Regime actors' role in the transition of carbon dioxide removal technologies in Brazil

A Multi-Level Perspective Approach

Bruna Vaz Soares da Silva

Delft University of Technology

TU Delft

Regime actors' role in the transition of carbon dioxide removal technologies in Brazil

A Multi-Level Perspective Approach

by

Bruna Vaz Soares da Silva

to obtain the degree of Master of Science
in Sustainable Energy Technologies
at the Delft University of Technology,
to be defended publicly on Tuesday February 10th 2026, at 12:30 PM.

Student number:	4396642	
Project duration:	May, 2025 – February, 2026	
Thesis committee:	Dr. L. Kamp,	TU Delft, supervisor
	Dr. E. Schröder,	TU Delft, assessment committee

Cover: Generated by OpenAI (2025)
Style: Report Style with TU Delft Report Style

An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

Acknowledgements

This thesis marks the conclusion of my Master's degree at TU Delft. It was a period filled with intense emotions and intense self-development, both academic and personal. The experiences I had and the growth I achieved are unforgettable and will forever be part of who I am. The most difficult moments were also the ones from which I learned the most. I am very grateful and proud to complete this journey with a subject that I value so much.

I would like to express my sincere gratitude to the thesis committee for their guidance, support, and constructive feedback throughout this process. Their contributions were essential in helping me deliver a stronger thesis and provided valuable encouragement along the way.

I would especially like to thank my supervisor, Linda Kamp, who was always available when I needed support. Your attention and kindness created a safe environment in which I could feel confident, while also giving me the push I needed to continuously improve my work.

I would also like to thank my former supervisors at PSR, Luana Gaspar and Rafael Kelman. Although they were not directly involved in this process, my time at PSR provided me with valuable experience and fresh perspectives that greatly contributed to the development of this research topic.

Additionally, I deeply appreciate the contributions of the professionals who agreed to be interviewed and helped bring my work to a deeper level of insight and understanding.

Por fim, gostaria de agradecer à minha família e aos meus amigos, que sabem o quanto esse processo foi difícil em muitos momentos, mas que sempre me deram apoio e amor para continuar, não desistir e dar o melhor de mim. Aos meus pais e irmãos, agradeço por serem minha base e por estarem sempre ao meu lado me fortalecendo e sempre acreditando em mim. Aos meus amigos na Holanda, agradeço por me aguentarem quando eu não estava tão bem, por me distraírem por serem minha fonte de alegria.

Finishing this thesis is an incredible accomplishment that makes me proud of my journey and confident about the next steps and opportunities to come.

Bruna Vaz Soares da Silva
Delft, January 2026

Abstract

Carbon Dioxide Removal (CDR) technologies are increasingly becoming a part of climate change mitigation strategies. Considering the Paris Agreement and the goal of limiting the temperature increase to 1.5 °C above the pre-industrial level, CDR can be a helpful complement to emissions reductions, especially during the transition toward net-zero. Nevertheless, CDRs are novel technologies, with few applications and significant uncertainties. Integrating novel technologies into established systems is not a purely technical challenge, but one shaped by socio-technical and political-institutional dynamics. In this context, the Brazilian sugarcane and ethanol (sugar-energy) sector is powerful and influential, raising critical questions about its role in enabling or constraining technological change.

In this thesis, three CDR technologies are studied, namely Bioenergy with Carbon Capture and Storage (BECCS), Biochar Carbon Removal (BCR), and Enhanced Rock Weathering (ERW). These technologies have the potential to be integrated into existing agricultural and energy systems, such as sugarcane plantations and ethanol production chains. The research aims to investigate how CDR technologies are developing and diffusing in Brazil's sugar-energy sector, focusing on the interactions between niche innovations (CDR technologies), the established regime (sugar-energy sector), and broader landscape pressures (long-term, exogenous pressures). The study is guided by the Multi-Level Perspective (MLP) framework, which provides a structured framework for analyzing technological transitions in socio-technical systems through a socio-political and technological perspective.

Using a qualitative methodology, the thesis addresses the question: "What role do sugar-energy incumbents play in shaping the diffusion of BECCS, BCR, and ERW in Brazil's low-carbon transition?" The analysis is based on the MLP framework and on seven semi-structured interviews with industry actors and niche innovators. The findings suggest that CDR development benefits from rising climate concern and emerging policy initiatives in Brazil, but its diffusion is constrained by limited incumbent interest, insufficient economic incentives, and regulatory uncertainty. Incumbent firms can play a crucial role in enabling technological diffusion by providing legitimacy, resources, and access to infrastructure; however, this support tends to materialize only when CDR technologies align with existing regime structures and complement current production processes. As a result, Incumbent firms tend to reinforce gradual transition dynamics rather than transformative change.

The thesis concludes that CDR diffusion in Brazil's sugar-energy sector requires explicit policy recognition, dedicated financial instruments, and deeper integration of CDR technologies by large sugarcane and ethanol incumbents, beyond experimenting and early commercial scale. By examining the socio-technical and political-institutional dimensions of CDR diffusion, this research contributes to deeper debates on negative emissions, sustainable innovations transitions, and climate governance in Brazil.

Contents

Acknowledgements i

Abstract ii

1 Introduction 1
1.1 Research Question 3
1.2 Methodology 4
1.3 Thesis Outline 4

2 Methodology 5
2.1 Data Collection 5
2.1.1 Interview 5
2.1.2 Limitations 7
2.2 Data Analysis 7
2.2.1 Multi-Level Perspective (MLP) 8

3 Brazilian Socio-Technical Landscape 13
3.1 Governance and Policy Landscape 13
3.1.1 RenovaBio 13
3.1.2 National Energy Transition Policy (PNTE) 14
3.1.3 Energy Transition Acceleration Program (PATEN) 14
3.1.4 Fuels of the Future Law 14
3.1.5 Regulated Carbon Market 15
3.2 Nationally Determined Contributions (NDC) 16
3.3 Market Dynamics 16
3.3.1 Investments Profile 17
3.3.2 Carbon Monetization 18
3.4 Cultural shift 19
3.5 Main Findings 20

4 Socio-technical niche of BECCS, BCR and ERW 21
4.1 Carbon Dioxide Removal 21
4.2 Bioenergy with Carbon Capture and Storage (BECCS) 23
4.2.1 Technology map 23
4.2.2 Niche actors 28
4.2.3 Technology development phase 29
4.3 Biochar Carbon Removal (BCR) 30
4.3.1 Technology map 31
4.3.2 Niche Actors 35
4.3.3 Technology Development Phase 36
4.4 Enhanced Rock Weathering (ERW) 37
4.5 Main Findings 38

