic analysis process. However, the researcher applied the following guidelines in the data analysis process.

Phase 1: Immersion into the Data

In the initial phase of the thematic analysis process, the researcher immersed themselves in the dataset. This involved multiple thorough readings of the data to gain familiarity with its nuances, interesting elements, and potential patterns. Braun and Clarke (2022) emphasize the importance of critically engaging with the data during this phase.

To achieve this, the researcher employed several techniques, including:

- Creating detailed notes that captured thoughts and impressions related to the dataset. These notes served as brief narratives that prepared the researcher for the subsequent coding phase.
- Engaging deeply with the data to uncover its rich diversity of meaning.
- Asking critical questions to provoke deeper insights into the data.
- Identifying initial trends related to factors affecting the CTC industry.
- Generating memos that encapsulated initial reflections on the dataset.

To further familiarize themselves with the data, the researcher carefully reviewed all interview recordings and thoroughly examined the interview transcripts. Memos were instrumental in noting intriguing data points during this process.

Phase 2: Exploration through Coding

In the second phase, the researcher delved into the dataset to explore its diversity and patterns of meaning. This involved reading each data item meticulously and tagging segments of text that held relevance to the study's research questions with appropriate code labels.

The coding process was dynamic:

- Initially, it produced one hundred and sixty-five codes.
- These codes were then organized into a more manageable set.
- Relevant codes were systematically assigned to sections of data containing information pertinent to the research questions.
- A second round of coding ensued, resulting in the creation of two hundred and eighty codes. Appendix C has a list of the codes and code groups.

Throughout this phase, the researcher continued to evolve and adapt the code labels as new insights emerged from the data (Braun & Clarke, 2022).

Phase 3: Uncovering Initial Themes

In this stage, the researcher engaged with the data codes that had been developed to uncover similarities in meaning. The goal was to identify emerging patterns that formed coherent and potentially significant insights related to the research questions (Braun & Clarke, 2022).

Codes that seemed interconnected were clustered into initial themes or broad concepts. This phase generated numerous starting themes and allowed the researcher to contemplate the information they conveyed about the dataset and its relevance to the research questions.

Phase 4: Developing and Reviewing Themes

The focus in this phase shifted to a comprehensive review of all coded data within the entire dataset. The researcher closely examined the initial themes, aiming to refine and clarify any unclear clusters. This phase served both as a validation of the preceding stage and as a quality control check.

Candidate themes were rigorously assessed against the entirety of the data for their viability as themes. Viable themes were characterized by identifiable boundaries, sufficient meaningful data to substantiate their existence, and their ability to convey important information pertinent to the research questions. Some themes may have required adjustments or even a return to the coding phase.

Phase 5: Precision, Definition, and Naming of Themes

In the final phase, the themes were further refined to achieve greater accuracy and coherence. The flow and structure of the analysis were determined, and theme definitions were crafted. Researchers worked to provide clear and descriptive names for the themes, ultimately shaping the thematic analysis into a coherent and insightful narrative.

3.5 Integration of SWOT and Porter's Five Forces Analyses: Insights from SLR and In-Depth Interviews

To derive strategic implications, the insights from the thematic analysis and narrative synthesis were synthesized into actionable strategies. This process involved translating the identified themes and narratives into strengths, weaknesses, opportunities, and threats within the SWOT analysis. Furthermore, these qualitative insights were integrated with the strategic considerations outlined in Porter's Five Forces, informing strategies to leverage strengths, address weaknesses, seize opportunities, and mitigate threats within the industry.

Combining these analytical approaches and integrating qualitative research findings provides a comprehensive assessment to guide strategic planning, risk assessment, and potential areas of improvement for the South African CTC industry. The SWOT analysis offers a holistic understanding of the industry's current state, potential challenges, and opportunities (Jiskani *et al.*, 2020). This analysis aids in identifying areas of concern and opportunities that enhance the industry's feasibility.

During the literature review phase, information from existing studies, reports, and publications was gathered to meet the research objectives related to the feasibility evaluation of the South

African CTC industry. The industry's strengths, weaknesses, opportunities, and threats were identified based on historical data and current trends. The data collected from the literature review was analysed to detect patterns and recurring themes associated with the industry's strengths, weaknesses, opportunities, and threats.

In the research project on the South African coal-to-carbon industry, a comprehensive approach was employed by integrating both SWOT analysis and Porter's Five Forces analysis, alongside conducting a systematic literature review and interviews. This multifaceted methodology provided a holistic understanding of the industry's dynamics.

The SWOT analysis played a crucial role in assessing internal strengths and weaknesses and external opportunities and threats. By drawing from qualitative data collected through interviews and the literature review, the identified themes and narratives were aligned with the industry's strengths, weaknesses, growth opportunities, and potential areas of concern.

Similarly, the integration with Porter's Five Forces analysis contributed valuable insights into the competitive landscape of the industry. It explored how the emerging themes and narratives influenced each force:

Threat of New Entrants: Examination of whether qualitative findings illuminated barriers or opportunities for new entrants.

Bargaining Power of Suppliers and Buyers: Analysis of how the identified themes and narratives affected relationships between suppliers, buyers, and industry stakeholders, impacting the balance of power.

Threat of Substitutes: Investigation of whether qualitative insights revealed emerging trends or alternative solutions that could act as substitutes and their impact on the industry's susceptibility.

Competitive Rivalry: Assessment of whether qualitative themes and narratives reflected competitive dynamics discussed in the research, influencing the analysis of the competitive landscape.

3.6 Reliability, Rigor, and Validity

Reliability, rigor, and validity are pivotal aspects of a well-designed research study, ensuring the accuracy and credibility of its findings (Creswell & Creswell, 2017). In the holistic feasibility assessment of the South African CTC industry, multiple measures were implemented to enhance these crucial elements in the study design.

The research design was meticulously crafted using appropriate methods, emphasizing the soundness of the methodology. Careful documentation of the research process aimed to enhance the reliability of the study.

Rigor in the design was emphasized through a comprehensive and multidisciplinary approach. A robust research methodology, incorporating both primary and secondary data collection, was employed to thoroughly examine various industry factors. Ethical research practices and scenario planning were integral, ensuring a well-rounded, credible, and scientifically sound evaluation of the coal-to-carbon industry's feasibility.

Interviews were conducted to gather expert views, and to enhance validity, researcher biases were minimized through careful consideration, validation of assumptions, and continuous self-reflection. Data collected through interviews were organized using Atlas.ti 22, with constant testing and comparison to enhance authenticity.

Preliminary findings were discussed in feedback sessions with participants, who were invited to review, reflect, and provide input. The researcher considered their feedback, adjusting findings, interpretations, or conclusions based on participant input.

Procedures were implemented to maintain accurate transcription of interview recordings. A detailed audit trail documented the research process, decisions, and changes made during data collection and analysis, ensuring transparency and traceability. Reflexivity was employed by acknowledging and addressing the researcher's biases and preconceptions.

Direct quotations from participants were included in the findings, providing readers with a sense of participants' voices and perspectives, further enhancing the study's validity and authenticity.

In the systematic literature review, strict inclusion and exclusion criteria and a comprehensive search strategy ensured the reliability of secondary research findings. This approach guaranteed the inclusion of only relevant and credible sources.

The interview protocol's reliability and validity were further strengthened through the application of the refinement framework (Castillo-Montoya, 2016). Multiple data sources, including interviews and a literature review, were employed to ensure the robustness and reliability of the findings.

3.7 Ethical Considerations

The researcher adhered to ethical guidelines and principles applicable to this study, guided by the NWU Engineering Research Ethics Committee (NWU-ENG-REC) ethics process. Compliance

with all national and international research rules and guidelines was ensured, and the researcher's ethics number is NWU-01083-21-A3. Prospective participants were interviewed for selection, and their consent was obtained through signed consent forms. Participation was voluntary, and participant information was treated confidentially.

Ethical considerations required by the North-West University were strictly followed, involving the completion of the Research Ethics Committee application form and the use of the North-West University Informed Consent Form for Coal Conversion Industry Experts. All interviews were conducted by the researcher, ensuring no harm to participants.

Data collection occurred through online interviews, minimizing risks to participants. Interviews were kept under an hour, averaging 30 minutes, to prevent fatigue and psychological harm. Confidentiality of collected data was enhanced using a personal password-protected laptop.

Privacy of participants was respected, with any accessed participant information kept strictly confidential and not included in the study's data or shared. Participation was entirely voluntary, without coercion, and participants could withdraw without consequences. No remuneration was provided for participation.

Data collected was stored on password-protected researcher computers, with only the researcher having access. Care was taken to protect participant identities, and results and findings will be published in aggregated form to maintain confidentiality.

3.8 Chapter Summary

In this research, two main approaches were employed: Systematic Literature Review (SLR) and semi-structured interviews. The SLR involved a review of existing literature to gather valuable insights and knowledge on the factors affecting the industry. Semi-structured interviews, on the other hand, allowed for in-depth discussions with expert practitioners and researchers to acquire firsthand information and perspectives.

For analysis, a combination of thematic analysis and narrative synthesis was used. Thematic analysis helped identify recurring themes and patterns in the collected data, while narrative synthesis facilitated the construction of a coherent and comprehensive narrative based on the key research findings.

The integration of the Strategic Framework involved two key methodologies. First, the SWOT-TOWS analysis was applied to assess the internal Strengths and Weaknesses and external Opportunities and Threats, providing a comprehensive strategic understanding of the subject.

Second, Porter's Five Forces analysis was utilized to evaluate the industry's competitive forces, including the bargaining power of suppliers and customers, the threat of new entrants, the threat of substitutes, and the intensity of rivalry among existing competitors.

As we move forward, the next three chapters will delve into the findings and insights derived from these approaches. Chapter 4 focuses on the results of the SLR. Chapter 5 will explore the data collected through semi-structured interviews, offering a deeper understanding of stakeholder perspectives. Chapter 6 will provide a strategic analysis, integrating the SWOT-TOWS and Porter's Five Forces analyses to guide the formulation of strategic recommendations and future directions for the research.

Chapter 4

SYSTEMATIC LITERATURE REVIEW

The chapter covers the qualitative systematic literature review of documents on the feasibility of the South African coal-to-carbon industry.

4 Systematic Literature Review on the Coal-to-Carbon Industry (Feasibility- Barriers and Enablers and Opportunities)

4.1 Introduction

The SLR was conducted to explore and analyse the feasibility barriers and enablers of developing valuable coal-based carbon products and technologies in South Africa, as well as identifying opportunities for new products in the CTC industry.

4.2 Data Summary

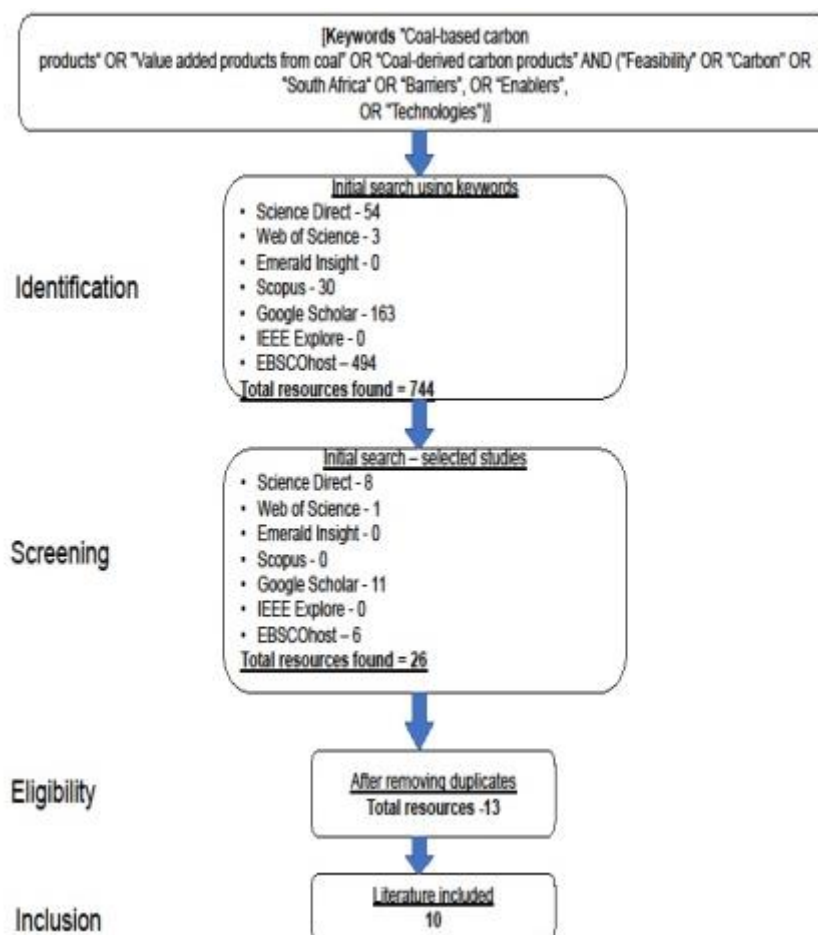


Figure 15 Selection Process Chart

Initially, the literature search and retrieval were conducted using the databases outlined in Section 3.4.4. This yielded **744** studies, of which 13 met the inclusion criteria. This yield was due to databases producing articles that referred to other coal studies (and not focused on coal-to-carbon processing) and some articles that were not on the coal-to-carbon industry but mentioned the keywords in their paper.

The selected publications are listed in Table 5. They were selected based on their relevance to the inclusion and exclusion criteria and aim of the SLR.

The initial screening based on titles and abstracts produced more than a hundred publications which led to the full-text assessment to further trim the number of publications. Eligibility and quality were assessed, and the cross-checking of the references and citations was done producing 13 publications. A second iteration of eligibility and quality assessment reduced the total of number of publications selected from the systematic literature review to 10.

Table 5 Literature Source Table

| Publication | Title | Authors | Year |
|-------------|--|---|------|
| L1 | Development of High Value-Added Carbon Materials from Coal | Wang, T. | 2021 |
| L2 | Coal in a New Carbon Age: Powering a Wave of Innovation in Advanced Products & Manufacturing | Atkins, R., W. Atkins, C., Cesar, M. N., Denton, D., Collins, D., Glesman, S., Swift, J., Targett, M., and Gellici J. | 2019 |
| L3 | Development of Microporous Shape-Selective Catalysts for Ethylene, Propylene, and other Value-Added Products via C-1 Chemistry. C1 | Prakash, A., Huang, X., Dubois, D., Obrzut, D., Jyothi, T., Liu, J. and Guin, J., | 2002 |
| L4 | Direct liquefaction of coal with coal-derived solvents to produce precursors for carbon products | Fenton, D. C. | 2001 |
| L5 | Traditional earth-abundant coal as new energy materials to catalyse the oxygen reduction reaction in alkaline solution | Chen, X., Huang, X., Wang, T., Barwe, S., Xie, K., Kayran, Y.U., Wintrich, D., Schuhmann, W. and Masa, J | 2016 |

| | | | |
|------------|---|--|------|
| L6 | Carbon Forward Advanced Markets for Value-Added Products from Coal | Andrews, R., Duddy, J., Gellici, J., Johnson, K., Meyers, L., and Skoptsov, G. | 2019 |
| L7 | A brief review on coal reserves, production, and possible non-power uses: The case of Mexico. | Dávila-Pulido, G.I., González-Ibarra, A.A. and Garza-García, M., | 2023 |
| L8 | Proceedings Report: Technological Innovations for a Low Carbon Society Conference. | Academy of Science of South Africa. | 2013 |
| L9 | Syngas production from South African coal sources using Sasol–Lurgi gasifiers | Van Dyk, J.C., Keyser, M.J. and Coertzen, M. | 2006 |
| L10 | Considering non-power generation uses of coal in the United States | Gagarin, H., Sridhar, S., Lange, I. and Bazilian, M.D. | 2020 |

The systematic literature reviews questions where: (1), what are the holistic feasibility barriers and enablers of the coal-to-carbon industry and (2) what the opportunities are offered by the coal-to-carbon industry. These questions guided the data extraction process. The objective was to gather data that would aid in exploring and analysing the feasibility barriers and enablers of developing valuable coal-based carbon products and technologies in South Africa, as well as identifying opportunities for new products in the CTC industry.

The researcher served as the primary reviewer in validating the SLR search results. Publications documented for the study included commissioned reports. The limited number of studies meeting the criteria is due to the specialized and emerging nature of the South African CTC industry, the narrow focus of the research, and the need for high-quality, directly relevant sources to support the work.

4.3 Data Extraction

The final ten publications focusing on the feasibility of the coal-to-carbon industry were documented and narrative synthesis was conducted. The summary of the included studies, study design, research methods and core findings are given in Table 6.

Table 6 Data Extraction Form

| Publication | Study Design | Research Methods | Core Findings |
|-------------|-------------------------------------|--------------------------------|--|
| L1 | Experimental | Laboratory Experiments | Coal shows significant potential as a feedstock for high-value carbon materials with a strong reliance on aromatic structures, such as graphene, carbon fibres (CFs), and carbon quantum dots (CQDs). To maximize coal's utility while minimizing environmental impact, innovative eco-friendly technologies must be developed. Encouragingly, there have been promising developments in the sustainable utilization of coal, yielding products like carbon nanofibers and carbon quantum dots. As a result, coal tar pitch is being assessed as a potential precursor for carbon fibre production (CF). |
| L2 | Qualitative, directional assessment | Nine-block analysis Surveys | The coal-to-carbon industry presents significant growth opportunities in the United States, potentially surpassing coal power generation. This is driven by the expanding market for carbon-based products with an 18% annual growth rate. These products include batteries, graphene sensors, graphite, and carbon fibres, all important in various industries. Embracing these markets can benefit the U.S. economy and address various issues. However, challenges like financing, permits, and technology barriers need to be addressed. Successful initiatives often involve |

| | | | |
|-----------|--------------|------------------------------|---|
| | | | collaboration between public and private sectors. |
| L3 | Experimental | Laboratory Experiments | There are various viable processes to produce high value carbon products. For each carbon product, there are different routes for its production. |
| L4 | Experimental | Laboratory Experiments | The study focused on creating carbon product precursors using coal as the raw material. Coal is a feasible source of carbon for manufacturing carbon-based products. Different methods exist for producing pitch, which serves as a potential precursor for carbon products. Anisotropic pitch can be generated irrespective of the choice of solvent. Coal offers advantageous conditions for manufacturing precursors like pitches and cokes/chars. |
| L5 | Experimental | Electrochemical measurements | While coal is a readily available energy source, its direct burning leads to significant environmental pollution. Hence, there is a crucial need to create higher-value products from coal and optimize its overall value chain. Non-precious catalysts, like carbon-based materials such as graphene, carbon nanotubes, carbon foams, and amorphous carbon, have gained significant interest as potential alternatives for ORR catalysts. These materials can be prepared from various coal sources. |
| L6 | Qualitative | Surveys Consultations | The coal conversion value chain is well established. To successfully implement technologies for producing high value products from coal, it's crucial to bridge the variance between basic laboratory research and practical applications. This entails the development of advanced manufacturing |

| | | | |
|-----------|--------------------------|-------------------|---|
| | | | <p>techniques. Additionally, a shortage of seasoned project managers with extensive experience has been identified as a potential obstacle to the success of commercial project demonstrations. In many instances, using coal as a raw material or feedstock simplifies the production process, leading to lower energy requirements, reduced production costs, improved product performance, and minimized environmental impacts. However, competition exists with other hydrocarbon feedstocks like natural gas and petroleum coke. The industry also promotes interdisciplinary research and facilities for the industries are advanced and can be co-located.</p> |
| L7 | Quantitative/Qualitative | Literature Review | <p>There is potential to explore alternative non-power uses of coal. These include utilizing coal for the extraction of rare earth elements, manufacturing carbon-based materials, and producing humic substances and materials. These alternative applications present avenues for industry development in Mexico. The availability of resources like coal enables the industry. The advanced carbon product Industry is an alternative to the current coal utilisation. Critical factors to the industry are external funding and competition.</p> |
| L8 | Mixed methods | Reviews | <p>Transition management is essential, and there is a significant need for establishing regulations, standards, and accessing international financing options. Developing innovative business models is also crucial. Emphasizing the collaboration between the government and the private sector, including</p> |

| | | | |
|------------|---------------------------------|----------------------------|--|
| | | | all stakeholders through public-private partnerships, is important. The transition to a low-carbon society in South Africa may not hinge primarily on technological aspects. |
| L9 | Experimental Qualitative | Experiments Reviews | There are abundant feedstocks and skills that enables the coal-to-carbon industry. Valuable by-products like tars, pitches, oils, and chemicals are manufactured by Sasol through the Fischer-Tropsch technology, and this forms the basis of high value carbon products production. |
| L10 | Qualitative | Literature Review | There are technically feasible products for coal to produce carbon products, but there are environmental impacts and high costs. The CTL infrastructure is major building block of the CTC industry. Issues of emission are critical to the production of coal-based products. The lack of carbon technology is a barrier to the industry. |

4.4 Reflection on SLR Results

The results showed that there are limited publications on the coal-to-carbon industry as it is a relatively new and novel industry. The industry is not universally termed coal-to-carbon, but the publications referred to the production of high-value carbon products. Five of the publications in the review are grey literature (conference reports, working papers, theses, technical reports etc) with the five papers published in Journals. This shows that the status of research published on the industry is still in its infancy. The scarcity of papers suggests a pressing need for further research into the various aspects of the industry.