5 Brazilian Sugar-Energy Socio-Technical Regime 40
5.1 Economic and Political Role of the Sugarcane and Ethanol Sector 40
5.1.1 Sugarcane 40
5.1.2 Ethanol 41
5.1.3 Economic Numbers and Political Influence 42
5.1.4 Important Considerations 44
5.2 Stakeholders Analysis 45
5.2.1 Government and Policies 47
5.2.2 Industry Incumbents 48
5.2.3 Niche Innovators 50
5.2.4 Knowledge & Research 51
5.2.5 Civil Society 52
5.2.6 Investors 53
5.2.7 Power x Interest Matrix 54
5.3 Actors' narratives on innovation and carbon removal 56
5.4 Main Takeaways 58

6 Discussion: Cross-Level Dynamics Shaping CDR Technologies Diffusion 59
6.1 Barriers 59
6.1.1 Enabling factor 61
6.2 Interplay Between Socio-Technical Levels 62
6.3 Implications for the Diffusion of CDR Technologies in the Sugar-Energy Sector 63
6.4 Reflections 65
6.5 Scientific Contributions 66
6.6 Research Limitations 67
6.7 Summary 68

7 Conclusion 69
7.1 Answer to the Research Questions 69
7.1.1 Sub-RQ-1: What global and national trends influence the development of CDR technologies in Brazil's sugar-energy sector? 69
7.1.2 Sub-RQ-2: How are the emerging socio-technical niches of CDR technologies developing in Brazil's sugar-energy sector? 70
7.1.3 Sub-RQ-3:What are the existing institutional, political, and market structures and incumbent actors in the sugar-energy regime? And how do they influence the development and diffusion of CDR technologies? 71
7.1.4 Research Question: What role do sugar-energy incumbents play in shaping the diffusion of BECCS, BCR, and ERW in Brazil's low-carbon transition? 72
7.2 Recommendation for Actors 73
7.2.1 Recommendations for sugar-energy incumbents 73
7.2.2 Recommendations for policymakers and government institutions 73
7.2.3 Recommendations for public financing bodies and development banks 74
7.2.4 Recommendations for niche actors and innovators 74
7.3 Recommendation for Future Research 74

References 76

A Interviews Risk Assessment, and Ethics Approval **86**
A.1 Human Research Ethics Checklist - Risk Assessment 86
A.2 Letter of Approval from Educational Institution 94

B Informed Consent Interviews **95**

C Interviews Summary **98**
C.1 ERW Practitioner (INT-01) 98
C.2 BECCS Practitioner (INT-02) 101
C.3 Sugar-energy sector Practitioner (INT-03) 104
C.4 Energy and Climate Policy Expert (INT-04) 107
C.5 Hard-to-decarbonize Industry Practitioner (INT-05) 110
C.6 Hard-to-decarbonize Industry Practitioner (INT-06) 112
C.7 Sugar-energy and Hard-to-decarbonize Industry Practitioner (INT-07) . . . 112

D Interview Questionnaire **115**
D.1 Questionnaire for Niche Actors 115
D.2 Questionnaire for Sugar-Energy Incumbent Actors 116
D.3 Questionnaire for actors in Hard-to-Decarbonize Sector 117

List of Figures

2.1 Multiple levels as a nested hierarchy (Geels, 2006, 2002) 9
2.2 Power x Interest Grid 12

4.1 BECCS Technology Map 24
4.2 Biochar Technology Map 31

5.1 Stakeholder Map for CDR Technologies in Brazil 46
5.2 Influence Diagram - Government & Policy Actors 48
5.3 Influence Diagram - Industry Incumbents Actors 49
5.4 Influence Diagram - Niche Innovators Actors 51
5.5 Influence Diagram - Knowledge & Research Actors 52
5.6 Influence Diagram - Civil Society Actors 53
5.7 Influence Diagram - Investors Actors 54
5.8 Power X Interest Grid 55

List of Tables

Table2.1 List of interviewees 6

Table4.1 CDR Methods Categories (Smith et al., 2024) 22

Table6.1 Main barriers and potential enabling factors 62

Chapter 1

Introduction

Climate change has become an important issue since the end of the last century. The relationship between greenhouse gases released in the atmosphere with the high temperature increase and extreme weather events has created the need to develop sustainable, innovative technologies and market solutions that could tackle the problem. Decreasing GHG emissions and therefore controlling the temperature from rising has become a must. As the world suffers from the escalating impacts of global warming, the urgency to meet the Paris Agreement's objectives and challenges increases. The main goal of the agreement is to keep global temperature increase below 1.5 ^{o}c since pre-industrial levels (UNFCCC, n.d.-b). As global efforts to reach net-zero emissions intensify, Carbon Dioxide Removal (CDR) technologies have gained attention as a complementary strategy to emissions reduction. Although the energy transition is often associated with replacing fossil fuels with renewable energy sources, this change is neither immediate nor complete. Hard-to-decarbonize sectors and infrastructure lock-ins require transitional solutions. These technologies are designed to capture CO_2 from industries, power plants, and/or the air, removing part of the carbon dioxide from the atmosphere or after being burned (IPCC, n.d.).

CDR are emerging technologies still in the early stages of development, and the trajectory of new technologies' innovation and implementation is shaped by socio-technical dynamics, such as institutional arrangements, incumbent interests, infrastructures, cultural meanings, and broader political–economic trends. When a new technology emerges, it becomes part of a socio-technical system, which is ruled by socio-technical dynamics. As a result, technological transitions in the system are rarely driven by technological performance alone. Innovations often face structural resistance when trying to transform existing rules and practices in the system. Incumbent firms and system actors might resist technological advancements, especially if they will affect their products and impact their revenues. The relationship between incumbent firms and policymakers might be an extra resistance force, allowing actors in the regime to position for a low-carbon future without any fundamental system change, delaying actual carbon reduction (Geels, 2014). The core concept is that policymakers and incumbent firms can often form a central alliance at the regime level, aimed at preserving the status quo (Geels, 2014). While CDR could offer real mitigation potential, it also risks being co-opted by existing fossil-fuel dependent regimes seeking to delay more transformative change. This raises important questions about who drives the diffusion of these technologies and for what purposes.

Brazil is the world's largest producer of sugarcane, followed by India, China, Thailand,

and the United States (USDA, 2024; Walton, 2024). Brazil also stands out not only for its production scale but also for the integration of ethanol generation and electricity co-production, which makes it a global reference in bioenergy systems. Furthermore, the country plays an active role in international debates on renewable fuels and low-carbon development. This is one of the main reasons to choose the sugarcane and ethanol sectors as the scope of this study. Their economic, energy, and political relevance in Brazil, in addition to the country's leadership in ethanol production, and its favorable climatic conditions for sugarcane cultivation. These characteristics reinforce the sector as a strategic environment for exploring how carbon dioxide removal technologies can be integrated into existing production chains. Such integration could contribute to lower net-zero commitments and further improve the sustainability of Brazil's bioenergy systems.