4.5 Coding and Categorization

The publications selected from the systematic literature review provided insights into the feasibility of the coal-to-carbon industry. Analysing the key findings resulted in the identification of specific codes and code groups or categories, which are presented in Table 7.

Table 7 Codes and Categories

| Categories | Codes |
|--|--|
| 1. Carbon Products from Coal | <ul style="list-style-type: none"> • Carbon materials like graphene, carbon fibres, and quantum dots. • Innovative eco-friendly technologies. • Sustainable utilization of coal. • Coal tar pitch as a precursor. |
| 2. Growth Opportunities in the industry | <ul style="list-style-type: none"> • Growth potential in the industry. • Expanding market for carbon-based products. • Collaboration between public and private sectors. |
| 3. Diverse Carbon Production Processes | <ul style="list-style-type: none"> • Various processes for high-value carbon products. • Different routes for production. |
| 4. Coal as a Precursor for Carbon Products | <ul style="list-style-type: none"> • Coal as a feasible source of carbon. • Methods for producing pitch. • Advantageous conditions for manufacturing precursors. |
| 5. Value Optimization and Environmental Concerns | <ul style="list-style-type: none"> • Creating higher-value products from coal. • Non-precious catalysts. • Utilization of coal sources for carbon-based materials. • Environmental impact of coal burning. |
| 6. Bridging Laboratory Research to Practical Applications | <ul style="list-style-type: none"> • The established coal conversion value chain. • Advanced manufacturing techniques. • Competition with other feedstocks. • Interdisciplinary research and co-located facilities |

| | |
|---|---|
| <p>7. Alternative Non-Power Uses of Coal</p> | <ul style="list-style-type: none"> • Rare earth element extraction. • Humic substances and materials. • Industry development opportunities. |
| <p>8. Transition Management and Collaboration</p> | <ul style="list-style-type: none"> • Establishment of regulations and standards. • International financing options. • Innovative business models. • Public-private partnerships. |
| <p>9. Abundant Feedstocks and Skills</p> | <ul style="list-style-type: none"> • Valuable co-products from Fischer-Tropsch technology. • Basis for high-value carbon products production. |
| <p>10. Technically Feasible but Environmental Concerns</p> | <ul style="list-style-type: none"> • Technically feasible coal-to-carbon products. • Environmental impacts and high costs. • CTL infrastructure and emission issues. • Barrier due to lack of carbon technology |

The codes and categories presented in Table 8 are a result of the constant comparison done in relation the questions the study is answering. The iterative process led to the final 10 categories with corresponding codes.

4.6 The Summary of Themes

The systematic literature review selected publications provided insights into the feasibility of the coal-to-carbon (CTC) industry. The publications included the publications that focused on the global coal-to-carbon industry. These feasibility factors (enablers, barriers, and opportunities) are applicable to South African industry. The analysis yielded the following themes: resource availability, feasibility of production processes, technology readiness, advanced markets opportunities, value chain transformation and the effects of pollution.

4.6.1 Resource Availability

Many countries, including the United States, China, Mexico, and India, possess significant coal reserves. This assures a reliable and ample supply of feedstock for coal-to-carbon processes, reducing concerns about resource scarcity. From studies done in these countries (L1, L2, L6, L7, L10), it shows that the availability of coal resources is major enabler to the industry. South Africa has abundant coal resources (Sasol, 2021; Van Dyk *et al.*, 2006).

A single carbon precursor that is a resource to the CTC industry is coal tar pitch. (L1, L4, L6, L9) In areas that are coal dependent, coal tar pitch is readily available from various production processes like the carbonization processes. Coal tar pitch is a precursor used in the production of advanced carbon materials (carbon fibres and composites, resins, carbon black, and nano carbons); char produces activated carbon; and volatile coal gases produce hydrocarbons, nano products and carbon materials (Reid, 2021).

The resources required for the CTC industry are vast, but from the systematic literature review, it emerged that the major ones are raw coal, processing facilities, conversion technologies, water, market access and financing (L2, L3, L6, L7, L10).

Availability of freshwater resources is essential for coal gasification and carbon capture. Regions with access to abundant freshwater resources have a competitive advantage in establishing coal-to-carbon facilities.

4.6.2 Production Processes

The coal-to-carbon industry converts coal or carbon precursors from coal into high-value non energy carbon products. There are various technically feasible carbon products from coal (L3, L7, L10). The CTC is a rapidly growing industry (Reid, 2021), it is expanding in research and development, as companies and government units seek to create sustainable and innovative production processes. The industry uses a variety of paths to manufacture value-added carbon products from coal, as well as a variety of technologies.

Continuous research and development in gasification and carbon capture and sequestration (CCS) technologies have resulted in more efficient processes. These advancements can potentially lower production costs, making the coal-to-carbon industry more economically viable.

Larger production facilities benefit from economies of scale, which can significantly reduce production costs per unit of carbon product. Scaling up operations may be a key strategy for improving economic viability.

Lack of carbon technology to produce the final carbon products is a current barrier that needs to be confronted (L2, L10). The technology barriers limit the expansion of the industry but also at the same time it's an opportunity for research and development.

4.6.3 Technology Readiness

The CTC industry often incorporates advanced technologies for carbonization, gasification, and carbon material production. These technologies can be integrated into existing coal conversion processes, leading to more efficient and environmentally friendly operations. The coal conversion industry has been there for decades, (L3, L8, L9, L10) and therefore the major building blocks for the industry are already in place. From coal mining to coal beneficiation, the industry is rock solid. The only technology barriers are the final product technologies (L2, L10).

It can influence the downstream part of the value chain by expanding markets for coal-derived products. While traditional coal conversion products serve established industries, high-value carbon products have applications in emerging sectors like automotive, aerospace, and renewable energy, creating new market opportunities.

4.6.4 Advanced Markets

The advanced markets of the CTC industry are characterized by the production of high-value carbon-based materials and products with diverse applications. These markets offer strategic importance, growth potential, and innovation opportunities across various industries, making them a focal point for the coal-to-carbon sector's development and economic impact. The industry offers a great opportunity as it has current expanding markets (L2, L6). The studies in the US showed that the opportunities offered are compelling.

These advanced markets exhibit significant growth potential, driven by the need for improved materials in various sectors. Carbon fibres, graphene, carbon-based batteries, and High-performance composites headline the advanced markets for the industry. These materials are essential for improving energy storage and efficiency, contributing to the growth of the energy storage market. Coal-derived carbon materials can be used in various components of renewable energy systems (Reid, 2018, 2021).

4.6.5 Value Chain Transformation

The CTC industry has the potential to transform the coal conversion value chain by introducing new products, advanced technologies, and environmental considerations. This transformation can create opportunities for diversification, market expansion, and improved efficiency while also necessitating changes in coal processing and the development of a skilled workforce.

The industry broadens the product range in the coal conversion value chain. While traditional coal conversion processes primarily focus on energy production and chemical feedstocks, the coal-to-

carbon industry introduces high-value carbon products like carbon fibres, activated carbons, and advanced materials. This diversification adds new revenue streams to the value chain.

For the complete value chain transformation of the industry, there is need for collaboration across the various disciplines. The cited areas that need collaboration are in bridging the gap between laboratory research and practical applications (L6), interdisciplinary research (L6), technology development (L10).

4.6.6 Pollution Challenges

The combustion of coal and certain coal conversion processes release enormous amounts of carbon dioxide (CO₂) into the atmosphere, leading to climate change (L5, L10). The CTC production processes also release various air pollutants, including sulphur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter, and volatile organic compounds (VOCs). These pollutants can have adverse effects on air quality and human health.

Discharges from coal mining and processing can contaminate water sources with pollutants such as heavy metals, sediment, and chemicals. Runoff from coal storage areas or disposal of waste by-products can also lead to water pollution.

Coal processing generates significant amounts of solid waste, such as ash and sludge. Improper disposal of these wastes can result in environmental contamination.

4.7 Chapter Summary

The chapter discusses the systematic literature review conducted in the study and presents the findings from various publications. The results indicate a scarcity of publications on the CTC industry. The primary discoveries from the review highlight that coal holds considerable potential as a feedstock for high-value carbon materials and products. Additionally, there are notable growth opportunities and potential markets within the industry that can be advantageous. The review also identifies several viable processes for producing high-value carbon products and underscores significant environmental concerns associated with the industry.

Chapter 5

THE INTERVIEWS – DATA, FINDINGS AND ANALYSIS

This section provides the findings and analysis from the interviews

5 Interviews

5.1 Introduction

Semi-structured interviews were conducted with practitioners in the coal-to-carbon industry in South Africa and expert researchers in coal-based carbon products. The interviews were designed to gather primary data and insights on the feasibility barriers and enablers for developing valuable coal-based carbon products in South Africa, as well as identifying opportunities for new products in the coal-to-carbon industry. The researcher wrote a paper on the findings from the interviews, which was accepted and presented at the SAIIIE33 conference. The paper can be found in Appendix H.

5.2 Data Summary

The thematic analysis of interview transcripts resulted in the identification of various codes. Initially, 25 participants were approached for the study, but not all opted to participate. Following a process of snowballing and reaching saturation, the final number of participants settled at 13. A sample transcript, analysed thematically with associated codes, is provided in Appendix E.

The coding process was facilitated using Atlas.ti. Figures 16, 17, and 18 are included, presenting network diagrams that illustrate the relationships between codes and the emerging themes. Figure 16 highlights the codes associated with the availability of enablers in the coal-to-carbon industry.

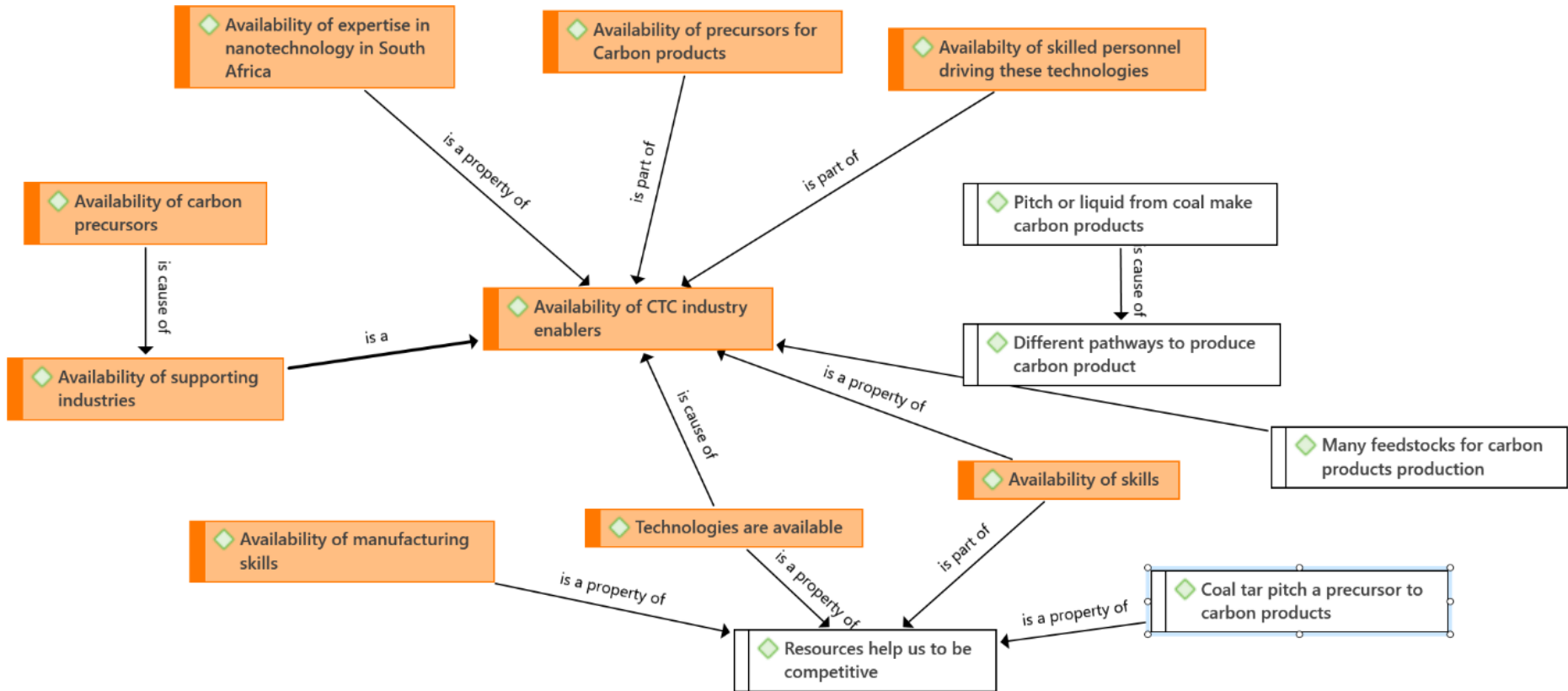


Figure 16 Network Diagram Depicting Availability of CTC Industry Enablers.

Figure 17 shows the codes associated with the opportunities highlighted by the participants in the study for the coal-to-carbon industry.

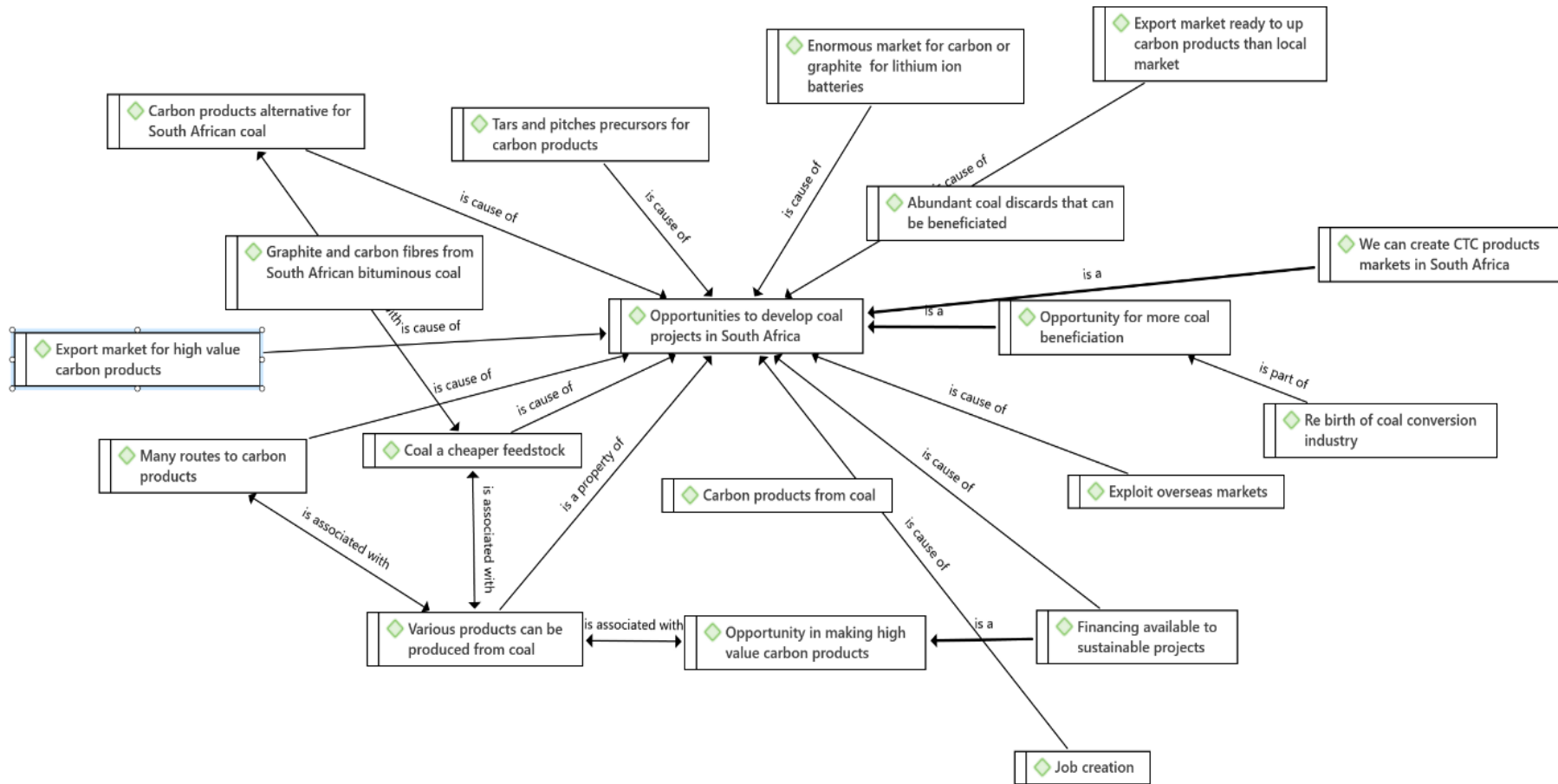


Figure 17 Network Diagram Depicting Opportunities in the CTC industry.

Figure 18 illustrates the challenges within the coal-to-carbon industry, with corresponding codes indicating each challenge for clarity.

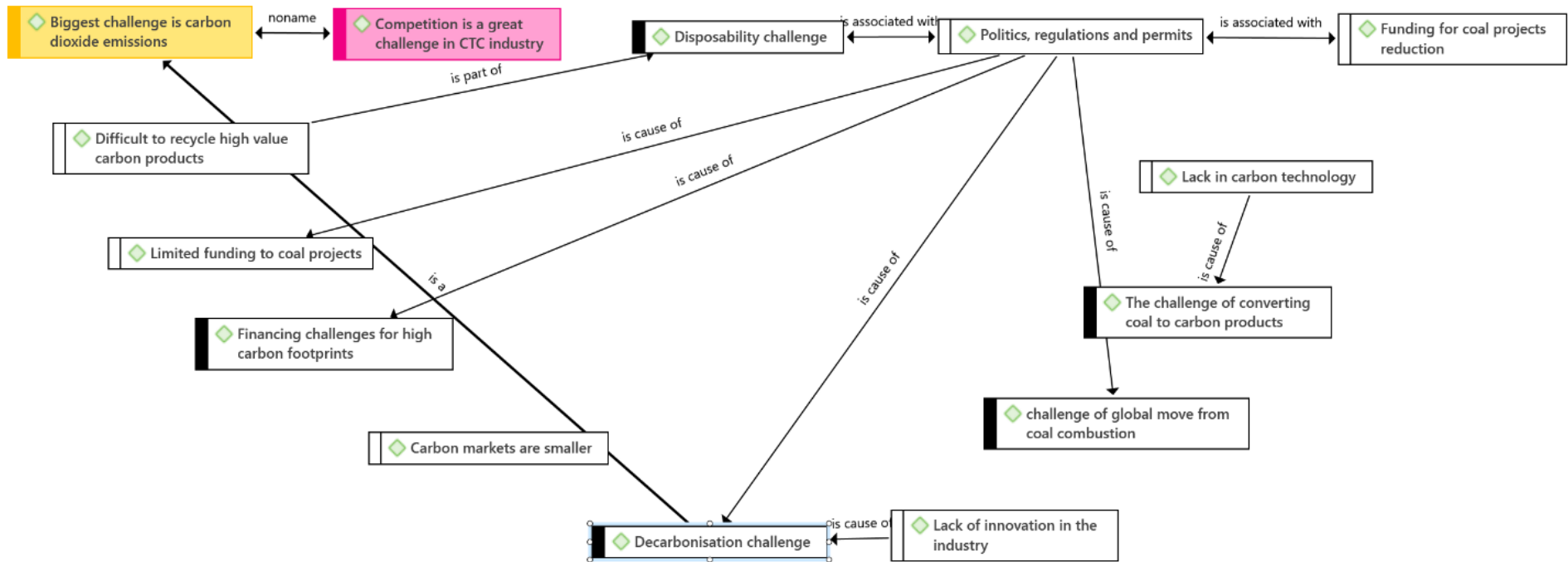


Figure 18 Network Diagram Depicting Challenges in the CTC industry.