This thesis investigates the interplay between CDR technologies and incumbent firms in Brazil's sugarcane and ethanol industries. Brazil has favorable conditions for several CDR approaches, including Bioenergy with Carbon Capture and Storage (BECCS), Biochar Carbon Removal (BCR), and Enhanced Rock Weathering (ERW). These technologies could be integrated into existing agricultural and energy systems, particularly in sugarcane plantations and ethanol production chains, potentially adding environmental and economic value. BECCS could be applied in the fermentation process of ethanol production. Biochar is made from crops residue and could be used in the soil of sugarcane plantations, improving its quality while absorbing carbon from the atmosphere. Enhanced Rock Weathering consists of crumbled rocks scattered on the soil that would enhance the capture of CO_2 already occurring in nature, by increasing the surface contact of the rocks with the air, while also enhancing soil quality. This method can also be applied to sugar plantations.

A central contribution of this thesis is the Multi-Level Perspective (MLP) framework to analyse CDR prospects in the sugar-energy sector in Brazil. The MLP framework was well described in Geels (2006), and it provides a structured way to examine technological transitions in socio-technical systems. To study innovation technologies transitions, Geels (2006) defines three socio-technical levels: *socio-technical niche* (protected spaces where emerging innovations can develop),*socio-technical regime*(the dominant structures, rules, and actors that stabilize existing systems), and *socio-technical landscape* (long-term, exogenous pressures). Defining these levels gives a structured approach to help understand how innovations, such as CDR, emerge as a novel technology in the socio-technical niche to become part of the socio-technical regime, which is governed by the socio-technical landscape. Their prospects depend on how they interact with incumbent agro-industrial structures, national climate politics, global decarbonization agendas, and the strategic behaviour of powerful actors such as ethanol producers, technology providers, oil and gas companies, and hard-to-decarbonize industries.

By using the MLP, the thesis assesses the socio-political context of BECCS, BCR, and ERW, identifying barriers, drivers, and diffusion. More clearly, the MLP helps examine how pressures at the landscape level (e.g., Brazil's NDC commitments, policy frameworks, market behavior and cultural costumes), regime dynamics (e.g., lock-in around ethanol and sugarcane production, sector market dynamics, and stakeholders' interactions), and niche developments (pilot projects, innovation expectations, and entrepreneurial initiatives) together shape the potential diffusion for CDR in the sugar-energy regime. The theory behind MLP framework allow the thesis to investigate the political, institutional, and socio-economic conditions under which CDR may be diffused in Brazil's existing sugar-energy regime, or how they may not go beyond the niche level. The focus is not only to make technological evaluations regarding CDR but instead to reach a deeper understanding of how climate solutions unfold within complex political economies and how actors could influence the diffusion of CDR technologies.

1.1 Research Question

In addition to being the biggest producer of sugarcane (USDA, 2024; Walton, 2024), ethanol from Brazil mostly originates from sugar plantations (S. Oliveira & G.Cruz, 2023). Due to the size of the market and importance to the Brazilian economy, sugarcane and ethanol players also have political influence. Drawing on the multi-level perspective framework, this research explores how power dynamics and institutional relationships between incumbent firms and policymakers might shape the diffusion or resistance of CDR technologies in Brazil. Much of the existing research emphasizes the technological potential of these methods, with little attention given to their relationship with society and its institutions. This study aims to fill this gap by asking:

What role do sugar-energy incumbents play in shaping the diffusion of BECCS, BCR, and ERW in Brazil's low-carbon transition?

To answer the research question, the following sub-questions were defined for each socio-technical level:

1. **What global and national dynamics influence the development of CDR technologies in Brazil's sugar-energy sector?**

   This question aims to understand the socio-technical landscape, which will shape the development of these technologies. It considers cultural shifts and global and national dynamics, including climate governance, sustainability goals, societal expectations, and economic conditions, which create opportunities or barriers for the diffusion of the technologies.

2. **How are the emerging socio-technical niches of CDR technologies developing in Brazil's sugar-energy sector?**

   This sub-question aims to map the niche configurations of biochar, enhanced rock weathering, and BECCS within the sugar-energy sector in Brazil. It focuses on identifying the key technological characteristics, the current phase of development or diffusion of each technology, and the main actors involved in their development and application.

3. **What are the existing institutional, political, and market structures and actors in the sugar-energy regime? And how do they influence the development and diffusion of CDR technologies?**

   This sub-question investigates the socio-technical regime surrounding Brazil's sugar-energy sector. It analyzes how existing structures, infrastructures, and the actions of powerful incumbents support or hinder the scaling of the studied CDR technologies. It also identifies the system's stakeholders and analyzes their interconnections and influence.

This study addresses a critical and yet underexplored dimension of Brazil's climate mitigation strategies: the influence of incumbent firms and regime-level actors on the diffusion of carbon dioxide removal technologies in the sugarcane and ethanol sector. It is crucial to understand the effectiveness of political influence on climate policy in Brazil and how stakeholders participate in decision-making processes. Although existing studies have analyzed the role of actors and power structures in sustainability transitions across different sectors and countries, e.g. UK and Canada, but also the Brazilian ethanol trajectory (Geels, 2014; Benvenutti, de Souza Campos, Vazquez-Brust, & Liston-Heyes, 2023; Rosenbloom, 2019), little attention has been given to how these dynamics affect emerging CDR technologies in Brazil. By focusing on Brazil's sugar-energy regime, this study aims to fill this gap, offering insights into how incumbent power, regulatory frameworks, and environmental governance intersect in shaping sustainable technological transitions.

1.2 Methodology

The research adopts a qualitative case-study approach, combining desk research and semi-structured interviews to examine the dynamics of CDR diffusion in Brazil's sugar-energy regime. Through literature review and stakeholder analysis, the study explores how political, industrial, and institutional actors influence the diffusion of biochar, enhanced rock weathering, and BECCS. Interviews will provide context-specific insights into current expectations, obstacles, and opportunities from actors within the ethanol and sugarcane sectors, but also positions of representatives in hard-to-decarbonize sectors, policymakers and other involved stakeholders. A comprehensive explanation of the research design and methods can be found in the methodology in Chapter 2.

1.3 Thesis Outline

Followed by this introductory chapter presenting the research topic, its relevance, objectives, and subquestions, this thesis is structured into seven chapters. Chapter 2 contains the methodology used in this study. Chapter 3 focuses on describing the socio-technical landscape, analysing current Brazilian climate governance and policies, market structures, global trends, and carbon markets, and helping identify opportunities and barriers to the development of technologies. Followed by Chapter 4 that presents the socio-technical niche state for each CDR technology studied, i.e. BECCS, biochar, and ERW, drawing a technology map and identifying key projects and players in the field, and assessing their phase of technological development according to the Multi-Level Perspective (defined in Chapter 2). Chapter 5 discusses the economic and political relevance of the sugar-ethanol sector in Brazil and the stakeholders within the study's scope. Together, they help design a view of the socio-technical regime that includes the CDR niche technologies. Chapter 6 contains the discussion of the findings of the study. In that chapter, it is possible to find the barriers, the socio-technical interactions, reflections along the work process, and the research limitations. Chapter 7 concludes the thesis by summarizing the key findings, offering recommendations for future research, and reflecting on the potential pathways for deploying carbon dioxide removal technologies in Brazil.

Chapter 2

Methodology

This chapter presents the methodological approach adopted in this study. It explains the research design, data collection and analysis procedures, and the application of the multi-level perspective to address the research question and sub-questions. The main research question, **”What role do sugar-energy incumbents play in shaping the diffusion of BECCS, BCR, and ERW in Brazil’s low-carbon transition?”** is approached with qualitative research. The goal is to explore the current stage and development of CDR technologies within the Brazilian sugarcane and ethanol sector. Qualitative methods, combined with a case study approach, are found to be a suitable way to address studies and investigations regarding innovative technologies: biochar, enhanced rock weathering, and BECCS.

2.1 Data Collection

A comprehensive literature review, combined with in-depth semi-structured interviews, was conducted. The literature review provided a foundational understanding of the Brazilian sugar-energy sector, CDR technologies, and their interaction. Desk research involved analyzing existing literature, articles, and reports relevant to the research topic to establish a robust knowledge base. This process offered a broader perspective on the current sugar-energy system and its stakeholders, identified barriers to the diffusion of CDR technologies, and explored policy solutions. Additionally, the literature review examined legislation, policies, and political debates on GHG emissions and carbon removal in the Brazilian context. It also investigated how these elements have evolved in recent years in response to growing climate awareness. Further research focused on developing the CDR niche, examining expectations for future growth, and identifying key trends and challenges that may shape its diffusion pathway. Participants for the semi-structured interview were selected based on their relevance to the sugar-energy sector, their involvement with CDR technologies, and their knowledge of political or industrial dynamics.

2.1.1 Interview

Because desk research to understand the complexity of the socio-dynamics can be limiting, especially with technologies still in the early stages of development, interviews added more practical market knowledge and insights into the social and political perceptions of these technologies. It allowed for a focused examination of the country’s specific landscape and regime, helping capture the particular dynamics and interactions that influence how CDR technologies are developing in this sector.

Interviewee	Role Type	Sector	MLP level	Format
INT-01	ERW technology developer	Niche Innovator	Niche	Online
INT-02	BECCS technology developer	Niche Innovator	Niche	Online
INT-03	Sugar and ethanol producer	Industry Incumbent	Regime	Online
INT-04	Energy expert	Civil society/ Knowledge & Research	Regime	Online
INT-05	Hard-to-decarbonize industrial actor (steel)	Industry Incumbent	Regime	Online
INT-06	Hard-to-decarbonize industrial actor (steel)	Industry Incumbent	Regime	Online
INT-07	Sugar-energy & Hard-to-decarbonize industrial actor	Industry Incumbent	Regime	Online

Table 2.1: List of interviewees

The semi-structured interviews were chosen for their ability to balance flexibility and structure, enabling exploration of specific topics while maintaining consistency across all interviews. It facilitates a thorough understanding of the diffusion of carbon dioxide removal technologies within the Brazilian sugar-energy sector, which provides insights into potential scenarios for their diffusion. This approach helped close current knowledge gaps and shed light on the main opportunities, challenges, and prospects for CDR technologies in Brazil.

In total **seven** actors were interviewed for this study. They were representatives from CDR technology companies, sugar-energy producers, energy experts, and players from hard-to-decarbonize sectors, and the list of interviewees is shown in Table 2.1. Each interview lasted approximately one hour and was conducted in online and in Portuguese. All participants were informed about the academic purpose of the research and signed an informed consent form before the interview, as shown in appendix B. The interviews were recorded, and later summarized to identify common patterns, divergences, and relationships between the interviewees' views and their positions within the socio-technical regime. Thematic analysis was used to organize responses around the main research questions, enabling comparison with the literature data. But specific answers that are unique yet recognizable due to the actor's field of work and bias are also highlighted as valuable. The Ethical approval for this research was granted by TU Delft's Human Research Ethics Committee; the risk assessment and the ethics approval are detailed in Appendices A.1 and A.2, respectively.

The diverse selection of interviewees ensures a comprehensive understanding of perspectives across relevant industries and sectors. However, it was initially expected to include a larger number of interviewees from the sugar-energy sector, at least one niche actor working with biochar, representatives from Knowledge and research institutions linked to the government, one actor from the cement industry, and two policymakers. Five actors from biochar projects were contacted, with little to no response. Thirteen actors from the sugar-energy sector, from different companies, were approached; only one accepted to participate. Three others replied to the initial contact but were not open to interviews. As initially expected, reaching researchers within government institutions and policymakers proved challenging, and no interviews were conducted in this field. And from the cement industry, three actors were contacted, but no response was received. All potential participants were identified through LinkedIn or mutual connections. Several actors initially responded positively but did not continue communication or confirm participation. Nevertheless, it is believed that the set of interviewees in this research shows a comprehensive picture of the studied case and has contributed to the depth of the analysis.

Questionaire

The actors who agreed to participate were interviewed in semi-structured interviews to assess their opinions, roles, and expectations regarding the respective technology and its implementation. The questionnaire followed the same structure for all actors, with only minor changes depending on the interviewee's field and expertise. The questionnaire is presented in Appendix D, along with its variations based on the stakeholders interviewed. Each interview summary is in the appendix, except for one that did not authorize its inclusion in the thesis. Still, the summary was sent to the thesis assessment committee for reference. This summary includes the general participant description, interview details, the interview purpose, key themes discussed, the most relevant insights, and their relevance to the research.

2.1.2 Limitations

It is important to acknowledge that when studying new technologies, there are always both advocates and opposing forces, which can sometimes be a challenge when finding a middle ground and remaining impartial and objective in the analysis of the collected data. Some sources may present partial views, either influenced by specific interests or by resistance to certain technologies. Moreover, some of these technologies are still emerging and not yet widely researched, which can corroborate that most of the available information may lean towards optimistic perspectives rather than providing a realistic evaluation. This limitation may also appear in the interviews, as participants can hold strong positions for or against the technologies. Another limitation of this study is the difficulty of reaching all expected interviewees. As mentioned above, several actors did not respond to the interview invitation or declined to participate, which may limit the final perspectives drawn in the analysis. For instance, it was considered important to include a representative from biochar projects, a larger number of actors from the sugar-energy sector, and policymakers. However, that was not possible, whether due to a lack of response, refusal to participate, or confidentiality concerns preventing the publication of the results. To minimize these issues, information from different sources was compared and cross-checked, and the data were interpreted through a triangulation process seeking reliability and balance in the findings.