5.3 Themes and Sub themes

The interview data produced themes and sub-themes that captured the feasibility factors (enablers and barriers) and opportunities that affect the viability of the CTC industry in South Africa. Table 8 shows the themes and subthemes that were consolidated after an initial set of 20 themes.

Table 8 A List of Themes and Sub-Themes

| THEMES | SUB-THEMES |
|----------------------------|--|
| 1. ENABLERS | Availability of feedstocks |
| | Availability of skilled personnel |
| | Availability of supporting industries |
| | Market availability |
| | Coal is a cheaper feedstock |
| 2. CHALLENGES | Environmental |
| | Funding |
| | Markets |
| 3. COMPETITION | Feedstocks |
| | Markets |
| 4. INDUSTRY GAPS | Lack of carbon manufacturing industries |
| | Lack of visibility |
| 5. COAL UTILISATION | Primary, predominant and /traditional uses |
| | High-value utilisation |

5.3.1 Enablers

The coal-to-carbon sector in South Africa is poised to be dynamic and competitive, as indicated by study participants. The production of valuable carbon products from coal necessitates specific skills, technologies, and resources for success. Enablers for the South African coal-to-carbon industry were identified by participants, with the first being the accessibility of feedstocks or entities producing carbon precursors. South Africa boasts abundant coal as a feedstock according

to Van Dyk *et al.* (2006), and the high carbon content of its coking coals makes them a source of high-value carbon products.

A crucial industry enabler identified was the production of carbon precursors from coal, specifically pitches and tars from Sasol and ArcelorMittal. Coal-tar pitch, a significant precursor, is used in the production of advanced carbon materials (Reid, 2021). The tar, chars, and coke from the carbonisation process are currently employed in the synthesis of synthetic carbon materials (Mikociak *et al.*, 2014; Moothi *et al.*, 2012).

Key to the processes involved in manufacturing carbon-based products with significant economic value are facilities that produce carbon precursors, and South Africa possesses Sasol, which produces tars, pitches, and light charcoal. The high-temperature pitches from ArcelorMittal's coking processes can be utilized to manufacture carbon fibres and other carbon nanomaterials, while the cokes can produce activated carbons and carbon electrodes.

South Africa was acknowledged the availability of proficient and qualified personnel manufacturing, operating state-of-the-art facilities in various fields. The country is actively training personnel to handle advanced technologies, including Sasol's Fischer Tropsch technology, nuclear power stations, and Eskom power plant technologies. Leveraging this skilled workforce, South Africa can further develop the coal-to-carbon industry by either developing or acquiring the necessary technologies for high-value carbon product production.

In the realm of the coal-to-carbon industry, nanomaterials emerge as high-value products showing great promise, and South Africa is well-equipped to support their production. The government's investment in the industry, specialized research entities focusing on nanotechnology, and facilities producing nanomaterials using various feedstocks contribute significantly to the industry's growth.

"So, what we got is many people who understand nanotechnology . . . High tech carbon is nanotechnology basically. It's just a component, nanotechnology is the overriding issue, so carbon is one component of it." (P4)

Another enabler highlighted is the presence of supporting industries for the coal-to-carbon sector in South Africa. These industries, providing carbon precursors and stable electricity, play a crucial role in the industry's success. The carbon products find applications as raw materials in various South African industries, with the automotive sector being a prominent consumer of high-value carbon products.

"...you've already got some industries you can go to." (P2).

The international and local markets were identified as complementary enablers for the industry. The local market readily absorbs relatively cheaper carbon products, while the international market supports high-value products. Participants expressed optimism that the international market could embrace high-quality products.

"I think high tech you(‘ve) got to go to the international market. The low tech you got a local market. Remember you can use these high-tech materials if you can make them cheaply, they may have properties that you want so you may want to put high-tech carbon into low-tech places." (P4)

The study, evaluating the feasibility of carbon product production from coal, underscores another industry enabler—the cost advantage of coal as a feedstock. Coal is considerably less expensive (\$12-\$50/ton) compared to traditional feedstocks like petroleum (\$400-\$500/ton) (Atkins *et al.*, 2019), providing a cost advantage in carbon material production.

5.3.2 Challenges

Numerous obstacles surround the viability of the coal-to-carbon industry in South Africa, with environmental concerns identified as the foremost challenges according to study participants. The existing processes for producing carbon precursors in the country contribute significantly to greenhouse gas emissions. The technologies involved in coal carbonisation and liquefaction, which generate tars and pitches, release substantial amounts of carbon dioxide and sulphur into the atmosphere. Overcoming this environmental hurdle is crucial for the industry's success.

"It's a fossil fuel and it's a major cause because I mean in South Africa it contributes quite a lot to see CO₂ emissions. Right, that is one of the biggest challenges with this industry." (P7)

Addressing the environmental issues could involve considering investments in carbon capture and sequestration technologies tailored to the South African context. These technologies are designed to capture and store carbon dioxide and other greenhouse gases produced during the manufacturing of carbon products, offering a potential solution to the identified environmental challenges.

Another impediment to the feasibility of the coal-to-carbon industry is intertwined with environmental apprehensions. Securing financing for new coal projects becomes a daunting task due to perceived environmental risks. The shift away from unabated coal use poses limitations on funding for coal-based projects. Nevertheless, participants argue that sustainable coal projects can still access funding, emphasizing the importance of adhering to environmentally sound practices.

Despite the high value of products in the carbon industry, the market remains relatively small. The local carbon market is constrained by several factors, with traditional materials such as steel, aluminium, and concrete dominating. However, there is potential for carbon materials and products to expand their market share, given their superior properties. The challenge lies in overcoming the established dominance of traditional materials in the market.

"The market is there, but it's small. It's not sustainable." (P13)

5.3.3 Competition

The competition within the coal-to-carbon industry manifests in two dimensions: the competition for precursors required in carbon product production and the competition among final products. The production of high-value carbon products relies on the availability of carbon in feedstocks. The petrochemical industry, acting as a supplier of carbon-containing feedstocks, emerges as a direct competitor to the coal-to-carbon industry.

Certain carbon products already have established feedstocks in their production processes. For instance, in the production of carbon fibres, polyacrylonitrile currently dominates, accounting for 90% of all feedstocks, followed by Rayon (Reid, 2021). Additionally, activated carbon can be derived from various trees in South Africa, which serve as abundant biomass materials.

The market plays a pivotal role in determining the success of an industry. The South African coal-to-carbon industry faces competition in the market from advanced economies in Europe, the United States of America, and Asia. These countries, with more sophisticated carbon product manufacturing industries, present formidable competition to the South African coal-to-carbon industry. With their advanced manufacturing capabilities, these economies hold dominance in the markets for advanced carbon materials. Consequently, South Africa may encounter challenges entering the market for carbon fibre products and securing market share against these well-established economies.

"You are competing with international people, and you've got to look at your markets, so you know the type of thing is the low-level stuff is easier to get a handle on because the market is here." (P4).

5.3.4 Industry Gaps

To achieve full functionality, certain gaps must be addressed within the South African coal-to-carbon industry. Presently, only a fraction of the industry is operational, with the production of carbon precursors standing out as the predominant segment. Optimization of the industry's value

chain is imperative, and participants in the study identified notable gaps and sectors in the industry narrative.

The most conspicuous gap is the absence of carbon manufacturing industries. Although South Africa currently produces final carbon products such as carbon black and activated carbon, there is a notable deficiency in the production of other high-value carbon products. The country, in general, lacks sufficient carbon technologies.

"I think in terms of market availability that is also where there is a very big gap there. The coal producers in the country do not know, they're not necessarily aware of all the different markets that they could sell their product into." (P1).

The coal-to-carbon industry faces a visibility challenge, being a niche component within the broader coal conversion industry that remains relatively obscure. Local coal producers primarily target traditional markets for conventional coal utilization rather than tapping into the potential market for the coal-to-carbon industry, where coal serves as a feedstock.

While the country has made significant investments in coal research, there remains a gap in the production of carbon products derived from coal. Despite extensive research in the realm of coal conversion, these concepts have not been effectively implemented.

A recurring theme emphasized by the participants is the necessity for collaboration or participation among various stakeholders in the industry. For the South African coal-to-carbon industry to progress, stakeholders must unite and collectively propel the industry to the next level.

"So, I think those are some of the issues that need to be . . . collaboration between the universities, research institutions, the industry, the government is key also to ensure success in this program." (P13)

5.3.5 Coal Utilisation

South Africa possesses abundant coal resources and reserves (Van Dyk *et al.*, 2006), extensively utilized in power generation, synthetic fuel production, steel manufacturing, and for export purposes, as highlighted by the participants. The country is recognized for its advanced utilization of coal resources, particularly in pioneering synthetic fuel production and other applications. This perception of extensive coal resource utilization is grounded in the current practices observed in South Africa.

"Because these are the technologies that are available for power generation and for coming up with fuel so basically based on the technologies that we have, we are using it to the fullest." (P3)

However, when considering the comparison between the country's coal resources and the production of coal-based materials and products, some participants expressed differing opinions, indicating that the utilization might not be at its optimum. The production of carbon products from coal is notably deficient in South Africa. Therefore, to achieve optimal use, there is potential in leveraging coal resources to produce high-value carbon products. The high-quality, low-ash South African bituminous coals serve as excellent starting materials for manufacturing high-value carbon products that can be exported to international markets.

Despite this, there is no unanimous agreement among participants regarding whether coal resources are being fully utilized in South Africa. The potential to use available coal resources for carbon product production exists, but underutilization is attributed to various interrelated reasons cited by participants. Lack of knowledge about using coal for carbon products, coupled with the predominant use of coal for traditional purposes, contributes to underutilization. Additionally, the local coal conversion industry is perceived as lagging in terms of innovation.

"In South Africa, ... most of the companies haven't been innovating in that they don't do R and D (research and development). Whereas overseas, most industries actually support, and are highly innovative." (P9)

Finally, participants pointed out that the current use of coal is anticipated to undergo changes in the future, with certain utilization processes expected to cease. Potential future uses of coal in South Africa include chemical production and the production of carbon materials. The 26th Conference of Parties held in Glasgow in 2021 resolved to pursue the reduction of unabated coal use. Consequently, traditional coal use in power generation or other applications that pollute the environment could see a decline in the future.

"In my opinion over the course of the next let's say 10 to 20 years, there is going to be a shift from industries that use coal and emit a lot of carbon dioxide and if coal is to have a future it's not in combustion or gasification it's going to be chemicals production and carbon materials production." (P6)

5.4 Convergence of Themes

The South African coal-to-carbon industry has notable enablers, but it faces challenges related to environmental impact, funding, market size, and global competition. To reach its full potential, the industry needs to address these challenges, develop missing components, and foster collaboration among stakeholders while considering the changing landscape of coal utilization.

5.5 Chapter Summary

This chapter presents the data gathered through interviews and outlines the themes that emerged from the subsequent data analysis. The thematic analysis process conducted led to crucial findings. In South Africa, there are noteworthy factors supporting the feasibility of the industry. However, challenges include the significant contribution of existing processes for producing carbon precursors to greenhouse gas emissions, limited financing for coal-based projects, and a relatively small market. Currently, only a fraction of the industry is operational, with the production of carbon precursors standing out as the predominant segment, highlighting gaps in the CTC industry narrative. The insights gained from interviews and the analysis process shed light on the industry's feasibility.

Chapter 6

STRATEGIC ANALYSIS

An in-depth strategic analysis of the feasibility factors that affects the coal-to-carbon industry.

6 Strategic Analysis

6.1 Introduction

This chapter delves into strategic analysis of the feasibility factors influencing the industry. By employing tools such as SWOT analysis, TOWS matrix, and Porter's Five Forces model, the aim is to comprehensively assess the strengths, weaknesses, opportunities, and threats that shape the landscape of our industry. This strategic examination will provide valuable insights into the dynamics and potential avenues for success in the competitive business environment.

6.2 The Porter's Five Forces Analysis

An industry according to Porter's five forces framework is affected by five forces, which help understand the industry and these dynamic forces show the high-level feasibility of the CTC industry. The South African CTC industry is placed in a framework with the findings offering a unique insight into its bargaining position and therefore its relative feasibility.

The CTC industry has features of competitive forces which are analysed and shown in Figure 16. Using (data), the various forces were evaluated in accordance with this strategic tool. Each theme that emerged from the systematic literature review and the semi-structured interviews is analysed using the strategic tools, leading us to strategies that can be applied to the South African coal-to-carbon industry.

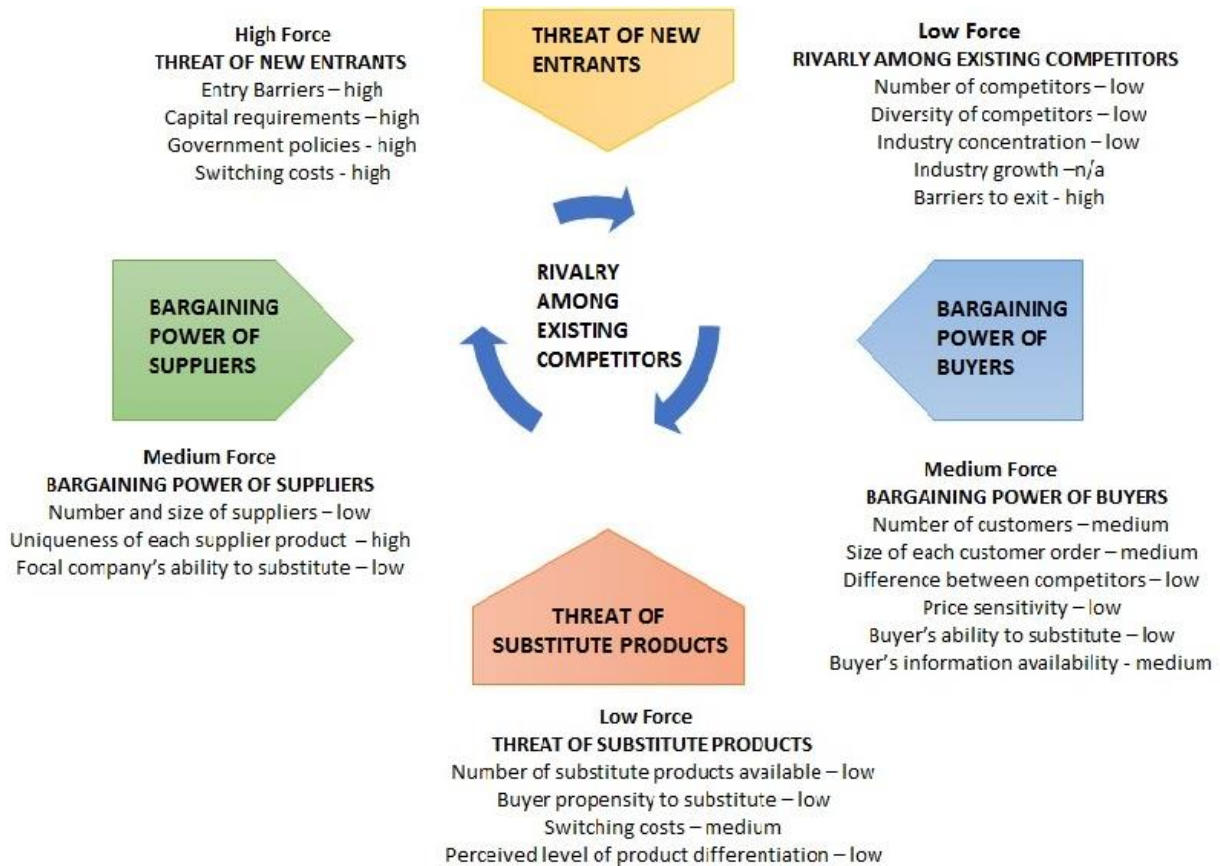


Figure 19 Coal-to-Carbon Industry's Porter's Five Forces Analysis

6.2.1 Bargaining Power of Buyers (Competition, Resource Availability)

Buyer bargaining power in the South African coal-to-carbon industry is influenced by a combination of global competition, resource availability, market dynamics, and the nature of the products involved. The accessibility of information, economic challenges, customization requirements, switching costs, and the global market expansion contribute to the varying degrees of bargaining power held by buyers. The industry must carefully navigate these factors to maintain balanced relationships with buyers and adapt strategies accordingly to remain competitive in a globalized marketplace.

Global competition, especially in advanced markets, contributes to increased buyer bargaining power. The accessibility of information in the information age enables buyers to compare offerings from various suppliers worldwide. This global perspective allows buyers to demand more favourable terms and prices.

The availability of resources, such as coal, plays a significant role in influencing buyer power. If alternatives are readily accessible, buyers gain increased leverage in negotiations. The presence

of diverse suppliers offering similar resources provides buyers with choices, enhancing their bargaining power.

The information age has empowered buyers with extensive information, giving them greater bargaining power. Local buyers of activated carbon and carbon black benefit from having local producers, strengthening their negotiating position. In contrast, for products like carbon fibre, where customization is prevalent, buyers may have less bargaining power due to limited readily available options.

Economic challenges within the local market further amplify buyer bargaining power. In a constrained market, sellers may be compelled to retain customers, giving buyers an advantage in negotiations.

Carbon fibre, being a custom-made product, introduces a unique dynamic in buyer-supplier relations. While this limits the number of readily available options for buyers, suppliers must be attentive to specific needs. This dynamic provides buyers with a certain degree of bargaining power, especially when dealing with products requiring specialized customization.

Low switching costs enhance buyer bargaining power. If the costs associated with changing suppliers are minimal, buyers are more inclined to explore alternative options. This flexibility gives them the ability to negotiate favourable terms and conditions with their current or potential suppliers.

The global market for activated carbon, carbon black, and carbon fibre is expanding. Buyers, particularly from overseas markets, gain increased bargaining power as they have more options and can explore alternative suppliers. However, local buyers in South Africa may face challenges due to limited suppliers, potentially reducing their bargaining power.

South Africa's ability to export products introduces an interesting dynamic. Overseas buyers, especially those in ready markets, provide additional opportunities for sellers. This global exposure potentially diminishes the bargaining power of local buyers, as sellers have alternative markets to explore.

The global nature of the industry enables buyers to leverage competition among suppliers on a global scale. Overseas markets allow buyers to compare prices, terms, and conditions more broadly, strengthening their bargaining power.

6.2.2 Threats of New Entrants (Enablers, Challenges)

The barriers to new entrants in the coal-to-carbon industry are significant due to its capital-intensive and highly technical nature, requiring specialized technologies. Threats to the industry include regulatory pressures and the need to reduce greenhouse gas emissions. Although the existing barriers are considered high, the potential emergence of radical new technologies could disrupt the current industry landscape, creating an open market for multiple entrants.

Enablers such as technology readiness, the presence of supporting industries, skilled personnel, availability of feedstocks, and advanced market opportunities can attract new entrants. However, challenges, such as high capital requirements, pollution concerns, and industry gaps, may act as barriers.

The coal-to-carbon industry faces a deficiency in carbon technology, posing a threat to companies seeking to enter the market. Larger-scale operations, such as those by Sasol or ArcelorMittal, often require substantial investments in research and development (R&D) and technological advancements. Economies of scale allow these companies to allocate more resources to innovate and enhance efficiency, yield, and quality in coal-to-carbon conversion processes. This can result in cost reductions, improved product performance, and enhanced environmental sustainability.

Companies operating on a larger scale can gain a competitive advantage when entering or expanding into new markets. Economies of scale enable them to offer competitive prices, negotiate favourable contracts with suppliers, and have greater bargaining power with customers. This can lead to increased market share, stronger customer relationships, and improved profitability.

Promising developments in the sustainable utilization of coal are evident, with large-scale operations optimizing resource utilization. This includes effective use of coal feedstock, waste minimization, and maximization of valuable carbon product output. Economies of scale facilitate more efficient extraction, processing, and utilization of resources, contributing to better resource management and reduced environmental impact.

The industry's pursuit of advanced technologies, processes, and products necessitates substantial investments in R&D. Economies of scale provide the financial resources required for significant R&D activities, enabling the industry to drive innovation, improve operational efficiency, and create new value-added products from coal.

Successful market entry strategies require comprehensive market research, risk assessment, and strategic planning to mitigate threats. Adapting to the unique characteristics of each market is essential for long-term success in the dynamic coal-to-carbon industry.

6.2.3 Bargaining Power of Suppliers (Industry gaps, Coal utilisation)

The bargaining power of suppliers in the South African coal-to-carbon industry is multifaceted. For bituminous coking coal suppliers, their influence is intricately tied to global market prices, with higher coal quality correlating with increased bargaining power. The concentration of exclusive producers controlling carbon precursor inputs further consolidates their negotiating strength.

The dependence on imported coking coal due to limited domestic production elevates the bargaining power of these suppliers. South African producers may face challenges in negotiating favourable terms due to this reliance on external sources.

The identification of industry gaps also plays a pivotal role. Suppliers who can effectively address these gaps hold a position of strength, potentially influencing industry dynamics. Additionally, the ability of suppliers to diversify coal utilization aligns with the industry's evolving needs, expanding their role, and bargaining power.

In conclusion, while global market dynamics and the concentration of precursor producers enhance supplier bargaining power, the industry's responsiveness to industry gaps and the versatility of coal utilization provide levers for negotiation. The coal-to-carbon industry in South Africa should carefully navigate these factors to maintain a balanced and mutually beneficial relationship with its suppliers.

6.2.4 Threats of Substitute Products (Value Chain Transformation)

The threat of substitute products for the South African coal-to-carbon industry is present, considering the established substitutes already in the market. However, the industry has the potential to counter this threat through value chain transformation.

By successfully transforming the value chain, the industry can optimize its processes, reduce costs, and introduce innovative products. This can create a competitive edge, making the coal-based products more attractive compared to existing substitutes.

The strategic introduction of products with superior qualities and competitive prices becomes a key element in mitigating the threat of substitutes. Despite the higher prices associated with CTC

industry products, the emphasis on superior properties provides a distinctive advantage, making them more appealing to consumers.

In conclusion, the threat of substitutes can be effectively managed through continuous value chain transformation, strategic product innovation, and maintaining a competitive pricing strategy. The industry's ability to leverage its strengths in product quality and value will play a pivotal role in minimizing the impact of substitute products in the market.

6.2.5 Rivalry Among Existing Firms (Competition, Industry Gaps)

The intensity of competitive rivalry in the South African coal-to-carbon industry is shaped by global competition, industry gaps, and the unique dynamics of a small market. While local rivalry remains low due to the niche nature of the industry, international competition is a significant factor.

Filling identified industry gaps becomes crucial for gaining a competitive advantage. However, the application of Porter's Five Forces underscores the industry's vulnerability to external factors, including supplier power fluctuations and buyer demands for sustainability.

The disruptive potential of new entrants and the need for carbon-neutral alternatives highlight the sector's evolving nature. The emphasis on innovation and adaptability is critical for businesses operating in this industry to thrive amidst intense competitive forces. Overall, the coal-to-carbon sector is characterized by its dynamic and disruptive nature, necessitating strategic agility for sustained competitiveness.

6.3 The SWOT Analysis

The strengths and weaknesses, opportunities and threats to the South African coal-to-carbon industry are shown in Table 9.

Table 9 The Coal-to-Carbon Industry's SWOT Analysis

| | Positive factors | Negative factors |
|-------------------------|--|---|
| Internal factors | <p>Strengths</p> <ul style="list-style-type: none"> Abundance of coal resource, which is a most readily available source of carbon. South Africa has technologies producing carbon precursors for carbon products production. | <p>Weaknesses</p> <ul style="list-style-type: none"> Some of the current CTC applications and or processes are uneconomical. Applications produce high level of emissions across their lifecycles. |

| | | |
|-------------------------------|--|---|
| | <ul style="list-style-type: none"> • Coal currently provides the least expensive source of carbon. • The cost effectiveness of the carbon precursors from coal • A pitch process eliminates the need for large-scale chemical plants. • Coal pitch possesses a high carbon content than other carbon precursors. • Carbon products are of high value. | <ul style="list-style-type: none"> • South African bituminous coal has high ash content. • The CTC industry is capital intense employing specialised technologies. • The current carbon precursor production technologies available in South Africa require carbon capture and sequestration technologies, which are expensive. • Pitch based CTC processes are complicated compared to the PAN based fibres. |
| External possibilities | <p>Opportunities</p> <ul style="list-style-type: none"> • Abundance of coal resources which are feed stocks to the SA CTC industry. • Creation of employment • Economic growth through high value products manufacturing • Reviving the coal sector • South Africa has available carbon precursors producing facilities. • The production of carbon products comes with opportunities for production of other products like various pitches which are commercially viable products. | <p>Threats</p> <ul style="list-style-type: none"> • The environmental regulations or policies. • Stiff competition from oil and gas derivatives as precursors and final products. • Commitments to COP 26 move to reduce use of unabated coal threatens the feasibility and commitments and investments to the industry are limited. |

The strengths and weaknesses, opportunities and threats to the South African coal-to-carbon industry are shown in Table 10.

Strengths

Abundant Coal Resources: South Africa possesses abundant coal resources, providing a readily available source of carbon. This abundance ensures a stable and continuous supply of raw material, a fundamental strength for the coal-to-carbon industry.

Advanced Market Opportunities: The industry benefits from advanced market opportunities, indicating potential for growth and expansion. This advantage allows the South African coal-to-carbon industry to tap into evolving global markets, fostering competitiveness and innovation.

Technology Readiness: South Africa boasts technologies capable of producing carbon precursors to produce various carbon products. This technological readiness positions the industry to adapt to changing demands, implement efficient processes, and stay at the forefront of carbon production.

Cost-Effective Carbon Source: Coal currently provides the least expensive source of carbon. The cost-effectiveness of coal as a carbon source enhances the industry's competitiveness, making it economically viable and attractive for production processes.

Efficient Carbon Precursors from Coal: The coal-to-carbon industry in South Africa utilizes efficient processes for producing carbon precursors. The pitch process eliminates the need for large-scale chemical plants, streamlining production and potentially reducing operational costs.

High Carbon Content in Coal Pitch: Coal pitch, a product of the industry, possesses a high carbon content compared to other carbon precursors. This characteristic contributes to the quality of the final carbon products, enhancing their value proposition in the market.

High-Value Carbon Products: The carbon products generated by the industry are of high value. This strength reflects the market demand for these products and the industry's ability to deliver valuable, sought-after carbon materials such as carbon fibre, activated carbon, and synthetic natural gas.

Weaknesses

Pollution Concerns: Pollution concerns represent a significant weakness for the coal-to-carbon industry. The negative environmental impact associated with certain processes and emissions raises concerns among consumers, regulators, and the public, potentially affecting the industry's social license to operate.

Industry Gaps: The presence of industry gaps constitutes a weakness for the coal-to-carbon sector. Unaddressed gaps may hinder overall efficiency, innovation, and competitiveness. Failure to bridge these gaps could result in missed opportunities for growth and development.

Limited Value Chain Transformation: Limited value chain transformation is a weakness within the industry. The lack of comprehensive transformation throughout the value chain may impede the industry's ability to adapt to changing market demands, reduce costs, and enhance overall sustainability.

Economic Viability of Some Applications/Processes: Some current coal-to-carbon applications or processes suffer from being uneconomic. This weakness can limit the industry's profitability and competitiveness, especially when compared to alternative technologies or energy sources.

High Emissions across Lifecycle: Certain applications within the coal-to-carbon industry produce high levels of emissions across their lifecycles. This environmental impact poses a challenge in an era where sustainability and carbon footprint are critical considerations for both consumers and regulatory bodies.

High Ash Content in South African Bituminous Coal: South African bituminous coal, a primary resource for the industry, has high ash content. This characteristic may pose challenges in terms of process efficiency, environmental impact, and the quality of the final carbon products.

Capital-Intensive and Specialized Technologies: The coal-to-carbon industry is capital-intensive and employs specialized technologies. This characteristic can be a weakness as it requires significant upfront investments, potentially limiting entry for new players and posing financial challenges for existing ones.

Carbon Capture and Sequestration Costs: The current carbon precursor production technologies in South Africa require carbon capture and sequestration technologies, which are expensive. The associated costs may hinder the economic viability of certain processes within the industry.

Complexity of Pitch-Based Processes: Pitch-based coal-to-carbon processes are complicated compared to PAN (polyacrylonitrile) based fibres. This complexity can be a weakness in terms of process efficiency, cost-effectiveness, and scalability, impacting the industry's ability to meet market demands.

Opportunities

Diversification in Coal Utilization: Opportunities lie in the diversification of coal utilization within the coal-to-carbon industry. Exploring new applications and processes for coal can lead to the creation of additional valuable products, expanding the industry's product portfolio.

Global Market Expansion: The global market for carbon products is expanding, providing opportunities for the South African coal-to-carbon industry to tap into new markets. This growth offers the potential to increase exports, revenue, and establish a stronger global presence.

Filling Identified Industry Gaps: The identification and filling of industry gaps present opportunities for the industry. Addressing gaps in processes, technology, or product offerings can enhance competitiveness, meet evolving market demands, and contribute to the industry's overall growth.

Abundance of Coal Resources: The abundance of coal resources in South Africa, serving as feedstocks to the coal-to-carbon industry, provides a strategic opportunity. The availability of this essential raw material ensures a reliable and consistent supply, supporting sustained production.

Creation of Employment: The coal-to-carbon industry has the potential to create employment opportunities. The development and expansion of the industry can contribute to job creation, supporting economic development and livelihoods in the region.

Economic Growth through High-Value Products Manufacturing: The manufacturing of high-value carbon products presents an opportunity for economic growth. The production of sought-after carbon materials, such as carbon fibre and activated carbon, contributes to the generation of high-value products that can drive economic prosperity.

Reviving the Coal Sector: There is an opportunity to contribute to the revival of the coal sector. By demonstrating sustainable and innovative uses for coal, the industry can play a role in ensuring the continued relevance and viability of the coal sector within the broader energy landscape.

Available Carbon Precursors Producing Facilities: The presence of available carbon precursors producing facilities in South Africa offers opportunities for the industry. Leveraging existing facilities can streamline production processes, reduce costs, and enhance efficiency in the generation of carbon precursors.

Production of Other Commercially Viable Products: The production of carbon products opens doors to opportunities for manufacturing other commercially viable products. Various pitches

derived from the process can serve as valuable raw materials for different industries, contributing to economic diversification.

6.4 The Tows Matrix

The TOWS analysis provides a strategic framework for the South African coal-to-carbon industry, emphasizing the importance of aligning internal strengths and weaknesses with external opportunities and threats to drive holistic feasibility.

Strengths-Opportunities (SO)

1. Leverage Abundant Coal Resources to Exploit Advanced Market Opportunities:

The industry can maximize its strengths in abundant coal resources by strategically exploiting advanced market opportunities. By aligning production with market demands, the industry can secure a competitive advantage, ensuring a consistent and high-value supply to global markets.

2. Capitalize on Technology Readiness to Diversify Coal Utilization:

Leveraging the existing technology readiness in South Africa provides an opportunity to diversify coal utilization. Exploring new applications and processes for coal can lead to the creation of additional valuable products, aligning with market trends and demands.

Weaknesses-Opportunities (WO)

1. Address Pollution Concerns to Capitalize on Global Market Expansion:

By addressing weaknesses related to pollution concerns, the industry can unlock opportunities for global market expansion. Implementing environmentally sustainable practices and technologies can enhance the industry's reputation and attractiveness in international markets.

2. Fill Industry Gaps by Transforming the Value Chain:

Transforming the value chain to fill industry gaps becomes a strategic approach to capitalize on opportunities. By addressing weaknesses related to limited value chain transformation, the industry can enhance efficiency, innovation, and overall competitiveness.

Strengths-Threats (ST)

1. Use Abundant Coal Resources to Counter Threats of High Capital Requirements:

The industry can strategically utilize its abundant coal resources to counter threats associated with high capital requirements. Optimizing processes and emphasizing efficiency in coal utilization can contribute to cost-effectiveness, reducing the impact of capital-intensive operations.

2. Leverage Technology Readiness to Mitigate Threats from Intense Global Competition:

Leveraging technology readiness becomes a key strategy to mitigate threats from intense global competition. By continuously adopting and adapting advanced technologies, the industry can enhance its competitive position, offering superior products and processes.

Weaknesses-Threats (WT)

1. Address Pollution Concerns and Industry Gaps to Mitigate Threats from Substitutes:

By actively addressing weaknesses related to pollution concerns and industry gaps, the industry can mitigate threats from substitutes. Developing environmentally friendly processes and closing existing gaps will enhance the industry's resilience against alternative products.

2. Work on Value Chain Transformation to Counter Threats from High Capital Requirements:

Addressing weaknesses through value chain transformation becomes essential to counter threats associated with high capital requirements. Streamlining the value chain can contribute to cost reduction and operational efficiency, making the industry more resilient in the face of capital challenges.

6.5 Chapter Summary

The strategic analysis incorporated the Porters five forces, the SWOT, and the TOWS matrix to analyse the factors from the findings of the systematic literature review and the interviews. The analyses brought to light the dynamics of the industry, the potential avenues for success and the strategies that can be used to propel the industry forward. The South African coal-to-carbon industry faces a dynamic landscape, balancing internal strengths and weaknesses with external opportunities and threats. Success hinges on adeptly navigating factors like buyer bargaining power, barriers to entry, and supplier influence. Potential avenues for success include leveraging abundant coal resources, advanced market opportunities, and technology readiness, while addressing challenges such as pollution concerns and limited value chain transformation. Strategies involve optimizing value chains, investing in R&D, and adapting to shifting buyer demands. By implementing these strategies, the industry can capitalize on opportunities, mitigate threats, and ensure sustained competitiveness.

Chapter 7

Discussion

This chapter interprets the findings, considering their broader significance of existing knowledge and literature and exploring their implications to the coal-to-carbon industry.

7 Discussion

7.1 Introduction

This chapter distills the research, data analysis, and expert insights into a comprehensive interpretation of our findings. South Africa, rich in coal reserves, faces a crucial juncture in navigating towards a sustainable and low-carbon future. The holistic feasibility assessment sheds light on the potential pathways, opportunities, and constraints in developing an economically viable, sustainable, and responsible coal-to-carbon industry. The exploration scrutinizes technological, environmental, economic, market, and operational feasibility. Drawing insights from systematic literature review, interviews, Porter's Five Forces, and SWOT TOWS analyses, this chapter provides a foundational guide for stakeholders, policymakers, and industry leaders aiming to construct a roadmap towards a more sustainable, prosperous, and responsible future for the South African coal-to-carbon industry.

This research had the following questions:

- What is the status of the South African coal-to-carbon industry?
- What are the holistic feasibility barriers and enablers of the coal-to-carbon industry in South Africa?
- What are the opportunities offered by the coal-to-carbon industry in South Africa?

7.2 Feasibility Discussion

The section covers a feasibility discussion of all the feasibility types included in the study. It also discusses the research questions and gives a consolidated feasibility factors summary.

7.2.1 Market

The potential for coal-based enhanced carbon materials and coal-based chemicals is substantial. The global market for products and minerals derived from coal is extensive (Andrews et al., 2021; Atkins et al., 2019).

The Current State of the South African Coal-to-Carbon Industry: The coal-to-carbon industry in South Africa has been around for decades, and it has played a vital role in the country's economy. However, the industry is facing several challenges, including regulatory hurdles, declining coal prices, and increasing competition from other countries. Nevertheless, there is still significant potential for growth and profitability in the industry, as demand for carbon products continues to increase.

Market Size/Major Players/Trends in the Coal-to-carbon Industry: The CTC industry in South Africa has the potential to significantly contribute to the country's GDP, and it comprises several key players, including Sasol, ArcelorMittal, Exxaro Resources, and Anglo American. Sasol and ArcelorMittal are the dominant players in the industry, accounting for most of the country's coal-to-carbon's precursor's production. The industry is also witnessing several trends, including the adoption of clean coal technologies, which are designed to reduce the environmental impact of coal-based products.

Demand for Carbon Products/Production Capacity and Pricing: The industry's success depends on the demand for high-value carbon products, both domestically and internationally. The market demand for carbon products may be affected by factors such as the price of alternative materials and consumer preferences for sustainable and eco-friendly products.

The demand for carbon products in South Africa is driven by several factors, including the growth of the automotive industry, which uses carbon-based materials in the manufacturing of vehicles. The construction industry is also a significant consumer of carbon products, as they are used in the production of cement and other building materials. However, pricing for carbon products is subject to fluctuations in global demand, commodity prices, and other market factors.

Market Factors: The South African CTC industry is influenced by several market factors, including regulatory policies, technological advancements, and global economic conditions. Regulatory policies, such as carbon emissions regulations, can impact the industry's profitability, while technological advancements can increase production efficiency and reduce costs. Global economic conditions, such as fluctuations in oil prices and currency exchange rates, can also affect the industry's competitiveness and profitability.

The South African coal-to-carbon industry plays a substantial role in contributing to the country's economy, with significant potential for growth and profitability. While the industry is facing several challenges, including regulatory hurdles, and declining coal prices, there are opportunities for innovation and growth, particularly in the adoption of clean coal technologies.

7.2.2 Technical

The coal-to-carbon industry in South Africa involves the conversion of coal or its precursors into various high-value carbon products, such as activated carbon, carbon black, carbon fibre, carbon nanomaterials, and carbon electrodes. The technical feasibility of the industry in South Africa depends on several factors, including the availability of suitable technology and equipment, as well as any potential challenges or limitations.

Technology and Equipment: The CTC industry in South Africa requires specialized equipment and technology to produce high-quality carbon products. The production processes typically involve pyrolysis, gasification, or hydrothermal carbonization, which require high temperatures, pressure, and precise control over the reaction conditions. Sasol and ArcelorMittal have equipment to produce the precursors. The equipment needed for these processes includes reactors, furnaces, and other specialized machinery. The availability of suitable technology and equipment is crucial for the industry's success.

Potential Challenges and Limitations: The CTC industry in South Africa faces several potential challenges and limitations, including the availability of suitable coal feedstock and the impact of carbon emissions on the environment. The quality of the coal feedstock can significantly affect the quality of the final carbon product, and the industry must source high-quality coal feedstock to produce high-value carbon products. Additionally, the industry must manage the environmental impact of carbon emissions, as regulations become more stringent, and consumers demand more environmentally friendly products.

Scalability and Efficiency: The scalability and efficiency of the coal-to-carbon industry in South Africa depend on the production processes and equipment used. The industry must adopt processes that are scalable, efficient, and cost-effective to produce high-value carbon products. Efficiency is critical for the industry's profitability, as it directly affects production costs and the quality of the final product. The industry must also adopt sustainable practices to minimize waste and reduce the environmental impact of production.

Technology Readiness and adoption: The readiness of technology is essential for the coal-to-carbon industry in South Africa. The industry must continuously evaluate and adopt new technologies that can enhance production processes, reduce costs, and improve the quality of the final product. The industry must also invest in research and development to develop new and innovative carbon products to meet market demands. South Africa has also invested in coal conversion technologies that contribute to the success of this industry.

CTC facilities exhibit a greater level of complexity than conventional power plants or petrochemical facilities, leading to increased water usage and wastewater generation. Consequently, without additional advancements and research, employing CTC in nations with emission reduction goals would seem counterproductive (Gagarin et al., 2020).