2.2 Data Analysis

The data were collected from the perspective of the theoretical framework and from literature, reports, and interviews. The MLP framework guides the interpretation of the data collected, and the interviews serve as a way to fill the gap in the desk research. The application of the framework alone provides valuable insights into CDR technologies, but the study also conducted interviews with actors in the system. The addition of the interviews serves as data triangulation, as the theoretical insights will be compared with empirical reality in the sugar-energy Brazilian system, helping cross-check the data's findings. The interviews will include a summary to identify patterns and common perceptions among interviewees and to compare different points of view based on each actor's role within the regime. The results from both sources can then be compared with the literature, revealing consistencies or new interpretations. This combination is expected to turn the findings more reliable and provide a more complete understanding of the position of CDR technologies in the Brazilian context and their potential diffusion within the socio-technical regime.

2.2.1 Multi-Level Perspective (MLP)

2.2.1.1 Theory

This research approaches Carbon Dioxide Removal technologies analytically through the lens of the multi-level perspective, a framework for understanding transitions in socio-technical systems such as energy, transport, and agriculture. A socio-technical system refers to the interconnected configuration of technologies, institutions, markets, cultural norms, and actors that collectively shape how a sector operates. New technologies often encounter challenges in becoming part of the socio-technical regime, which may result from feasibility constraints, lack of large-scale applications, uncertainties in study results, or several other factors. Many innovations remain confined to niche environments and never diffuse into the dominant regime. By applying the MLP, this study explores how BECCS, biochar, and enhanced rock weathering emerge, develop, and interact with socio-technical structures in Brazil.

The MLP conceptualizes transitions as the dynamic interaction of three levels. The *socio-technical landscape* (macro-level) as broader contextual factors like cultural shifts, political priorities, environmental crises, economic cycles, or societal expectations (Geels, 2006). Actors do not influence the landscape and cannot change it easily. The *socio-technical regimes* (meso-level) refers to the dominant structures, practices, and rules governing a particular sector, which often resist change due to established routines and vested interests (Geels, 2006, 2011). The *socio-technical Niches* (micro-level) represent spaces where radical innovations, technologies, or practices develop outside the mainstream (Geels, 2019).

MLP emphasizes the interaction between these levels. For transitions to occur, pressures from the landscape (e.g., climate change or political movements) may destabilize the regime, creating opportunities for niche innovations to grow. It is a hierarchy where regimes are embedded within landscapes and niches within regimes, as it can be seen in the figure 2.1. For instance, renewable energy technologies like wind and solar were initially developed in niche environments, supported by research grants and small-scale pilot projects. Over time, as societal pressures to decarbonize increased, these technologies found pathways to challenge and eventually diffuse into the energy regime, contributing to the global energy transition. The framework helps mapping innovation systems over time, focusing on the important links between technology and society, understanding the technology diffusion path (Geels, 2006; van Bree et al., 2010).

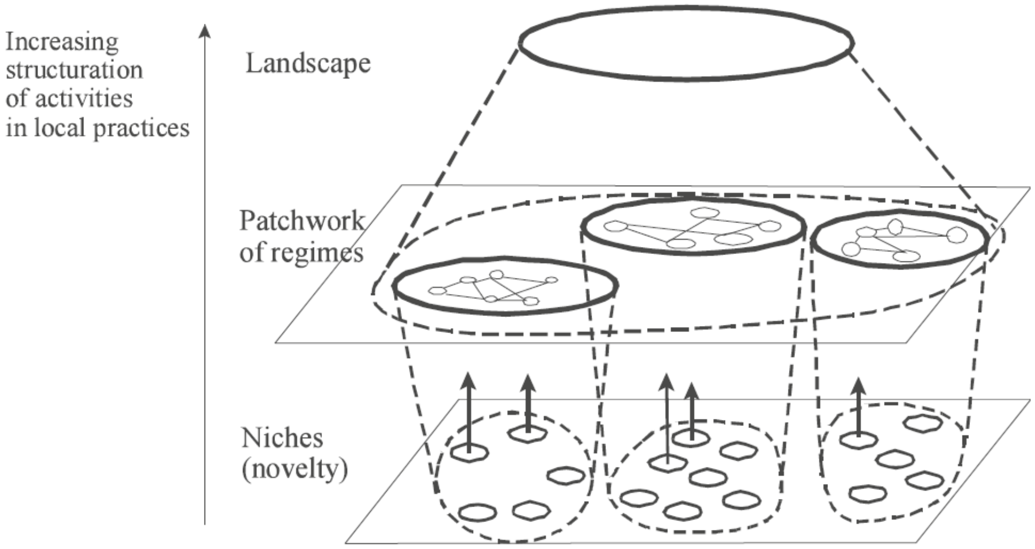


Figure 2.1: Multiple levels as a nested hierarchy (Geels, 2006, 2002)

The three levels also interact mutually over time. There are four phases of that interaction dynamics according to Geels (2006, 2019). In the first phase, innovations emerge at the niche levels. The context for that appearance can be problems identified on the regime or landscape, specific changes due to scientific discoveries, or new organizations. In that way, many innovations can emerge for a particular problem. In this new setup there is still no pressure or dominant design to push the novelties in certain directions, and they start competing with each other. With the instability of new technologies emerging, actors in the regime start engaging with the niches.

In the second phase, a novelty is used in small market niches, where it can develop while being protected from the big markets and the regime. As the technology improves, it starts getting support from engineers and companies, which can help improve it. The novelty becomes the focus of discussion between involved actors and while it develops and evolves, new rules are being formed. Rules stabilize once the novelty is added by users to their routines and practices.

In the third phase, after the stabilization of rules and a dominant design is achieved, the novelty is diffused in the socio-technical regime. Dynamics in this phase are explained by external circumstances and internal drivers. External circumstances are called windows of opportunity, which are favorable situations that might push novelties to a wide diffusion path. A window of opportunity can happen due to internal technical problems in the regime, problems external to the system, stricter regulations, changing user preferences, and landscape changes pressuring the regime. On the other hand, internal drivers can have different aspects, such as economic, socio-technical, and sociological. This is the case when cost/performance is improved, more elements are linked together (more actors adopt the new technology), and a change in social mechanisms occurs. It is important to highlight that internal drivers occur in the niche, while external circumstances occur in the regime and/or the landscape. System innovations are the result of the interaction of many processes and actors.

In the last phase, the newly developed and widely distributed technology becomes the regime, replacing the old one. This is not a rapid process as it takes time to establish a new regime. There will be resistance from actors of the older technology, due to investments, lobbies, and attempts to improve the old technologies. Transitions are non-linear and require alignment across multiple levels for lasting change to take place. Landscape pressures alone are insufficient; niche innovations must mature and demonstrate viability, while regimes must be flexible enough to incorporate or adapt to these new ideas. This perspective is useful for understanding why some transitions, such as the shift to sustainable energy, are slow-moving and require efforts across various levels of society, policy, and technology.

The complexity and uncertainties are intrinsic to system innovations, due to the multiple processes and aspects it encompasses, and how one or multiple actors can change a novelty path. Policymakers try to understand how they can change system innovations, but are only one social group of actors among many others; their influence is limited (Geels, 2006). Therefore, apart from policymakers or actors trying to push a novelty, 'windows of opportunity' are needed (Geels, 2019). Policymakers can stimulate niches and try to modulate the processes with regulations and rules.

2.2.1.2 Application

The MLP was applied to the case study of CDR technologies in the sugar-energy regime in Brazil. The socio-technical niche is now the CDR technologies themselves. They emerged as innovations in the sugar-energy socio-technical regime, which is governed by cultural shifts, global trends, and market structures of the Brazilian landscape. MLP is particularly suitable for emerging CDR technologies because it captures the interactions between niche innovations, established sectoral structures, and broader political and economic pressures—factors that strongly influence the development of BECCS, biochar, and ERW in Brazil. To analyze CDR development and diffusion through the MLP lens, the research question was divided into three sub-questions that intended to contemplate each socio-technical level of study defined by Geels (2006). These sub-questions are enumerated below with the description of how they were approached.

1. *What global and national trends influence the development of CDR technologies in Brazil's sugar-energy sector?*

   This question focused on the socio-technical landscape and sought to examine Brazil's ongoing efforts to decarbonize various sectors and whether there is current pressure to reduce emissions. It explored the policies and plans currently in effect and those projected for the near future in relation to climate goals. Understanding this context is crucial to assessing the status of technologies like biochar, enhanced rock weathering, and BECCS, as well as determining how they can be strategically positioned within Brazil's climate agenda. It was chosen as the first analytical chapter because landscape-level dynamics shape both regime and niche levels. Presenting this chapter first provided essential background information that is referenced in the subsequent chapters, such as policy frameworks and market behavior

   To answer this question, desk research was done. The data sources of the desk research were legal frameworks on the theme, government reports, policy documents, scientific articles, public industry white papers, and news media. It focused on identifying international agreements and commitments, trends in the industrial and energy sectors, public opinion on climate change and emissions regulations, and economic pressures, such as trade agreements and carbon pricing mechanisms.

2. *How are the emerging socio-technical niches of CDR technologies developing in Brazil's sugar-energy sector?*

   This question corresponds to the socio-technical niche level. A technology map was designed for each CDR method studied here. Through desk work, the needed technology for production, capture, and storage of CO_2 was investigated, along with the sectors and industries in which they can be applied. This was done by researching mostly online sources, including websites, reports, and scientific articles. Additionally, the technologies were classified according to their development phase using the theory presented on Geels (2006, 2019). To achieve this, the data collected, particularly regarding the applications of these technologies in the Brazilian context, were analyzed to determine the current development phase of each technology.

3. *What are the existing institutional, political, and market structures and actors in the sugar-energy regime? And how do they influence the development and diffusion of CDR technologies?*

   Stakeholders play a critical role in shaping policy decisions on energy, land use, and climate goals, using their economic influence to shape regulations and incentives that foster innovation and maintain their competitiveness. Their involvement with carbon dioxide removal technologies, such as BECCS, BCR, and ERW, positions them as key drivers in the transition to a low-carbon economy. Holding substantial economic and political leverage influences the diffusion and widespread adoption of these technologies. In this context, a stakeholder analysis is a crucial component in a case study, providing insights into the roles, interests, and influences of various actors across different levels (niche, regime, landscape) and helping situate the technologies within their socio-technical context. This step also helps understand how shifts and pressures can influence stakeholders' behavior and decisions.

   To gather the stakeholders' information and linkages, desk research was also performed. Through researchers on an online basis, in newspapers, on Google, and in reports. After the information is gathered, the actors were placed on a power interest grid, which helped assess their level of impact and evaluate the power dynamics of the actors. This step was important to know who holds decision-making power, who can drive change, and who might resist transitions. This was essential for understanding how the regime maintains stability or becomes open to niche innovations.

   Power Interest Matrix (PIM)

A power-interest matrix is a tool used in stakeholder analysis to categorize actors of a system based on their level of power (influence or authority) and interest (level of concern or engagement) in a specific project, policy, or change initiative. It helps identify how stakeholders should be managed to ensure effective communication and engagement. This grid helps prioritize stakeholder management by identifying where to focus resources and communication efforts to maximize success probability. The grid is two-dimensional, where the X-axis represents the power and the Y-axis represents the interest. The power axis represents the ability of a stakeholder to influence or control outcomes, while the interest axis reflects the degree of concern or involvement of a stakeholder. The matrix is then divided in four quadrants, as it is illustrate Figure 2.2, which shows the Power–Interest Matrix as adapted by Olander and Landin (2005) and used for this analysis.

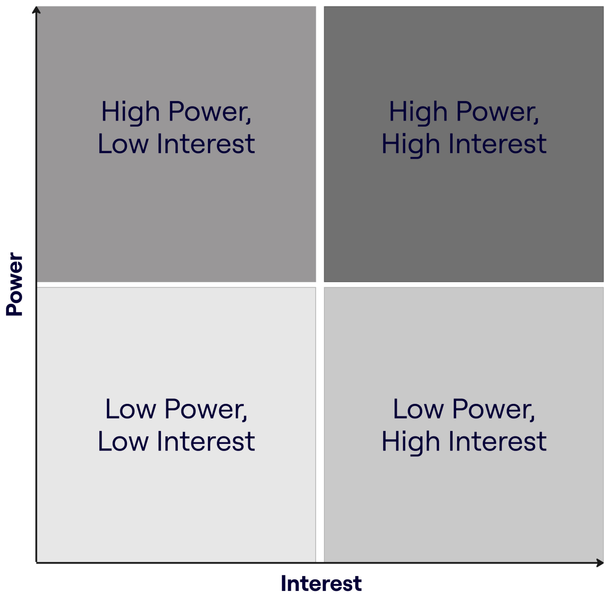


Figure 2.2: Power x Interest Grid

Chapter 3

Brazilian Socio-Technical Landscape

This chapter aims to answer the question: ”What broader socio-political, environmental, and economic pressures influence the diffusion of CDR technologies in Brazil’s sugar-energy sector?” It explores the key macro-level pressures shaping the Brazilian approach to decarbonization and carbon removal. The pressures are comprehensive and can include any cultural, environmental and market factor, however in this study it was decided to focus in the most important to understand CDR technologies and their path for development. Therefore, the discussion is divided into policy and governance, market dynamics, and cultural shifts. Understanding the main enabling structural factors, drivers, and barriers is crucial to determining the status of CDR technologies in Brazil. By examining these forces, the chapter provides an overview of the socio-technical landscape that shapes the opportunities and limitations for the diffusion of carbon dioxide technologies in Brazil.