However South Africa has a functional CTL industry which is key to the development of the CTC industry. The CTL produces feedstocks and fuels all that enable the CTC industry, the

corresponding infrastructure already exists, so that the use of CTL products contributes to a low transition costs."

Technology absorption in developing countries like South Africa is a critical challenge and opportunity. South Africa heavily relies on coal for energy and has a growing interest in transitioning to cleaner, low-carbon technologies. Technology absorption involves acquiring, adapting, and integrating advanced technologies to reduce carbon emissions from coal-based industries. This process requires significant investment in research and development, infrastructure, and workforce training to effectively adopt and implement technologies like carbon capture and utilization, renewable energy integration, and efficient coal-to-carbon conversion methods. Successful technology absorption in South Africa could lead to reduced greenhouse gas emissions, improved energy security, and economic growth, but it requires a concerted effort from government, industry, and international collaborations to ensure a sustainable and just transition away from coal.

7.2.3 Economic

The coal-to-carbon (CTC) industry in South Africa has the potential to be a significant contributor to the country's economy. The industry involves the conversion of coal or its precursors into various high-value carbon products, such as activated carbon, carbon black, carbon fibre, carbon nanomaterials, and carbon electrodes. The following aspects help to evaluate the economic prospects of the CTC industry in South Africa.

Availability of Resources: South Africa has large reserves of coal, which is a key raw material for the CTC industry. The country is the world's seventh-largest coal producer and has extensive coal reserves that are estimated to last for several decades. Therefore, the availability of resources is not a limiting factor for the development of the CTC industry in South Africa.

Cost of Production: The cost of production is a critical factor that affects the economic viability of the CTC industry. The production cost of different CTC products varies depending on the production process and the raw materials used. However, South Africa has a competitive advantage in terms of low-cost coal, which can be a significant factor in the industry's cost of production.

Potential for Export: The global demand for carbon products is growing, and South Africa can potentially export CTC products to other countries. The country's proximity to the growing markets in Asia and the Middle East can give it a competitive edge in the export market.

Economic Viability of Different CTC Production Processes: The economic viability of different CTC production processes varies depending on the product and the market. For example, the production of activated carbon is a relatively low-cost and straightforward process, while the production of carbon fibre is more complex and expensive. The economic viability of each process depends on the availability of raw materials, production costs, and market demand.

Financing: The development of the CTC industry requires significant investment in infrastructure, research, and development. However, the industry's potential for profitability can attract investors and financing from both domestic and international sources.

Potential Revenue Streams, Costs, and Profitability: The potential revenue streams for the CTC industry include the sale of finished products, royalties from patents, and licensing fees. However, the industry's profitability depends on the production costs, market demand, and competition.

Potential for Growth: The global demand for carbon products is growing, and the CTC industry has the potential for significant growth in South Africa. The industry's growth can be driven by the country's low-cost coal, the growing demand for high-value carbon products, and the potential for export to other markets.

The CTC industry in South Africa has significant economic prospects, given the country's abundance of coal reserves, low production costs, potential for export, and the growing global demand for carbon products. However, the industry's economic viability depends on various factors, such as the production process, market demand, and competition. Therefore, the industry's success requires a supportive policy environment, investment in research and development, and access to financing.

7.2.4 Environmental

The coal-to-carbon industry in South Africa has significant environmental implications, particularly in terms of air, water, and land pollution. The production of carbon products involves high-temperature processes that emit various pollutants, such as carbon dioxide, carbon monoxide, nitrogen oxides, sulphur oxides, particulate matter, and volatile organic compounds. These pollutants can have adverse impacts on air quality, contribute to climate change, and have negative health effects on the local population.

The industry's environmental feasibility depends on the implementation of regulatory frameworks and policies that promote sustainability and reduce environmental impacts. The South African government has established various regulatory frameworks and policies to mitigate the industry's

environmental impacts, such as the National Environmental Management Act (NEMA) and the Carbon Tax Act (Abel *et al.*, 2023).

The NEMA provides a legal framework for the management of the environment in South Africa, including the regulation of air, water, and land pollution. The act requires the industry to obtain environmental authorizations and comply with emission standards and other environmental regulations. The act also provides for public participation and the right to access environmental information, promoting transparency and accountability.

The Carbon Tax Act imposes a tax on carbon emissions to incentivize the industry to reduce its carbon footprint and promote low-carbon alternatives. The tax applies to various sectors, including the coal-to-carbon industry, and aims to encourage energy efficiency, renewable energy, and carbon capture and storage technologies. The official carbon tax rate was first set at R120 per ton of CO₂e and would be adjusted to R134 by the end of 2022. However, based on the carbon tax revenue collected, the predicted effective rate for financial year (FY) 2021-22 was less than R7 per ton of CO₂e (International Monetary Fund. African Dept., 2023). Despite the planned increase in the headline official rate in the future years, the effective carbon tax rate is expected to stay low as the transition phase of the carbon tax is extended from the end of 2022 to the end of 2025 (International Monetary Fund. African Dept., 2023).

The industry also has opportunities for sustainability and carbon capture. Carbon capture and storage technologies can capture carbon dioxide emissions from the production process and store them underground, reducing the industry's carbon footprint. The industry can also adopt sustainable production practices, such as using renewable energy and recycling waste materials, to reduce its environmental impact.

The South African government has implemented various regulations and policies aimed at reducing the country's reliance on coal and transitioning to renewable energy sources. These policies include the Integrated Resource Plan (IRP), which outlines the country's energy mix and capacity plans for the next 10 years. South Africa is also a signatory to the Paris Agreement, which commits the country to reducing greenhouse gas emissions and transitioning to a low-carbon economy.

The coal-to-carbon industry in South Africa has significant environmental implications, particularly in terms of air, water, and land pollution. The industry's environmental feasibility depends on the implementation of regulatory frameworks and policies that promote sustainability and reduce environmental impacts. The South African government has established various legal and environmental frameworks and policies to mitigate the industry's impacts, including the National

Environmental Management Act and the Carbon Tax Act. The industry also has opportunities for sustainability and carbon capture, which can reduce its environmental impact and promote a transition to a low-carbon economy.

7.2.5 Operational

The operational feasibility of the South African coal-to-carbon industry was evaluated based on various factors, that included the availability of skilled labour, infrastructure, technology, and supply chain.

Availability of Skilled Labour: The industry requires skilled personnel with expertise in chemical engineering, materials science, and manufacturing to operate and manage the production processes. The availability of skilled labour in South Africa is not a significant challenge, as the country enjoys an abundant supply of skilled workers in the STEM fields.

Infrastructure: The industry requires robust infrastructure, such as power supply, transportation networks, and water supply, to support its operations. The availability and reliability of infrastructure in South Africa can be a challenge, particularly in rural areas where the industry may need to be established.

Technology: The industry requires advanced technologies to convert coal into high-value carbon products efficiently. The availability of technology and its cost can be a challenge, particularly for smaller companies with limited resources.

Supply Chain: The industry requires a reliable supply chain of coal and carbon precursors, as well as a market for its products. The availability and accessibility of the supply chain can be a challenge, particularly in remote areas where the industry may need to be established. The coal-to-carbon value chain encompasses the entire process of converting beneficiated coal into various forms of carbon-based products. The South African value chain is well established in its primary activities and needs more investments in the tertiary activities of the carbon product manufacturing specifically the acquisition of carbon technologies.

Organizational Structure: The industry requires a well-structured organization that can manage the production processes, supply chain, marketing, and sales effectively. The organization may also need to comply with various regulatory requirements and maintain good relationships with stakeholders.

Financing: The industry requires significant capital investments to establish the production facilities, acquire technology, and maintain operations. The availability and accessibility of financing can be a challenge, particularly for smaller companies with limited resources.

The operational and organizational feasibility of the South African coal-to-carbon industry can be affected by various factors, including the availability of skilled labour, infrastructure, technology, supply chain, market demand, organizational structure, and financing. Addressing these challenges will require a collaborative effort from industry stakeholders, government, and other partners to promote the development of a robust and sustainable coal-to-carbon industry in South Africa. Partnerships between Universities, Industry and Government are needed to ensure that this new focus is strategically relevant to RSA and will create jobs and contribute to the GDP.

7.3 Consolidated Feasibility Factors

To demonstrate the prospects in the coal-to-carbon industry, the study consolidated the feasibility factors that demonstrates the prospects of the coal-to-carbon industry in South Africa. These steps included conducting a systematic literature review, gathering data from experts in the coal conversion industry and expert researchers, and analysing various feasibility factors that impact the South African coal-to-carbon industry using the Porters five forces SWOT-TOWS analyses.

The information collected through the above steps was organized into consolidated feasibility factors. These factors provide a comprehensive overview of the challenges, opportunities, and prospects of the coal-to-carbon industry in South Africa.

7.3.1 The Feasibility Factors Determining the Prospects.

The comprehensive examination of the South African coal-to-carbon industry in this study involved the consolidation of various factors that directly impact its prospects. These factors were derived from an in-depth process of data collection, analysis, and synthesis. The resulting insights are succinctly presented in Table 10, offering a detailed breakdown of enablers, feasibility barriers, and opportunities within the industry. This consolidated overview serves as a valuable resource for understanding the multifaceted dynamics shaping the industry's trajectory.

Table 10 Consolidated Feasibility Factors

| Feasibility Area | Feasibility factors |
|----------------------|--|
| Opportunities | <p>Diversification in coal utilization.</p> <p>Global market expansion.</p> <p>Filling identified industry gaps.</p> <p>Abundance of coal resources as feedstocks.</p> <p>Reviving the coal sector.</p> <p>Available carbon precursors producing facilities.</p> |
| Barriers | <p>Pollution concerns.</p> <p>Industry gaps.</p> <p>Limited value chain transformation.</p> <p>Uneconomic applications/processes.</p> <p>High emissions across lifecycles.</p> <p>High ash content in South African bituminous coal.</p> <p>Capital-intensive and specialized technologies.</p> <p>Carbon capture and sequestration costs.</p> <p>Complexity of pitch-based processes.</p> <p>Addressing pollution concerns to capitalize on global market expansion.</p> <p>Filling industry gaps by transforming the value chain.</p> <p>Addressing pollution concerns and industry gaps to mitigate threats from substitutes.</p> <p>Working on value chain transformation to counter threats from high capital requirements.</p> |
| Enablers | <p>Abundant coal resources.</p> <p>Advanced market opportunities.</p> <p>Technology readiness.</p> <p>Available carbon precursors producing facilities.</p> <p>Production of other commercially viable products.</p> <p>Global market expansion.</p> <p>Filling identified industry gaps.</p> <p>Economic growth through high-value products manufacturing.</p> <p>Creation of employment.</p> <p>Leveraging abundant coal resources to exploit advanced market opportunities.</p> <p>Capitalizing on technology readiness to diversify coal utilization.</p> |

| | |
|--|---|
| | <p>Using abundant coal resources to counter threats of high capital requirements.</p> <p>Leveraging technology readiness to mitigate threats from intense global competition.</p> |
|--|---|

7.4 The Industry Stakeholder’s Relationships

Collaboration plays a pivotal role in ensuring the viability of the coal-to-carbon industry in South Africa. The research has pinpointed the most influential stakeholders and outlined their interactions. These key stakeholders have the capacity to join forces and collectively foster the growth of the coal-to-carbon sector in South Africa. Figure 20 illustrates the principal stakeholders within the coal-to-carbon industry and their interconnected roles. Among these stakeholders, the government, research institutions (including tertiary educational establishments), and funding agencies emerge as the foremost players in shaping the coal-to-carbon industry.

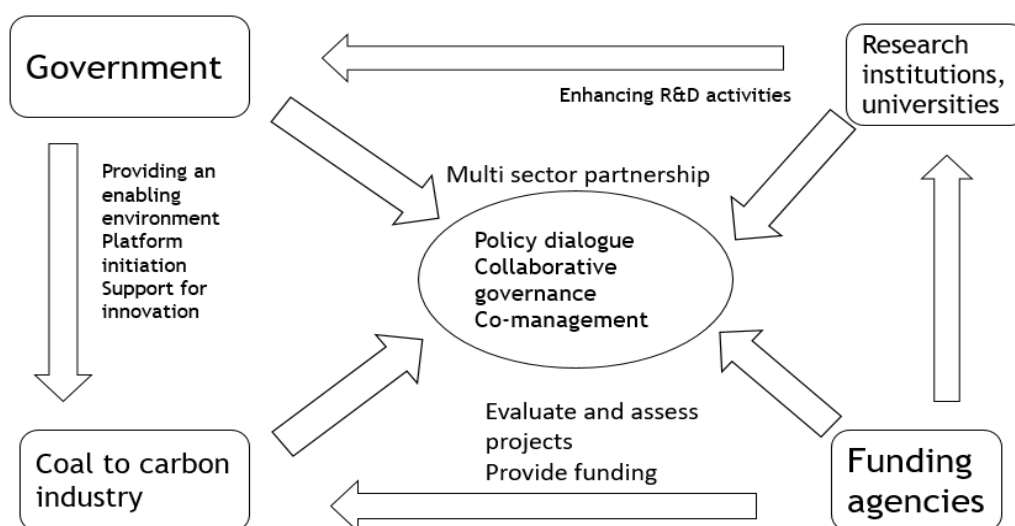


Figure 20 The Industry Stakeholders' Relationships

The decline of traditional coal markets and the urgent need for new, innovative market interventions present a formidable challenge for stakeholders deeply entrenched in the South African coal industry. Historically, coal has been a fundamental driver of economic development in South Africa, making the prospect of its decline particularly concerning for stakeholders ranging from government officials to industry leaders and local communities. The implications of this decline extend beyond economic considerations, touching upon social and environmental dimensions as well. Stakeholders must navigate the complexities of transitioning to alternative industries or adapting existing coal operations to meet changing market demands while mitigating potential socio-economic impacts such as job losses and community dislocation. Additionally,

there is a crucial need for stakeholders to engage in collaborative efforts to explore sustainable solutions the study has explored, the production of high value carbon products from coal that balance economic imperatives with environmental stewardship and social equity, ensuring a holistic approach to addressing the challenges facing the South African coal industry.

7.5 Reliability of the Findings

The findings discussed in the section are based on the systematic literature review conducted and the data collected from the South African coal-to-carbon industry experts which was then analysed. The validity of these sources and their accuracy in reflecting the current state of the coal-to-carbon industry in South Africa can be evaluated based on their reliability and objectivity.

Moreover, the reliability and validity of the findings depend on the quality of the data used to support the arguments and the analysis presented. The data used in the frameworks and discussions above are sourced from reliable and reputable sources, and expert data collected from captains of the industry.

7.6 Implications

The findings from the assessment of the South African coal-to-carbon industry's feasibility provide valuable guidance for decision-makers in government, industry, and education. They offer the potential for economic growth and diversification, but also call for careful consideration of environmental implications and the need for strategic planning and investments in human capital and technology. The practical applications of these findings can shape the future of this industry in South Africa.

1. **Strategic Decision-Making:** Organizations and government agencies can use these findings to make informed decisions about investments and policies related to the coal-to-carbon industry. They can determine whether it's a viable sector to enter, expand, or support financially.
2. **Resource Allocation:** Companies and policymakers can allocate resources more efficiently based on the identified strengths and opportunities in the industry. They can prioritize areas that offer the most potential for growth and economic benefits.
3. **Environmental Considerations:** Environmental agencies and regulatory bodies can assess the environmental challenges and potential mitigation strategies, such as carbon capture and sequestration, as identified in the findings.

4. **Skill Development:** The findings suggest a need for skilled personnel in the manufacturing and technological aspects of the industry. This can guide educational institutions and workforce development programs in South Africa to provide training in relevant fields.

5. **Market Development:** The findings reveal the potential for growth in high-value carbon products. Companies can explore opportunities in producing and exporting these materials to obtain a portion of the international market.

6. **International Trade:** The insights about the international market being complementary to the local market can inform trade policies and export strategies, potentially boosting South Africa's export earnings.

7. **Economic Growth:** Supporting the coal-to-carbon industry, given its growth potential, can lead to job creation, economic growth, and increased energy security in South Africa.

8. **Environmental Impact:** By addressing the environmental challenges identified, the industry can work towards reducing its environmental footprint and ensuring sustainability.

The potential consequences and benefits of these findings include:

Benefits:

- Economic growth and job creation.
- Diversification of industries, reducing reliance on traditional coal applications.
- Investment opportunities for both local and international investors.
- Development of a skilled workforce.
- Contributions to environmental sustainability through technologies like carbon capture and cleaner production methods.

Consequences:

- Environmental challenges, especially if not adequately addressed, can lead to negative impacts on the environment.
- Economic risks if the industry faces unforeseen challenges or market shifts.
- The need for regulatory changes and environmental investments.
- Competition in global markets from established players.

7.7 Chapter Summary

The discussion section has provided a comprehensive and insightful discussion and analysis of the findings and their implications. The feasibility analysis of the South African coal-to-carbon industry highlights its potential for significant growth and contribution to the country's economy. Despite challenges such as regulatory hurdles and environmental concerns, the industry benefits from abundant coal resources and access to global markets. Technical feasibility relies on specialized equipment and technology, while economic viability is supported by low production costs and export opportunities. Environmental implications require adherence to regulatory frameworks and adoption of sustainable practices. Operational feasibility depends on skilled labour availability, infrastructure reliability, and efficient supply chains. Overall, addressing these factors through strategic investments, technology adoption, and stakeholder collaboration can ensure the industry's sustainable development and competitiveness.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes the research investigation by presenting the outcomes, worth, and innovations derived from the study. Additionally, it outlines the limitations and offers future recommendations, culminating in closing remarks.

8 Conclusions and Recommendations

8.1 Research Study

In pursuit of the overarching aim to assess the feasibility of the coal-to-carbon industry in South Africa, this research rigorously examined the market status, technical capabilities, economic viability, environmental implications, and operational feasibility. Through the specific objectives outlined, we systematically investigated the current landscape of coal-to-carbon technologies, identified the critical barriers and opportunities for industry development, pinpointed potential areas for product diversification, and synthesized these findings into a cohesive analysis. By achieving these objectives, this study offers a comprehensive understanding of the feasibility factors, supported by a stakeholder relationship diagram, to inform strategic decision-making and foster sustainable development within the South African coal-to-carbon sector.

8.2 Research Contribution

The research makes both practical and methodological contributions to the field. On a practical level, it provides valuable insights into the coal-to-carbon industry, shedding light on its current status and developmental stage. This information is essential for policymakers, investors, and industry stakeholders to make informed decisions. Methodologically, the study employed rigorous research methods to collect and analyse data. This involved semi structured interviews and a systematic literature review.

The findings from this study, which delves into expert opinions and perspectives on the viability of the coal-to-carbon sector in South Africa, indicate the presence of several factors conducive to feasibility in the industry. The foundational components for a thoroughly optimized and productive sector exist, yet stakeholders need to address and bridge existing gaps within the business.

The coal-to-carbon sector in South Africa is currently in its early stages, marked by a prevalent shortage of appropriate carbon technology. This means that the methods and technologies used to convert coal into carbon-based products are not yet fully developed or optimized. To address this issue, the study proposes that South Africa can acquire advanced carbon technologies from more developed economies. By adopting these technologies and combining them with their abundant and relatively inexpensive coal feedstock, they can optimize the enablers of the industry.

Internationally, the South African coal conversion sector is highly competitive. This means that it has the potential to compete effectively with other players in the international market. Additionally, the industry is capable of innovation and upgrading its processes and technologies. This

adaptability can help it leverage its resources to develop the coal-to-carbon sector further. The study suggests that a viable strategy for the industry is to simultaneously pursue differentiation (offering unique products or services) and low-cost production. This approach can open new markets and create increased demand for South African coal-to-carbon products.

The challenges facing the South African coal industry underscore the pressing need for stakeholders to adapt to shifting market dynamics. As traditional coal markets decline, stakeholders must navigate the complexities of transitioning to alternative industries or innovating within the coal sector. This requires a concerted effort to balance economic imperatives with environmental and social considerations. By fostering collaboration and exploring sustainable solutions, the study has explored, namely the production of high value carbon products from coal, stakeholders can mitigate potential socio-economic impacts and pave the way for a more resilient and diversified energy landscape in South Africa.