3.1 Governance and Policy Landscape

Regulations and policies are part of the socio-technical landscape level of the MLP framework, representing a macro-level structure that shapes both stability and/or change in the socio-technical regime. They set the state’s rules and direction, determining how the country will be positioned regarding global and national trends and innovations. Policies define long-term visions, establish incentives, or constraints for technological transitions. Brazil’s regulatory and policy landscape plays a critical role in shaping the development and diffusion of carbon dioxide removal technologies. It influences how actors allocate resources and respond to national and global decarbonization pressures, creating either windows of opportunity for niche development or reinforcing the stability of the existing sugar-energy regime.

As a signatory to the Paris Agreement, Brazil has committed to ambitious climate goals, which have led to the formulation of new laws and regulatory frameworks aimed at reducing GHG emissions. This section reviews key national climate and energy policies to identify how national governance is shaping and enabling conditions for the diffusion of CDR technologies. Many of these initiatives were recently approved, signaling the country’s growing institutional support for low-carbon technologies, including those related to CDR.

3.1.1 RenovaBio

RenovaBio is a National Biofuels Policy, established in 2017 (*LEI Nº 13.576*, 2017). It is a cornerstone of the country’s strategy to reduce greenhouse gas emissions in the fuel sector. The goal is to promote the expansion of biofuels through a market-based mechanism that certifies the carbon intensity of biofuel producers and issues tradable decarbonization credits (CBIOs) (ANP, 2024; *LEI Nº 13.576*, 2017). Fuel distributors are required to acquire a certain number of CBIOs annually, aligning with the Brazilian climate targets under the Paris Agreement. It was not explicitly designed for carbon dioxide removal, however, RenovaBio creates incentives for low-carbon biofuel production chains, and in the future (ANP, 2024; *LEI Nº 13.576*, 2017), it could be a platform for integrating negative emissions technologies, which CDR technologies are included. For instance, ERW was recently included in the CBio mechanism, as mentioned in INT-01(C.1).

3.1.2 National Energy Transition Policy (PNTE)

The national energy transition policy is an initiative of the federal government of Brazil meant to turn the energy matrix of Brazil more sustainable and aligned with the commitments of GHG emissions. It was approved in 2024 and focus on a just and inclusive energy transition (Ministério de Minas e Energia, 2024). One of the main tools of PNTE is the National Plan of Energy Transition (Plante) and National Energy Transition Forum (FONTE). PLANTE sets actions to achieve net-zero emissions and sustainable economic development (Ministério de Minas e Energia, n.d.). FONTE is a space to make energy transition discussions more inclusive, helping elaborate energy recommendations and policies, and guarantee more transparency over taken actions (Ministério de Minas e Energia, n.d.). This plan has the potential to attract 2 trillion Reais in 10 years (Ministério de Minas e Energia, 2024). PNTE does not mention CDR technologies explicitly, but it establishes institutional and financial mechanisms that can support their development indirectly. It is a policy that defines decarbonization goals with net-zero emission goals, that creates a favorable governance environment for diffusion of BECCS, biochar and ERW.

3.1.3 Energy Transition Acceleration Program (PATEN)

The Energy Transition Acceleration Program (PATEN) was enacted in January 2025, and it was developed as a strategy to position Brazil as a global leader in decarbonization and sustainable development. Law No. 15.103/2025 (*LEI Nº 15.103*, 2025) provides both financial and regulatory support to projects that contribute to greenhouse gas emissions reduction. According to the government publication of Ministério de Minas e Energia (2025), the program scope includes the development of sustainable fuels, the modernization of electricity generation and transmission infrastructure, and the expansion of renewable energy alternatives. PATEN also promotes research development, and demonstration of carbon capture and storage (CCS) technologies, aiming to foster innovation and accelerate the deployment of low-carbon solutions across key sectors of the economy (Ministério de Minas e Energia, 2025). This policy is also relevant to CDR technologies. It is explicit regarding CCS, but not CDR, nevertheless, carbon dioxide removal technologies are included in the scope of ”projects contributing to GHG emission reductions”. Although the program is not specific about CDR, PATEN may contribute to building the enabling environment necessary for CDR diffusion by providing funding pathways and legitimizing carbon management technologies within Brazil's broader energy transition strategy.

3.1.4 Fuels of the Future Law

The Fuels of the Future Law, enacted in 2024, brings together a set of programs—including the National Sustainable Aviation Fuel Program (ProBioQAV), the National

Green Diesel Program (PNDV), the National Decarbonization Program for Natural Gas Producers and Importers, and Incentives for Biomethane (*LEI Nº 14.993*, 2024). These initiatives aim to promote the development and large-scale adoption of cleaner and more sustainable fuel alternatives.

The law seeks to accelerate the decarbonization of the transport sector and contribute to a just energy transition, aligning Brazil with its international climate commitments. A particular focus is placed on advancing biofuels and integrating carbon capture and storage (CCS) technologies in fuel production chains (EPE, n.d.). This policy benefits the sugar-energy regime, and the interviews mentioned that the sector lobbied for its approval (INT-02(C.2), INT-03(C.3), INT-04(C.4)). Among CDR technologies, it is mainly relevant for BECCS, as it directly links CCS with biofuel production chains, creating an institutional pathway for integrating BECCS into Brazil's decarbonization agenda. Such recognition is an important step towards creating a protected niche environment for its technological transition.

3.1.5 Regulated Carbon Market

On December of 2023 the Deputies Chamber of Brazil approved the proposal on the regulated carbon market. The text institutes the Brazilian Emission Trading Sytems (SBCE), where it stipulates emission limits and a market for title sales (Siqueira & Triboli, 2023). The law was sanctioned by the Brazilian President in December of 2024 (*LEI Nº 15.042*, 2024),and it must start operations in 4 to 5 years. SBCE creates the legal framework for a national carbon market, distinguishing between the regulated and voluntary markets (Agência Senado, 2024).

According to Agência Senado (2024), the regulated market will initially target large emitters who release over 10,000 tons of CO_2 equivalent (CO_2e) annually. These actors will be legally required to monitor and report their emissions under oversight from a regulatory institution that will establish rules and enforce compliance. While this framework creates accountability for major industrial sectors, it notably excludes agribusiness, a major source of emissions in Brazil.

On the other hand, the voluntary market, enables companies and individuals to engage in emissions offset outside the scope of formal national accounting (Agência Senado, 2024). These transactions are based on privately negotiated carbon credits, which represent certified emission reductions or removals, often from forestry, renewable energy, or carbon capture projects. Although not officially counted towards Brazil's national targets, these credits can support private net-zero goals and contribute to broader mitigation efforts.

By assigning market value to emissions reductions, the law reflects global trends, positioning carbon as both an environmental liability and an economic asset. The main goal is to internalize the environmental cost of emissions and create financial (dis)incentives for decarbonization. Although the law does not yet define specific methodologies for accounting carbon removal, its implementation could open the necessary space for the diffusion of CDR technologies in Brazil's emissions mitigation strategies, by creating the necessary pressure that pushes niche innovation towards diffusion. In this context, SBCE serves as both a compliance mechanism and a platform to stimulate investment in low-carbon technologies, which includes CDR.