Lastly, the study emphasizes the potential contribution of coal-derived carbon products, such as carbon fibre and composites, to mitigate the effects of climate change. Carbon products, when used in various applications, can play a role in reducing carbon emissions. For example, carbon fibre can be used to make lightweight, fuel-efficient vehicles. The single most important South Africa has is coal tar pitch, a starting material for the various carbon products.

8.3 Limitations and Future Recommendations

This study, assessing the feasibility of the coal-to-carbon (CTC) industry in South Africa had limitations. The focus was on high-value non-energy carbon products, and other carbon products were not thoroughly examined due to the industry's broad nature. Data on the standalone CTC industry in South Africa is limited, impacting the depth of qualitative research. However, the study gathered critical data from available literature and global sources.

Despite these limitations, the study aimed to provide insights into high-value carbon product production without generalizing. Small sample size limits generalizability, and the industry's complexity may not be fully captured by qualitative research. Future research should outline steps for developing carbon products, and industry stakeholders should collaborate on a strategic action plan based on the findings.

8.4 Concluding Remarks

The South African coal-to-carbon industry is feasible and increasingly available, and the evidence has shown the immense potential of South African coal and various precursors to contribute to high-value carbon products, offering a promising avenue for economic growth and innovation.

A solid business case is needed (economics/markets etc) followed by obtaining venture capital (TIA/IDC) and strategic partnerships formed. Research and development will be vital and collaborations with Republic of South African universities and abroad are needed.

The recommended path is to pursue distinctiveness and low cost at the same time to establish new markets and create new demand for the industry. By pursuing both differentiation and low cost, the industry can open new markets and create new demand for its products or services. By offering unique products at a lower price point than competitors, the industry can attract both customers who are looking for something different as well as those who are looking for a good value. The idea of pursuing differentiation and low cost at the same time can also help the industry stand out in a crowded market and win new customers, ultimately leading to growth and success for the industry.

Addressing the limitations, focusing on a well-defined strategy for product development, and undertaking further research into potential carbon products are essential steps to overcome challenges. Moreover, it is imperative for stakeholders to translate these findings into actionable plans and policies.

To capitalize on this potential, South Africa must foster a collaborative environment that encourages knowledge sharing, innovation, and investment. A dynamic policy framework aligned with the industry's goals and environmental sustainability is equally pivotal.

Lastly, we must keep a vigilant eye on future trends, adapting our strategies and technologies to align with evolving market dynamics, technological advancements, and environmental imperatives. The coal-to-carbon industry can be a driving force not only in economic development but also in mitigating climate change effects through sustainable practices and carbon product innovation.

In conclusion, the South African coal-to-carbon industry stands at a crossroads, with the potential to transform into a global leader. However, realizing this potential requires collective action, unwavering commitment, and a shared vision. As we move forward, let us work hand in hand to shape a future where South Africa's coal resources are harnessed for the betterment of our economy, environment, and society at large.

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APPENDIX A

**ETHICS APPROVAL LETTER OF
STUDY**

APPENDIX A: ETHICS APPROVAL LETTER OF STUDY



Private Bag X1290, Potchefstroom
South Africa 2520

North-West University Engineering Research
Ethics Committee (NWU-ENG-REC)

Tel: 018 299-2645
Email: ENG-REC@nwu.ac.za

24-Sep-21

ETHICS APPROVAL LETTER OF STUDY

Based on approval by the North-West University Engineering Research Ethics Committee (NWU-ENG-REC) on 24-Sep-21, the NWU-ENG-REC hereby approves your study as indicated below. This implies that the NWU-ENG-REC grants its permission that, provided the general and specific conditions specified below are met and pending any other authorisation that may be necessary, the study may be initiated, using the ethics number below.

| | | | |
|--|------------------------|-----------------|-------------|
| Study title: A holistic feasibility assessment of the coal to carbon industry: A South African case study | | | |
| Principal Investigator/Study Supervisor/Researcher: Mr. M. Roopa and Dr .T. Hattingh | | | |
| Student: Peter Mukodzani (40878104) pmukodzani@gmail.com | | | |
| Ethics number: | NWU-01083-21-A3 | | |
| | Institution | Study Number | Year Status |
| <u>Status:</u> S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation | | | |
| Application Type: Single | Risk: | Low Risk | |
| Approval date: 19-Sep-21 | | | |
| Expiry date: 19-Sep-22 | | | |
| Approval of the study is provided for a year, after which continuation of the study is dependent on receipt and review of annual monitoring report and the concomitant issuing of a letter of continuation. | | | |

| |
|---|
| <p>General conditions:</p> <p><i>While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, the following general terms and conditions will apply:</i></p> <ul style="list-style-type: none"> • <i>The principal investigator/study supervisor/researcher must report in the prescribed format to the NWU-ENG-REC:</i> <ul style="list-style-type: none"> - <i>Annually on the monitoring of the study, whereby a letter of continuation will be provided annually, and upon completion of the study; and</i> - <i>without any delay in case of any adverse event or incident (or any matter that interrupts sound ethical principles) during the course of the study.</i> • <i>The approval applies strictly to the proposal as stipulated in the application form. Should any amendments to the proposal be deemed necessary during the course of the study, the principal investigator/study supervisor/researcher must apply for approval of these amendments at the NWU-ENG-REC, prior to implementation. Should there be any deviations from the study proposal without the necessary approval of such amendments, the ethics approval is immediately and automatically forfeited.</i> • <i>Annually a number of studies may be randomly selected for active monitoring.</i> • <i>The date of approval indicates the first date that the study may be started.</i> • <i>In the interest of ethical responsibility, the NWU-ENG-REC reserves the right to:</i> |
|---|

APPENDIX B

INFORMED CONSENT FORM

APPENDIX B: INFORMED CONSENT FORM



Faculty of Engineering
Tel: 018 299 2645



INFORMED CONSENT ¹

Title of the research study: A holistic feasibility assessment of the coal to carbon industry: A South African case study

Ethics reference numbers: NWU-01083-21-A3

Student (researcher): Peter Mukodzani

Study leader(s)/promoter(s): Mr Meelan Roope and Dr Teresa Hattingh

Contact number: 0713400451

Email address: pmukodzani@gmail.com

You are invited to take part in a **research study** that forms part of a Masters study in Industrial Engineering. Please take some time to read the information presented here, which will explain the details of this study. Please ask the researcher any questions about any part of this study that you do not fully understand. It is very important that you are fully satisfied that you clearly understand what this research is about and how you might be involved. Also, your participation is **entirely voluntary**. If you decide not to participate, this will not affect you negatively in any way whatsoever. You are also free to withdraw from the study at any point.

This study has been approved by the **North-West University Engineering Research Ethics Committee** and will be conducted according to the ethical guidelines and principles applicable to this study. It might be necessary for the research ethics committee members or other relevant people to inspect the research records.

What is this research study all about?

- *This study intends to address the South African coal industry's needs for new innovative markets. In order to achieve this, the aim of this research is to assess*

¹ The Faculty of Health Ethics Office of the North-West University is acknowledged for the use of their document with minor adjustments made by the North-West University Engineering Ethics Committee (NWU-ENG-REC).

the market, technical, economic, environmental and operational feasibility of the coal to carbon industry in South Africa.

Why have you been invited to participate?

- *You have been invited to be part of this research because you are knowledgeable and experienced about coal based products and coal conversion technologies.*

What will be expected of you?

- *You will be expected to participate in interviews and provide your knowledge, views and opinions of the coal to carbon industry's feasibility, challenges and opportunities.*

Will you benefit anything from taking part in this research?

- *There will be no direct gains for you in the study, however the indirect gains associated with this study are that the study's outcome has potential to positively benefit the Coal industry and the South African economy.*

Are there risks involved in you taking part in this research and what will be done to prevent them?

- *The potential risks of this study are fatigue from long interview sessions but will be controlled by:
Limiting each interview session to no longer than an hour.*

How will we protect your confidentiality and who will see your findings?

- *Anonymity of your view will be protected by not including your personal information in the research data. The data will be anonymised so as to ensure any organisation or individual's identity is not revealed*
- *Your privacy will be respected by not collecting any of your personal information. Any participant information or records that the researcher might have access to will be kept strictly confidential and will not be included in any of the data to be used in the study or shared with anyone.*

How will the data be collected?

- *The interviews will be conducted online using the Zoom platform and the sessions will be recorded to capture data for the study.*

What will happen with the findings or data?

- *The data collected from this study will strictly be used for purposes of this study.*
- *The data collected from the participants will be kept confidential when transferred to the researcher's personal computer and it will be password protected. The transcribed data of your interview, in which all identifying information has been removed will be analysed to find meaning for the study.*
- *The original data will be retained until the exam board confirms the results of the dissertation.*
- *Extracts from the interview and the findings of this study may be quoted in the dissertation, conference presentations and published papers, but without mentioning the participants' identity.*
- *The findings from the interviews will inform the design of a framework that demonstrates the prospects in the coal to carbon industry in South Africa.*

How will you know about the results of this research?

- The researcher will provide the results of this research via email after the data collection process and data analysis process have been completed.

Is there anything else that you should know or do?

- You can contact Peter Mukodzani at 0713400451 or pmukodzani@gmail.com if you have any further questions or have any problems.
- You can also contact the North-West University Engineering Research Ethics Committee: Mrs Bettie Handford at 018 299 2645 or ENG-REC@nwu.ac.za if you have any concerns that were not answered about the research or if you have complaints about the research.
- You will receive a copy of this information and consent form for your own purposes.

Declaration by participant

By signing below, I agree to take part in the research study titled: A holistic feasibility assessment of the coal to carbon industry: A South African case study

I declare that:

- I have read this information/it was explained to me by a trusted person in a language with which I am fluent and comfortable.
- The research was clearly explained to me.
- I have had a chance to ask questions to both the person getting the consent from me, as well as the researcher and all my questions have been answered.
- I understand that taking part in this study is **voluntary** and I have not been pressurised to take part.
- I may choose to leave the study at any time and will not be handled in a negative way if I do so.
- I may be asked to leave the study before it has finished, if the researcher feels it is in the best interest, or if I do not follow the study plan, as agreed to.

Signed at (place) on (date) 20

.....
Signature of participant

.....
Signature of witness

Declaration by researcher

I *Peter Mukodzani* declare that:

- I clearly and in detail explained the information in this document to the participant signed above.
- I did not use an interpreter.
- I encouraged him/her to ask questions and took adequate time to answer them.
- I am satisfied that he/she adequately understands all aspects of the research, as discussed above
- I gave him/her time to discuss it with others if he/she wished to do so.

Signed at Potchefstroom on 27 August 2021

Peter Mukodzani

.....
Signature of researcher

.....
Signature of witness

APPENDIX C

SAMPLE CODES AND CODE GROUPS

Appendix C shows some of the codes from the analysis of the of the interview transcripts.

APPENDIX C: SAMPLE CODES AND CODES GROUPS

| Code | Code Group 1 | Code Group 2 | Code Group 3 | Code Group 4 | Code Group 5 | Code Group 6 | Code Group 7 | Code Group 8 | Code Group 9 | Code Group 10 | Code Group 11 | Code Group 12 |
|---|--------------------------|--------------|------------------------------|--------------|--------------|--------------|--------------|---------------|--------------|---------------|------------------------|---------------|
| Abundant coal discards that can be beneficiated | | | | | | | | Opportunities | | | | |
| Abundant coal resources | Availability of enablers | | | | | | | Opportunities | | | South Africa advantage | |
| Abundant resources are advantageous | Availability of enablers | | | | | | | Opportunities | | | South Africa advantage | |
| Activated carbon as electrode material | Availability of enablers | | | | | | | | | | | |
| activated carbon import | | | | | Competition | | | | | | | Status |
| Activated coal as an absorbent | | | Carbon products applications | | | | | | | | | |
| Air filters and carbon capture technologies | Availability of enablers | | | | | | | | | | | |
| Almost obsolete technologies | | | | Challenges | | | | | | | | |
| Alternative process | | | | | | | | Opportunities | | | | |
| Anthracite coal | | | | | | | | | | | | |
| Application in renewable energy industry | | | Carbon products applications | | | | | Opportunities | | | | |

| | | | | | | | | | | | | |
|--|--------------------------|--|------------------------------|--|--|--|--|---------------|--|--|--|--|
| Application of activated coal | | | Carbon products applications | | | | | Opportunities | | | | |
| Application of carbon fibre blades for wind turbines | | | Carbon products applications | | | | | Opportunities | | | | |
| Application of graphite in semi-conductor industry | | | Carbon products applications | | | | | Opportunities | | | | |
| Applications for carbon products | | | | | | | | Opportunities | | | | |
| Applications in electrochemical energy storage | | | Carbon products applications | | | | | Opportunities | | | | |
| Applications in renewable industry | | | Carbon products applications | | | | | Opportunities | | | | |
| Applications in the automotive industry | | | | | | | | Opportunities | | | | |
| Applications include batteries | | | Carbon products applications | | | | | Opportunities | | | | |
| Apply techniques to minimize pollution | | | | | | | | Opportunities | | | | |
| Aromatic pitch available | Availability of enablers | | | | | | | Opportunities | | | | |
| Availability of carbon precursors | Availability of enablers | | | | | | | Opportunities | | | | |

| | | | | | | | | | | | | |
|--|--------------------------|--|--|------------|--|----------------------|--|---------------|--|--|--|--|
| Availability of CTC industry enablers | Availability of enablers | | | | | | | Opportunities | | | | |
| Availability of expertise in nanotechnology in South Africa | Availability of enablers | | | | | | | Opportunities | | | | |
| Availability of feasibility enablers and barriers | Availability of enablers | | | | | | | Opportunities | | | | |
| Availability of manufacturing skills | Availability of enablers | | | | | | | Opportunities | | | | |
| Availability of precursors for Carbon products | Availability of enablers | | | | | | | Opportunities | | | | |
| Availability of skilled personnel | Availability of enablers | | | | | | | | | | | |
| Availability of skills | Availability of enablers | | | | | | | Opportunities | | | | |
| Availability of supporting industries | Availability of enablers | | | | | | | Opportunities | | | | |
| Availability of skilled personnel driving these technologies | Availability of enablers | | | | | | | Opportunities | | | | |
| Avoid products that end as carbon dioxide | | | | Challenges | | | | | | | | |
| Biggest challenge is carbon dioxide emissions | | | | Challenges | | Environmental issues | | | | | | |

APPENDIX D

SAMPLE PRESCRIBED NOTES

APPENDIX D: SAMPLE PRESCRIBED NOTES

SAMPLE PRESCRIBED NOTES

Interviewer: Researcher

Interviewee: Participant B1

Researcher: As we start this discussion, you have just said that you've been with Sasol for 25 years.

B1: Yes.

Researcher: So South Africa has abundant coal reserves and resources. Do you think they are being utilized to their fullest?

B1: Uhm Peter. At the moment Sasol, Uh, I think South Africa. Oh well, I think they are burning most of their coal as I remember, I remember it was five years ago that I really know.

B1: OK, but yeah, I mean look, they're burning most of their coal is. I know there's some research that's going on in the in the kind of trace metals area uhm, with the XXX at UJ.

B1: Hey, uh, and I don't know what YYY and his team have been kind of doing at your university, but yeah, I guess it's just being burnt. I doubt there's much more going on. The only thing I guess now it would be in the graphite electrodes area, but I don't think anything is specifically going on there.

B1: You guys, you've got the gold. I don't know what it's called now, but the new company in front of our park uh, that produces a high temperature pitch from coal. It's being used for, you know binder pitches and uh, and things like that for the anodes and the electrode markets. I guess that's the only really commercial Ah, I think South Africa has really kind of good game for at the moment with respect to alternative uses for coal. That's all I know of.

Researcher: OK, that's cool, that's cool. Thank you very much. In terms of coal conversion into useful products South Africa has excelled with this leading coal to liquid industry. Yeah, we are looking at Sasol specifically

B1: Yes.

Researcher: What do you think of the coal to carbon industry?

B1: Uhm South Africa has a lot of advantages and a lot of disadvantages. Let me tell you the advantages first.

Researcher: OK.

B1: For any carbon product you want to make, you have to be able to arrange the molecule, see, it's gotta go from a liquid phase to a solid type of phase. Like when you make a binder pitch or you make graphite electrodes. It's all going from a pitch tar type phase to a solid phase OK.

B1: The problem you have with normal coal is that it's bound, ok?

B1: Uhm, you have to go through some sort of liquid fraction type of process to get access to those free molecules where you could also remove all the minerals. OK, so you could just filter out the minerals. Now the advantage in South Africa is of course you have Sasol you have the coal to liquid type of process and apart from producing syngas and the whole Fischer Tropsch route you produce a whole lot of tars and pitches and you have the light charcoal and things like that so?

B1: You can mobilize the molecules that you would need for the conversion of coal to usable carbon if I can put it that way, so that's good, ok? I mean the the problem is I don't know what Sasol is doing at the moment.

B1: But there have been converting a lot to using natural gas as a feed rather than coal because they are starting to feel the heat from the emissions uh, the emission sector okay?

Researcher: Yes.

B1: And the problem with using coal is that, if you look at the fossil fuel industry we have coal with the highest CH ratio. Then you have the oils that crude oil. So let's say like not refers you will understand and then also you have the natural gas industry. But the problem with doing anything with coal is number one. You gotta, you gotta get the molecules flowing. OK so you could get also rid of the ash, but the CH ratio is so high that, um, you've also got to you can't go after things like hydrogen for example, forming hydrogen from coal. I know that was one of the things that was mentioned in your report.

B1: Uh, you know, using carbon capture and storage and all that type of stuff, the amount of CO₂ you have to store is so great coal and I'm talking on a global perspective now. For hydrogen is just not on the cards anywhere anymore so I wouldn't even think about that. Even the guys like natural gas with much better CH ratios are even struggling. So I wouldn't go there, but what I'm trying to say is that you need to go through some type of liquefaction process. You can go the Sasol route, you can go solvent hydrogenation route. You can just do a direct liquefaction with a, you know a normal type of organic solvent.

B1: Ah, but you need to mobilize those molecules essentially before you do anything, cause otherwise you're just not going to get there uh, the actual components out.

Researcher: OK, thank you very much for those insights.

B1: OK, cool.

Researcher: OK, so looking at the South African context, what do you think are the carbon products that that we can produce? Carbon products of higher value that you can produce, yeah.

B1: OK.

Researcher: Yeah.

APPENDIX E

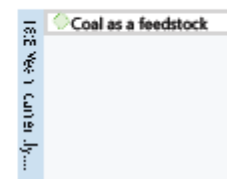
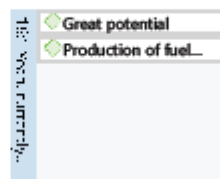
THEMATICALLY ANALYSED TRANSCRIPT

APPENDIX E: THEMATICALLY ANALYSED TRANSCRIPT

Thematically analyzed transcript

Interviewer: Researcher Interviewee: Participant G

- 1 Researcher: So I have a couple of questions that I need you to help me for this study.
- 2 G: OK.
- 3 Researcher: South Africa has abundant, coal reserves and resources.
- 4 G: That's correct.
- 5 Researcher: Do you think they are being utilized to their fullest?
- 6 G: Yeah, currently. If you look at what we do with coal, right. Uh, I think we are only country in the world that converts coal to liquids. And we do that through the sasol secunda plant. So all the fuel and the chemicals you get from the plant, the feedstock is coal.
- 7 Researcher: So that's cool.
- 8 G: So if you look at our electricity 90% or even more than 90 percent, 90% of our electricity is generated from coal.
- 9 Researcher: OK.
- 10 G: And in other industries, like your steel industries like as ArcelorMittal and that. The coal is used as a feedstock. So if you look at the uses of these products coal as a primary energy source, currently it is being used to full capacity and you may want to also look at the contribution of coal to the GDP. We we export quite a lot. Yeah, I think the biggest commodity there. The biggest revenue that we generate from any commodity is from coal.
- 11 Researcher: Cool.
- 12 G: Uh, Richard Bay Terminal is basically only coal. Yeah, and and uh. If you look at the Mpumalanga corridor, most of the products that get out of Mpumalanga to Richards Bay or to the export market is actually coal. So yeah, I would say I I think yeah, it is just used to full capacity currently.
- 13 Researcher: OK.
- 14 Researcher: Thank you very much for your opinion there.
- 15 Researcher: So you touched on the coal to liquid industry, which leads Researcher to my next question, which is in terms of coal conversion into useful products South Africa has excelled with this leading coal to liquid industry you have mentioned. What do you think of the coal to carbon industry?
- 16 G: OK, can you please explain coal to carbon?
- 17 Researcher: Alright. So when we are talking about the coal to carbon, we are looking at the conversion of coal into carbon products.



- 18 G: Uh-huh
 19 Researcher: And I can mention the products that we are specifically looking at for this study. These are the high value carbon products that include carbon fibers, carbon foams, uh, we have carbon black, activated coal as well as carbon electrodes.
 20 G: OK.
 21 Researcher: So for coal to carbon industry we are looking specifically at high value carbon products.
 22 G: Uh-huh
 23 Researcher: So what do you think of this industry?
 24 industry?

- G: Well I do not have, I do not know of that industry, yes, but I'm familiar with the products which you have mentioned.
 25 which you have mentioned.
 26 Researcher: OK. Alright.
 G: Right, But I'm not. I'm not quite aware of the level of beneficiation of coal in that extent.
 27 level of beneficiation of coal in that extent.

- G: So yeah, if you look at Sasol for example, yes it's coal to liquid by the by products that come from that, you know in your, in your production or manufacturing of fuel liquids you get chemicals that are coming from that coal as a feedstock, yeah, but I'm not aware of the of the processes or the industries that manufacture the products we just spoke about.
 28 the products we just spoke about.

- 29 Researcher: Alright, that's fine, that's fine.
 30 G: Ok.
 Researcher: But for the coal to liquid industry, that's specifically looking at Sasol, they they produce pitch. Pitch is a precursor or feedstock that can be used in the production of some of the products that I mentioned.
 31 the products that I mentioned.

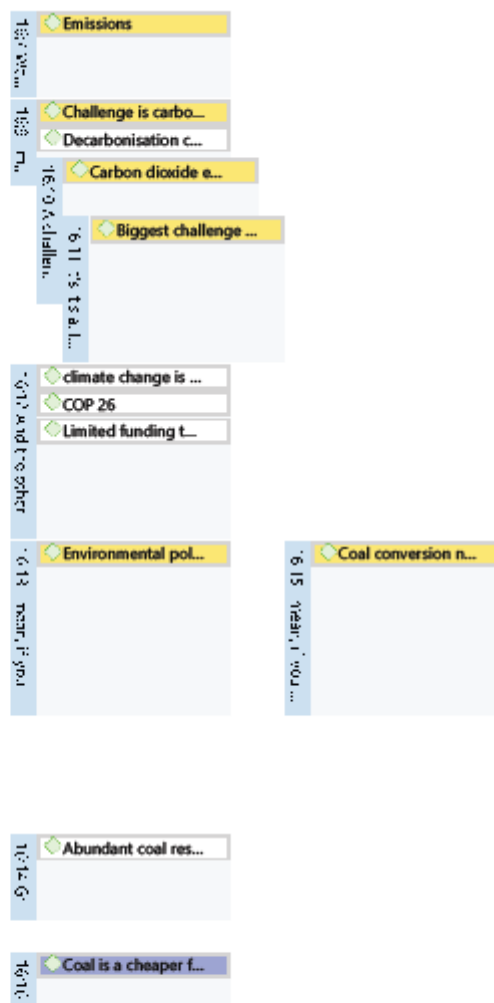
- 32 G: OK yeah yeah.
 33 Researcher: Yes.
 Researcher: So, still looking at the products that I have mentioned. Are there other industries in South Africa that are producing any of the products that you may be aware of?
 34 any of the products that you may be aware of?

- 35 G: Any of the products that you mentioned?
 36 Researcher: Yes.
 G: I am not aware of the yeah, I'm not aware. As I said, I'm not aware of the companies that produce those products.
 37 produce those products.

- 38 Researcher: Alright, that's fine.
 G: Not since I don't think I'm not that way, yeah?



39 Researcher: Alright, alright thank you very
 40 much. So we look at the coal to liquid, as the
 extension of.
 Researcher: Yeah, so we look at coal to carbon
 41 industry as an extension of coal to liquid
 42 industry so. G: Uh-huh
 Researcher: In the approach that I want us to
 take, we, we have coal to liquid industry. It is
 producing the pitch. Then you can take the
 43 pitch and produce other products.
 G: Let's let's shoot stuff. Yes, I fixed up two
 44 other yeah yeah.
 Researcher: Yeah.
 Researcher: So you as an expert in the coal to
 liquid industry, you may have witnessed or
 experienced some of the challenges currently
 facing this industry. Can you share some of
 46 these instances?
 G: Well, one of the biggest challenge and that is
 spoken about quite often is the issue of cleaner
 energy and emmissions. Right and now.
 47 G: I mean companies that are using coal as a
 primary energy source or as a feedstock are
 faced with a challenge of decarbonisation. A
 challenge where you have to, I mean coal in its
 nature. It's it's a. It's a fossil fuel and it's a major
 cause because I mean in South Africa it
 contributes quite a lot to see CO2 emissions.
 Right, that is one of the biggest challenges with
 48 this industry.
 G: And the other challenge, which is also
 related to that. And the providers of capital
 who are saying we will not fund any expansion
 or any project that uses energy that is not clean
 and coal is cited as pretty much the, one of the
 projects that would not be funded. So access to
 funding will be a problem. I mean, if you want
 to use coal for anything, and obviously before
 you make the products that you spoke about,
 the process of getting coal off the ground. I
 mean from mining to beneficiate in this coal is
 49 inherently not environmentally friendly.
 G: So in terms of environment, that is one of
 the challenges that will be faced. Uh, with the
 usage of coal as a primary source, or if it's
 50 feedstock to any product you want to make. G:
 The advantages of it, and I think you already
 mentioned that, is that coal, we have it in
 51 abundance.
 Researcher: Yes.
 52 G: And I think we have more than 100 years of
 coal that we can use at the current production



72 G: But in terms of the benefit of coal, let's look at the South Africa as a case study as you said.

73 Researcher: Yes.

74 G: I mean, the economy of the province of Mpumalanga is basically dependent on coal, and if you want to analyze their entire value chain from mining industry.

16:53:17 South Africa coal ...

16:53:17 Coal is one of the ...
Some communitie...

75 Researcher: Cool yes.

76 G: To where coal gets benefited there is a lot of value add that you can derive from coal, right? It's projects might be capital intensive if there's capital available. I'm sure that your payback period will be very short in terms of the product that we get from coal.

16:53:17 Great potential
Short payback per...

77 G: Right, so so your question, I think you were asking if would I? What is it?

78 Researcher: If you would either invest or not invest in the coal to carbon industry, the one that we are referring to as the extension of the coal to liquid industry.

79 G: Good.

80 G: Wait. Then there's the one condition will be if we can address the issue of cleaner energy the environmental issue. If that can be addressed. I would invest in in in a coal business. Because I said there's a lot of value, it's cheaper coal is cheap, cheap to mine, it's yeah. And then and. And the benefit that we derive from it are quite massive.

16:53:17 Design processes ...
Investments depe...
New coal projects...

16:53:24 Massive benefits f...

81 Researcher: OK, thank you. Thank you very much.

82 Researcher: To, uh, going with the discussion, its a holistic approach. Would you like to share some thoughts on the feasibility of technologies in the production of valuable coal products in South Africa, do we have technologies if we are to expand to the coal to carbon industry, or do we have the capacity like to develop new technologies to produce valuable coal products?

83 G: Well, I I think South Africa has has got technologies. Yeah though we don't have IP for most of these technologies. But I mean just the coal to liquid process. The Fischer Tropsch project that is used at Sasol for example. I mean that is state of the art technology. Right, so I think we we do have technologies we don't have to develop technologies ourselves. I mean, we don't really know we're not here to reinvent the wheel. Technologies are available for for, for, for this plant, and we have skills in the country. We have engineers, scientists,

16:53:17 South Africa has a...
South has technol...
State of art techn...
16:53:17 Buy technology d...
No need to devel...
16:53:17 Availability of skills
Great potential
Technologies are ...
16:53:17 Availability of skill...

- 83 technologists who are able to operate and maintain these technological systems. So in terms of technology, I mean most of the plants that you see running around. I mean we have we have state of the art and complex plants that are running on complex technologies.
- 84 G: I'll give an example with them. Uh koeberg power station for example, which was built many years ago, right? And you cannot have a nuclear power station if you really don't have technologies to run it, you look at Eskom plants. I mean those things are almost 100% automated.
- 85 Researcher: Right?
- 86 G: Right, Sasol plants, complex control systems that is employed to run this plants, so we are then. You may wanna ask how we already in the fourth industrial revolution. My answer will be not yet, but in terms of fulfilling the third industrial revolution which came about automation, I think we are then yes, there might be other factors that want to discourage us from fully automating our systems. And and if you want to look at the challenges that are facing the country, car challenges of unemployment skills and that.
- 87 G: So if we're not going to get you a point not in the near future. We want to fully automate our systems and fully why when when we want to have fully autonomous systems, because we still need to have people employed right so so in terms of technologies South Africa is there is on par and we have state of the art universities. I think even the university that you attend is quite in the forefront of this nuclear tech engineering nuclear technology.
- 88 Researcher: Yes.
- 89 G: So we trained the best engineers and you know these other people like driving these technologies. So my answer to your question would be yes, we do have technology and we do have access. If we don't have it have access to it and we are we have skills to be able to maintain and to end to operate these technologies.
- 90 Researcher: You have actually uh, answered one of the questions that I had for you which is South Africa's competitiveness globally in the production of valuable coal based products in

1:09

Great potential

South Africa has e...

Unemployment c...

State of the art un...

Availability of skill...

90 the admission that we have the expertise we have the all that we need to be competitive.

91 Researcher: Uh, maybe my next question.

92 G: Yeah.

93 Researcher: Would be according to you, how can the coal to carbon industry best realize its full potential in South Africa?

94 G: How can it be best OK?

95 Researcher: Yes, yes. How can it best realize its full potential?

96 G: Yeah, I mean there's a topic that has been with us for quite a number of years. Where we would look at local beneficiation for our resources and all resources not only coal, right? If you look at maybe I'll go back. Now that I thought about what you just said in terms of the other products coal to carbon products we are.

97 Researcher: Yes. Yeah.

98 G: We spoke about electricity. We spoke about coal to liquid but I think there's an opportunity to look into beneficiating more and that will be to strengthen our manufacturing capacity. Right now, if you look at manufacturing companies in South Africa we do have manufacturing companies and for many years South Africa has been ranked amongst the highest in terms of manufacturing. I'll give an example where we had even a steel company like a ArceloMittal when it was still in the uh, I mean during its hey times it was one of the biggest manufacturing, steel manufacturing industries in the country. So what that meant is because we have companies like that ArceloMittal being a big manufacturing company. We have Sasol being a big manufacturing company. It means now and also many other small manufacturing companies. Players in the country. Now that means we have skill around manufacturing and basically manufacturing we check this feed or raw materials transform it into a final product, right? So we have those skills now. All that is needed will be a conducive environment to be able to have this plants that are built here in South Africa to produce the products that we are talking about and also obviously produce these products. You will also have to look at your market. Who's going to buy these products? Are you closer to your customers and that sort of things you want to really be focusing on before you can start any project?

15:34 Or sp
Opportunity for m...

15:35 Right now, if y...

Manufacturing ec...

15:37 know that.

Availability of ma...

15:38 ...

APPENDIX F

SLR filtering process verification checklist

APPENDIX F: SLR FILTERING PROCESS VERIFICATION CHECKLIST

By completing this search result verification, I hereby acknowledge that I have tested the search strategy on the databases listed below, and that this was completed with research integrity.

| Criteria | Checked | Comment |
|---|---------|---------|
| Search strategy | ✓ | |
| Using the search strategy Coal-based carbon products “OR” Value added products from coal” OR “Coal-derived carbon products” AND (“Feasibility” OR “Carbon” OR “South Africa“ OR “Barriers”, OR “Enablers”, OR “Technologies”)] The following search results are obtained: | ✓ | |
| Science Direct – 54 | ✓ | |
| Web of Science-3 | ✓ | |
| Emerald Insight-0 | ✓ | |
| Scopus-30 | ✓ | |
| Google Scholar-163 | ✓ | |
| IEEE Explore – 0 | ✓ | |
| EBSCOhost – 494 | ✓ | |
| Total: 744 publications | | |
| Inclusion criteria | | |
| All non-English publications were removed | ✓ | |
| Exclusion criteria | | |
| By excluding publications focused no focusing on coal-based carbon products and the coal-to-carbon industry | ✓ | |

| | | |
|--|---|--|
| Science Direct: 8 | ✓ | |
| Web of Science: 1 | ✓ | |
| Emerald Insight: 0 | ✓ | |
| Scopus: 8 | ✓ | |
| Google Scholar: 11 | ✓ | |
| Scopus:0 | ✓ | |
| IEEE Explore: 0 | ✓ | |
| Total: 13 publications selected | | |

APPENDIX G

Interviews with experts of the South African coal-to-carbon industry

APPENDIX G: INTERVIEWS WITH EXPERTS OF THE SOUTH AFRICAN COAL-TO-CARBON INDUSTRY



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A HOLISTIC FEASIBILITY ASSESSMENT OF THE SOUTH AFRICAN COAL-TO-CARBON INDUSTRY

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ABSTRACT

This study explores the feasibility of the coal-to-carbon industry in South Africa through the eyes of the industry's experts. The aim is to assess the feasibility of South Africa's coal-to-carbon industry by exploring the market, technical, economic, environmental, and operational feasibility factors. Semi-structured interviews were conducted with industry experts and academics in the field. Purposive sampling was used alongside snowballing to reach participants most suited to provide relevant information to the study. A total of 13 interviews were conducted for this study. Interpretive thematic analysis was used, and the findings are presented using emergent themes and rich, narrative descriptions. The findings show that South Africa has skills, feedstocks for carbon products and supporting industries, which are feasibility enablers. The major feasibility barrier is the environmental factor as the current processes in the production of carbon precursors produce significant amounts of greenhouse gases. Recommendations are made for the collaboration of key stakeholders to bridge the coal-to-carbon industry narrative gaps.

Keywords: Coal, Carbon, Coal-based products, Feasibility, South Africa

* Corresponding Author





1 INTRODUCTION

1.1 Background

Coal resources are plentiful in South Africa [1]. They contribute significantly to the country's economy as applications in power generation, steel making, and cement production, and have wider implications for industrial development [2]. However, coal usage has negative effects on the environment from the production and release of greenhouse gases. To combat these effects, the world formulated interventions through the Paris agreement in 2015 [3] and, lately, the 26th conference of parties [4]. These interventions are encouraging a shift away from coal utilisation.

There are tangible adverse effects of shifting away from coal use in power generation, and other industrial uses as South Africa is a coal-dependent economy. Rademeyer [5] highlights the potential subsequent deterioration in international coal trade on South Africa's coal market and economy. When faced with declining demand for exported coal, the supply of coal for local power stations would decline due to decreasing profits for mines leading to the eventual closure of higher-cost mines [5].

The Covid-19 pandemic has exacerbated the current situation [6]. These factors indicate a need to diversify our use of coal to include more sustainable utilisation methods. The challenge for South Africa is developing a feasible and sustainable economic development model that encourages a shift away from unabated coal usage. By pursuing alternative coal uses, new job opportunities could be created in South Africa's competitive job market, which could act as a stepping stone to new applications of advanced forms of carbon [7].

Amidst all these challenges facing the coal industry, a market exists to obtain more value from coal by extracting carbon and producing carbon-based products. The coal-to-carbon industry converts coal or precursors (the raw material used to make carbon products) from coal into useful and valuable carbon products. The coal-to-carbon industry presents many opportunities in advanced markets for coal-derived products. The coal to solid carbon products global market is estimated to consume between 300-400 million tons per annum of coal, and the major areas are chemicals, fuels, and fertilisers [8]. Coal offers opportunities for both reducing the cost of manufacturing carbon products and, in many instances, providing a superior quality carbon feedstock [8]. Coal is also less expensive (\$12-\$50/ton) in many advanced market applications than traditional feedstocks such as petroleum (\$400-\$500/ton) [8].

1.2 Motivation for the study

The coal-to-carbon industry offers significant opportunities for coal and is an alternative to South Africa's current coal utilisation. Sales for carbon nanotubes are currently in excess of \$2.5 billion [9]. As South Africa has excellent coal resources that contribute significantly to the country's economy, it would be valuable to assess the feasibility and prospects of the coal-to-carbon industry. Smaller amounts of coal can generate more revenue in carbon products than larger amounts of coal when used as a feedstock in electricity and fuel generation. In South Africa, 53% of coal is used for power generation [10], 33% for fuel production, 12% for metallurgical industries, and 2% for domestic use. The purpose of this study is to explore the feasibility factors affecting the South African coal-to-carbon industry from the viewpoints of experts in the industry.

This study aims to answer the following questions.

- What is the status of the South African coal-to-carbon industry?
- What are the holistic feasibility barriers and enablers of the coal-to-carbon industry in South Africa?
- What are the opportunities offered by the coal-to-carbon industry in South Africa?

[87]-2





2 LITERATURE

2.1 Coal-to-carbon Industry

The coal-to-carbon industry focuses on non-energy products, advanced carbon materials, and products. The secondary sector, which is the conversion of beneficiated coal into final products, is the niche sector as it is still developing or in the feasibility phase globally [8]. The industry is relatively new, with various technologies still in development and testing stages [11]. However, some of the technologies used to produce carbon precursors are relatively old. The industry employs various pathways to produce value-added carbon products and incorporates many different technologies to produce the carbon products from coal. The high-value carbon products from coal include activated carbons, carbon fibres and composites, carbon nanomaterials, carbon black, carbon electrodes and carbon foams [8] [12] [9].

2.2 Feasibility

Factors that impact feasibility emanate from increasingly pressing global sustainability challenges, accelerating technological evolution, and escalating commercial and geopolitical competition [13]. Assessing feasibility with rigour is dependent upon looking at the many interlinked factors that contribute to long-term life cycle success, drawing upon many perspectives and inputs [13]. This study incorporates feasibility criteria relevant to the coal-to-carbon industry. Table 1 shows feasibility types and the rationale for their selection for the study.

The study assesses the technical viability of the industry. It also incorporates economic and operational feasibility and environmental and market feasibility. Critical to the coal-to-carbon industry is the environmental feasibility as coal is a feedstock that draws criticism due to its contribution to greenhouse gas emissions [14] and particulate matter emissions [15]. The abovementioned feasibility criteria are combined to comprehensively assess the factors relevant to the coal-to-carbon industry.

Table 1: Feasibility types and their specifications

| Feasibility type | Specifications | Rationale |
|----------------------------|--|---|
| Technical | Technical readiness level Physical-technical constraints and alternatives | To determine the suitability of technologies available in South Africa [13] |
| Economic | Cost-benefit analyses | To determine cost-effectiveness of the venture [16] |
| Operational/Organisational | Stakeholder identification | Helps identify key stakeholders to the industry [16] |
| Environmental | Sustainability, lifecycle assessment | To determine potential environmental effects and emissions [14] [15] |
| Market | Market research, total addressable market | To identify and segment the market for the products [17] |

Coal is well suited to produce high-value carbon products because of its inherent high carbon content. There are various technically feasible products that can be produced from coal that includes carbon fibres and carbon-based electrodes [18]. However, some of the current coal-to-carbon applications and processes are uneconomical as they are energy and capital intensive [18].

There are high costs involved in the production of these products but coal as a cheaper feedstock has the potential to reduce the overall production costs. Coal-based advanced

[87]-3





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carbon materials and chemicals from coal offer significant opportunities and there is a huge market globally for products and materials from coal [8] [19].

3 RESEARCH METHODOLOGY

3.1 Research Approach

The research follows a qualitative approach. The coal-to-carbon industry serves as an area of interest explored with the aid of experts in the field to provide valuable insights into this industry. The study presented in this paper forms part of a larger triangulated qualitative study that has also used literature review. A literature review was conducted preceding the empirical research reported in this paper. Various feasibility factors were surveyed focusing on the market, technical, operational, environmental, and economic aspects. This paper reports on findings from semi-structured interviews [20], [21] conducted with carbon experts from the South African industry and academia.

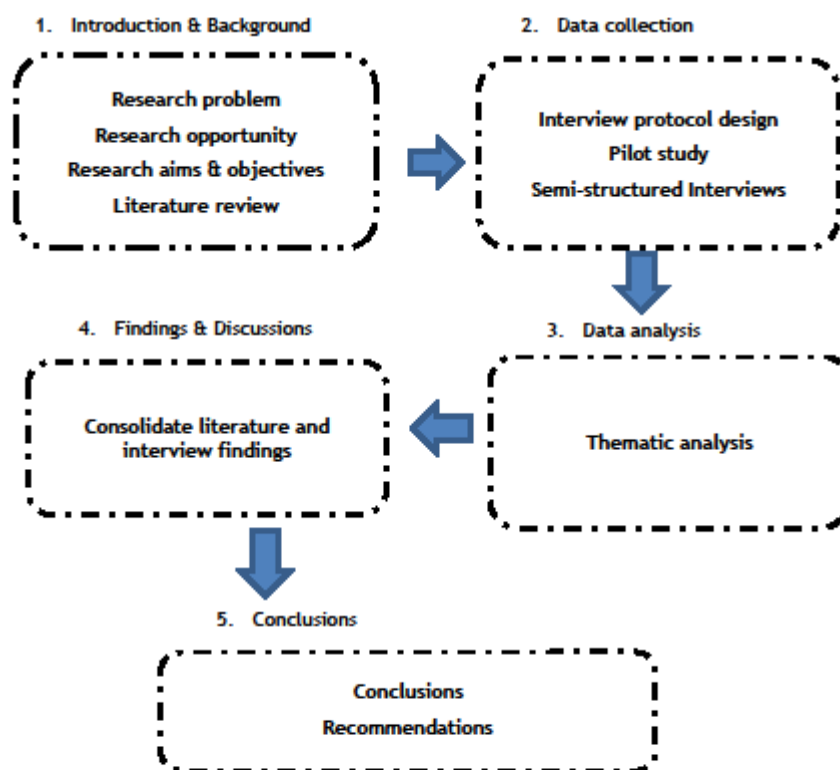


Figure 1: Visualised research method

3.2 Method

A semi-structured question guide with 13 questions was developed from literature using the research questions and objectives as a guide. The questions focused on the various feasibility criteria to cover the topic holistically. The interviews were hosted in a Zoom environment, recorded, and later transcribed. The list of questions is provided in Appendix A.

[87]-4





3.3 Data Collection and Sampling

The target population of this study are experts in the coal-to-carbon industry in South Africa including practitioners working with coal conversion technologies and expert researchers in coal-based carbon materials and or products. The industry is highly specialised, and therefore, a purposive sampling [20] method was utilised to select participants well positioned to provide data relevant to the study. The participants were continuously sourced until data saturation was reached. The LinkedIn platform was utilised to reach out to the participants and the snowballing method [20] was used to reach out to a wider area of eligible participants. At the end of the interview, the researcher would ask participants to refer others to the study.

There were 13 participants, 38.5% were practitioners, 38.5% were academics, and 23% were both practitioners and academics with experience ranging between 3 and 30 years. Participants P1, P2, P5, P7 and P10 were practitioners and participants P3, P4, P11, P12 and P13 were academics. Three participants in the study were both practitioners and academics, P6, P8 and P9.

3.4 Data Analysis

The analysis centred on the views and opinions of the participants. The researcher followed a thematic analysis process to capture the meanings of participants in the industry [22]. The process immersed the researcher in the data to identify multiple concepts and themes on the topic. The researcher went over the data several times to become acquainted with it. The data analysis was not a linear process, but rather a recursive one in which the researcher moved back and forth as needed through the various phases of the study [23]. The researcher first listened to the interview recordings and then read the transcripts taking notes of thoughts related to the dataset.

The researcher explored the diversity and patterns of meaning in the dataset, resulting in over one hundred and fifty formulated codes [22]. Each data item was read, and all the segments of text with meaning relevant to the research questions were labelled. This process was repeated, producing over two hundred codes, as the researcher gained new insights into the data. Next, there was engagement with data codes to discover similarities and meanings [22]. All potentially connected codes were clustered into initial themes. The coded data was revisited to improve and or clarify the code clusters. Some themes were dropped that were not relevant to the research questions. Lastly, the researcher refined, defined, and named the themes from the data set. The final thematic analysis reflects only the themes and subthemes that were articulated by our sample.

4 FINDINGS AND DISCUSSIONS

This section presents identified themes and sub themes from the data set using quotations as supporting evidence. Quotations are referenced back to the participants P1 to P13. The interview questions focused on the South African utilisation of coal resources in the production of carbon products, the feasibility factors and the opportunities offered by the coal-to-carbon industry. Table 2 shows the themes from the dataset and corresponding sub-themes.

[87]-5





Table 2: A list of themes and sub-themes

| THEMES | SUB-THEMES |
|---------------------|--|
| 1. ENABLER | Availability of feedstocks |
| | Availability of skilled personnel |
| | Availability of supporting industries |
| | Market availability |
| | Coal is a cheaper feedstock |
| 2. CHALLENGES | Environmental |
| | Funding |
| | Markets |
| 3. COMPETITION | Feedstocks |
| | Markets |
| 4. INDUSTRY GAPS | Lack of carbon manufacturing industries |
| | Lack of visibility |
| 5. COAL UTILISATION | Primary, predominant and /traditional uses |
| | High-value utilisation |

4.1 Coal-to-carbon industry status

Coal utilisation

South Africa has abundant coal resources and reserves [1], and the participants highlighted their extensive use in power generation, synthetic fuel production, steel making and the export market. South Africa boasts high utilisation of coal resources compared to other countries having pioneered the synthetic fuel production alongside other uses. The notion of extensive use of the coal resources was based on the current utilisation in South Africa.

"Because these are the technologies that are available for power generation and for coming up with fuel so basically based on the technologies that we have, we are using it to the fullest." (P3)

Comparing the country's resources of coal to the production of coal-based materials and products, other participants' opinions showed that the utilisation was less than optimum. The production of carbon products from coal is generally lacking in South Africa. Therefore, the optimum use of coal resources could be reached by leveraging this resource in the production of high-value carbon products. The low ash South African bituminous coals are excellent starting materials to manufacture high-value carbon products that are exported to international markets.

Overall, there seemed to be no agreement among the participants on whether coal resources are being utilised to the fullest in South Africa. There is much potential to use available coal resources to produce carbon products. The underutilisation could be attributed to various interrelated reasons as cited by the participants. Lack of knowledge regarding the use of coal to produce carbon products was cited as a reason for the underutilisation and coal resources

[87]-6



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are largely used for traditional purposes. The local coal conversion industry lags when it comes to innovation.

"In South Africa,... most of the companies haven't been innovating in that they don't do R and D (research and development). Whereas overseas, most industries actually support, and are highly innovative." (P9)

Lastly it was pointed out that the current use of coal is heading for a change in the future with some utilisation processes coming to a halt. Chemical production and carbon materials production are some of the potential future uses of coal in South Africa. The 26th conference of parties held in Glasgow in 2021, resolved to pursue the reduction of unabated use of coal. As a result, the traditional use of coal in power generation and or other applications which pollutes the environment could decline.

"In my opinion over the course of the next let's say 10 to 20 years, there is going to be a shift from industries that use coal and emit a lot of carbon dioxide and if coal is to have a future it's not in combustion or gasification it's going to be chemicals production and carbon materials production." (P6)

4.2 Feasibility enablers

The coal-to-carbon industry in South Africa is well-positioned to be vibrant and competitive as it has extensive industry enablers, as indicated by the study's participants. Coal conversion into valuable carbon products requires skills, technologies, and resources among other requirements for success. The participants identified the following enablers of the South African coal-to-carbon industry. The first enabler is the availability of feedstocks or carbon precursor-producing facilities or entities. Coal as a feedstock is abundant in South Africa [1]. High-value carbon products can be produced from feedstocks with high carbon content, and South African coking coals are a source of this carbon.

Carbon precursors from coal, such as the pitches, and tars from Sasol and ArcelorMittal, were singled out as a major industry enabler. Coal-tar pitch is a precursor used to produce advanced carbon materials [9]. The tar from the carbonisation process, chars and coke are currently being used in the production of synthetic carbon materials [24] [25].

Carbon precursor producing facilities are key in the production processes of high-value carbon products, and South Africa has Sasol that produces tars, pitches, and light charcoal. High-temperature pitches from the coking processes at ArcelorMittal can be used to produce carbon fibres and other carbon nanomaterials. The cokes from the same process can produce activated carbons and carbon electrodes.

South Africa was cited for having skilled personnel in the field of manufacturing. The participants referred to the state-of-the-art manufacturing facilities run by experts in various fields. As technologies are developing and becoming more advanced, South Africa is also training personnel to operate these technologies. The technologies mentioned include Sasol's Fischer Tropsch technology, the nuclear power stations, and Eskom power plant technologies. With an extensive base of skilled personnel in the field of coal conversion, South Africa can build on this to grow the coal-to-carbon industry. The necessary technologies for high-value carbon product production can be developed or acquired.

Within the coal-to-carbon industry, nanomaterials are high-value products that show great promise and South Africa has an enabling environment to support the production of these materials. The government has invested in this industry, there are research entities specialising in nanotechnology and there are facilities producing nanomaterials utilising other feedstocks. With expertise in the field it's a significant boost to the industry.

"So what we got is many people who understand nanotechnology . . . High tech carbon is nanotechnology basically. Its just a component, nanotechnology is the overriding issue so carbon is one component of it." (P4)

[87]-7



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The availability of supporting industries to the coal-to-carbon industry was highlighted as another enabler to the feasibility of the coal-to-carbon industry. The supporting industries are key to the success of any industry and in South Africa, there are industries that provide the carbon precursors, input suppliers like stable electricity and industries that take up the products. The carbon products are utilised as raw materials to the various industries in South Africa. The vibrant South African automotive sector is a leading market for high-value carbon products.

"...you've already got some industries you can go to." (P2).

The international market and the local market came out as complementary enablers to the industry. The local market can readily absorb the relatively cheaper carbon products while the international market can support high-value products. Participants were positive that if products are of high quality, the international market could take them.

"I think high tech you've got to go to the international market. The low tech you got a local market. Remember you can use these high-tech materials if you can make them cheaply, they may have properties that you want so you may want to put high-tech carbon into low-tech places." (P4)

The study assesses the feasibility of carbon products production from coal. Another enabler to the industry is that coal is a cheaper feedstock. Coal is also less expensive (\$12-\$50/ton) compared to other traditional feedstocks such as petroleum (\$400-\$500/ton) [8]. This gives an advantage to coal as a precursor to carbon material production, considering the production costs.

4.3 Feasibility barriers

4.3.1 Competition

Competition in the coal-to-carbon industry is twofold, the competition for the precursors to produce carbon products and final product competition. The production of high-value carbon products is dependent on carbon found in feedstocks. The petrochemical industry is a supplier of carbon-containing feedstocks, and therefore this industry is a direct competitor to the coal-to-carbon industry.

In the production of some carbon products, there are other feedstocks that are already established. In the production of carbon fibres, polyacrylonitrile currently accounts for 90% of all feedstocks followed by Rayon [9]. Activated carbon can also be produced from various trees in South Africa, which are abundant biomass materials.

The market is an important factor for the success of an industry. The South African coal-to-carbon industry's market battle is against advanced economies in Europe, the United States of America and Asia. Countries that have more advanced carbon products producing industries pose stiff competition to the South African coal-to-carbon industry. With advanced manufacturing capabilities, these economies dominate the advanced carbon material markets. Therefore, it will be difficult for South Africa to venture into carbon fibre products and secure markets against these established economies.

"You are competing with international people, and you've got to look at your markets, so you know the type of thing is the low-level stuff is easier to get a handle on because the market is here." (P4).

4.3.2 Challenges

There are many challenges regarding the feasibility of the coal-to-carbon industry in South Africa. The most significant of these, as cited by the study's participants, were environmental. The current processes producing carbon precursors in South Africa produce substantial greenhouse gases. Coal carbonisation and liquefaction technologies that produce the tars and

[87]-8

557





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itches also emit large quantities of carbon dioxide and sulphur into the atmosphere. This is a major challenge that the industry needs to overcome to be successful.

"It's a fossil fuel and it's a major cause because I mean in South Africa it contributes quite a lot to see CO₂ emissions. Right, that is one of the biggest challenges with this industry." (P7)

Investment in carbon capture and sequestration technologies could be an option for the South African context. This technology captures and stores carbon dioxide and other greenhouse gases from the production of carbon products and is one potential solution to these environmental concerns.

Another challenge that faces the feasibility of the coal-to-carbon industry is also fuelled by environmental concerns. New coal projects struggle to access finance due to perceived environmental issues. It emerged that funding for coal-based projects may be limited due to the transition from unabated coal use. However, the participants argued that for sustainable coal projects, funding is accessible.

Although the products for the carbon industry are high value, the market is relatively small. The local carbon market is still significantly small due to various reasons. Traditional materials such as steel, aluminium, and concrete dominate the market. However, carbon materials and products can increase their market share, as they have superior properties.

"The market is there, but it's small. It's not sustainable." (P13)

4.4 Opportunities for the coal-to-carbon industry

Industry gaps

Some gaps must be filled for the South African coal-to-carbon industry to be fully functional. Currently, only a fraction of the industry is functioning, with the production of carbon precursors being the most significant segment of the industry. The industry lacks: there is need to optimize the industry's value chain. The participants pointed to the gaps and or sectors in the industry narrative. The most visible gap is the lack of carbon manufacturing industries. The final carbon products that South Africa is currently producing include carbon black and activated carbon. It lacks in the production of other carbon products that are of high value. South Africa generally lacks carbon technologies.

The coal-to-carbon industry lacks visibility as it is a niche part of the coal conversion industry that is relatively unknown. The local coal producers utilise typical traditional markets for the predominant traditional coal utilisation, instead of the coal-to-carbon industry, a market that takes up coal as a feedstock.

"I think in terms of market availability that is also where there is a very big gap there. The coal producers in the country do not know, they're not necessarily aware of all the different markets that they could sell their product into." (P1).

The country has invested extensively in coal research, but there is still a gap in carbon products produced from coal. Extensive research in the field of coal conversion was never implemented:

"In South Africa, there's really nobody who does it because we don't even do it." (P9)

A concept that was echoed by most of the participants is the need for collaboration or participation between the various stakeholders in the industry. The South African coal-to-carbon industry needs stakeholders to come together and take the industry to the next level.

"So, I think those are some of the issues that need to be . . . collaboration between the universities, research institutions, the industry, the government is key also to ensure success in this program." (P13)

[87]-9





4.5 Further discussion

Collaboration is significantly important to the feasibility of the coal-to-carbon industry in South Africa. The study identified the top stakeholders and formulated their relationships. These stakeholders can work collectively to develop the coal-to-carbon industry in South Africa. The key stakeholders to the coal-to-carbon industry and their relationships are shown in figure 2. The government, research institutions including tertiary institutions and funding agencies comprise top stakeholders to coal-to-carbon industry.

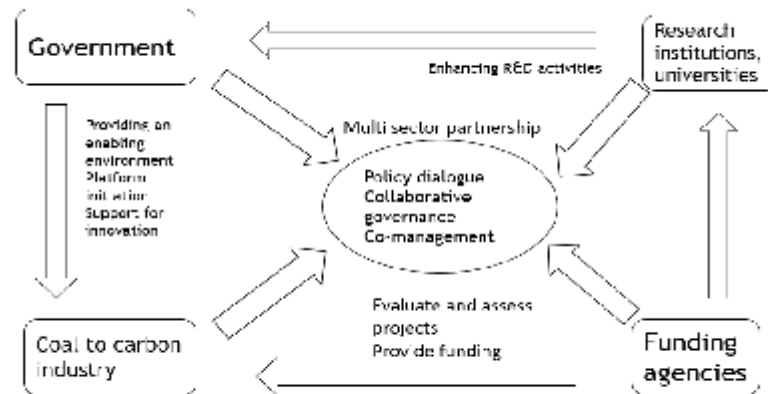


Figure 2: The industry stakeholders' relationships

5 CONCLUSIONS

The findings of this study on expert opinions and views of the feasibility of the coal-to-carbon industry in South Africa show that the South African coal-to-carbon industry is still in its infancy and generally lacks appropriate carbon technology. These technologies can be acquired from other advanced economies, and utilise the available cheaper feedstock, to optimise the enablers to the industry.

There are various feasibility enablers for the industry. The necessary building blocks for a fully optimised, productive industry are available but there is a need for stakeholders to collaborate and close the gaps within the industry. On the other hand, there are also feasibility barriers with the leading factor being environmental. The production of greenhouse gases and particulate matter in the production of carbon products is currently the limiting factor against the industry.

Lastly, the South African coal conversion industry is highly competitive globally, with a capacity to innovate and upgrade to leverage resources to develop the coal-to-carbon industry. There is potential to use available coal resources to produce carbon products. The recommended route is the simultaneous pursuit of differentiation and low cost to open new markets and create new demand for the industry.

This study used a novel approach that applied a feasibility framework relevant to the coal-to-carbon industry. The holistic approach allowed the most crucial feasibility aspects to be discussed. This exploratory study has set the stage for further investigation into the industry's potential.

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560



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[87]-12

561





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APPENDIX A

1. South Africa has abundant coal reserves and resources; do you think they are being utilized to their fullest? Why do you believe this is the case?
2. In terms of coal conversion into useful products, South Africa has excelled with its leading coal to liquid industry, what do you think of the coal-to-carbon industry?
3. What do you believe are the coal-to-carbon industry key success factors?
4. How do you see the current size and growth potential of the market for coal-based products in South Africa?
5. As an expert in the coal conversion industry, you may have witnessed or experienced some of the challenges currently facing this industry. Can you share some of these instances?
6. Would you like to share some thoughts on the feasibility of technologies in the production of valuable coal products?
7. I would like us to consider the environment as we look at the feasibility of the coal to carbon industry. From this perspective what do you perceive as critical issues that may affect the coal-to-carbon industry?
8. Are there any operational issues on the feasibility of the coal-to-carbon industry that you might want to discuss?
9. From studies done in other regions, the coal conversion industry is rapidly growing, what are your thoughts on South Africa's competitiveness globally in production of valuable coal-based products?
10. The coal conversion industry is capital intensive which makes it a high-risk business. In the current economic and political environment, would you tell us reasons why you would either invest or not invest in this industry?
11. What do you think are the benefits of the coal-to-carbon industry to the South African economy?
12. To what extent do you think the coal-to-carbon industry has potential to disrupt the coal conversion industry?
13. According to you, how can the coal to carbon industry best realize its full potential in South Africa?

[87]-13

562



APPENDIX H

AMENDED TITLE

APPENDIX H: AMENDED TITLE



NWU Higher Degree Administration

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South Africa 2520

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Fax: 018 299-4910
Web: <http://www.nwu.ac.za>

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Email: 26575779@nwu.ac.za

Dear Mr Mukodzani

REGISTRATION OF TITLE

At the recent meeting of the faculty your title was approved as follows:

A holistic feasibility assessment of the South African coal to carbon industry

The above-mentioned title may under **no circumstances** be changed without consulting your supervisor and obtaining the approval from the Faculty Board.

In the instance that you wish to submit for examination, please inform your supervisor/promoter accordingly. *Also ensure absolute adherence to the prescripts of A Rule 4.10 for the submission of a Master's study and of A rule 5.10 for the submission of Doctoral thesis.*

Upon approval of your supervisor/promoter, please ensure that the Notice of Submission form is submitted THREE months in advance to this office.

Note that the Notice of Submission-form is available at the Higher Degree Administration Officer or the Faculty Administrator of the faculty.

For ease of reference, herewith links to the following useful resources:

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Yours sincerely

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13 February 2019

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