3.2 Nationally Determined Contributions (NDC)

Brazil's Nationally Determined Contribution (NDC) was submitted in November 2024 as part of Brazil's commitment to the Paris Agreement, defining the country's climate targets and actions to limit global warming to 1.5°C above pre-industrial levels (UNFCCC, n.d.-a; Brazilian Government, 2024). The updated NDC sets a target to reduce net greenhouse gas emissions by 59–67% below 2005 levels by 2035 (equivalent to 0.85–1.05 $GtCO_2e$), with the long-term objective of achieving climate neutrality by 2050.

A central feature of this new NDC is the Pact for Ecological Transformation, which is a formal agreement that was made among the Executive, Legislative, and Judicial branches, that signals a long-term state commitment to sustainable development, social inclusion, and climate action. The priority measures in this agreement are the approval of a legal framework for a regulated carbon market, the regulation of carbon capture and storage, and incentives for biofuel use, particularly relevant to Brazil's energy and transport sectors. The NDC emphasizes increased public and private investment in research and commercial-scale deployment of low-carbon technologies, along with financial mechanisms to reduce the cost of credit and expand access to sustainable finance.

The strategy also includes sector-specific goals, reinforcing Brazil's already heavily renewable energy matrix (with 89.2% of electricity and 49.1% of total renewable energy). The main goals in the energy sector are to expand renewables, improve efficiency, and scale up advanced technologies. For the transport sector, the goal is to replace fossil fuels with electricity and biofuels like ethanol. Regarding the industry sector, the focus is to promote biofuel substitution and CCS development. The goal for agriculture and land use is to advance low-emission practices, restore native vegetation, and promote sustainable livestock. NDC outlines 12 key mitigation priorities, among which the most relevant to this study are to protect and restore national biomes; promote low-carbon agriculture and livestock; expand biofuels and bioenergy; suppor to electrification and clean energy; encourage CCS and CDR technologies in bioenergy and fossil sectors; enable carbon markets and economic instruments.

From a socio-technical perspective, the NDC provides broad policy directions that legitimize carbon management and, therefore, removal technologies in Brazil. It explicitly recognizes CCS and CDR as part of the national mitigation pathway, establishing political and institutional signals that can drive investments and guide technological innovation. This commitment functions as a macro-level pressure that can gradually destabilize incumbent high-emission firms, creating opportunities for niche innovations development and diffusion.

3.3 Market Dynamics

Market dynamics are an important landscape-level factor that contributes to shaping the diffusion of carbon removal technologies. Macroeconomic conditions (investment behavior and the mechanisms for monetizing emissions reductions) influence how firms behave regarding their assessment of investment risks, allocation of capital, and engagement with innovation. In the Brazilian context, these dynamics are particularly relevant given economic volatility, high capital costs, and uncertainty surrounding carbon-pricing instruments. Understanding these market conditions is therefore essential to explain why CDR technologies face significant challenges in scaling beyond niche applications, even though they have technical potential.

3.3.1 Investments Profile

Before exploring the investment profiles in Brazil, it is important to understand the country's broader economic conditions and structural characteristics. One of the most relevant features is the volatility of the Brazilian currency, the Real. The Real Plan was launched in the mid-1990s as a response to the high inflation rates experienced in the previous period and worsened in the 90s (TV Câmara, 2014). The main strategy was to introduce a currency with parity to the US dollar, this way, the domestic inflation would be anchored to the external inflation (Salomão, 2024). However, to maintain this parity, it was essential to keep the consumption in the country low and limit the country's expansion. The result was very high interest rates and strict exchange rate controls.

These measures contributed to a process of high deindustrialization, increasing Brazil's dependence on imports, particularly of manufactured goods and specialized machinery (Sawaya, 2024; Salomão, 2024). Privatizations and the dismantling of important institutions related to energy and transportation further contributed for the high dependency on the external market. The expectation was that minimizing the state intervention would allow Brazil to become a competitive industrialized economy (Salomão, 2024; Sawaya, 2024). Instead, the result was an economy highly dependent on the exchange rate stability, where the inflation would be controlled as long as the imports were not restricted and the exchange rate was "frozen," limiting Brazilian producers from raising their prices.

Since exports decreased drastically, Brazil stopped expanding economically, and when the exchange rate regime became more flexible, the fragility of the Brazilian economy and the dependency on external money became more evident. Currency fluctuations increasingly reflected external shocks and international financial crises. Until today, the Real remains highly sensitive to global movements, and Brazil still relies on imports, especially of capital-intensive and specialized equipment (TV Câmara, 2014; Sawaya, 2024). This structural dependence helps explain the volatility of the currency, high interest rates, and overall economic instability in Brazil.

This background is essential to understanding the investment behavior in Brazil. One interviewee explicitly mentioned that innovation in the country faces high capital costs, as the import of specialized machinery alone can make new projects economically unviable from the beginning (INT-03(C.3)). At the individual level, research conducted by CVM [1] found that most Brazilian investors are classified as bold when compared to moderate and conservative profiles (Comissão de Valores Mobiliários, 2025). However, this behavior is not seen across sectors and companies. For instance, in the sugar-energy sector, behavior is mixed, while some companies are more conservative and adopt low-risk strategies, others follow a more innovative path, investing in new technologies and products.

Small producers were described in the interviews as having a family-based culture and being more conservative, demand-driven, and risk-averse (INT-07(C.7)). The 2024/2025 harvest was difficult for the sector due to wildfires and climate adversities (Venditte,

---

[1] Securities and Exchange Commission of Brazil: regulatory body responsible for overseeing stocks, investments, and the fair functioning of the market.

2025). At the same time, the interest rates skyrocketed in 2025, increasing financial pressure on companies with higher levels of debt and more aggressive investment strategies (Gregorio, 2025). Expectations are that these challenges will remain for 2026. Especially companies that pursued bolder market strategies, such as Raízen, which invested in biogas and second-generation ethanol, now face tighter margins and higher uncertainty, particularly in relation to future carbon pricing (Gregorio, 2025). That signals to the market that a more conservative profile may prevail in the short to medium term.

Nevertheless, a counterpoint emerged in recent years: Brazil is trying to position itself internationally as a leader in sustainable development, innovation, and ESG practices. That appears to be a class where Brazil can be highly competitive in the global market, and some companies are interested in investing in it. Sustainable innovation is seen as a competitive advantage, and some companies are aligning their strategies with this narrative (Bonetto, 2025). Firms that adopt this culture tend to attract more investments, making renewable energy projects and emissions reduction technologies particularly appealing. The occurrence of COP-30 in Brazil in November of 2025 is an important event that reinforced the country's image as a destination for sustainable investment. Brazil's abundance of natural resources and a large potential for expansion and scaling sustainable solutions also strengthens this position (Equipe GNPW Group, 2025). At COP30, the presence of a dedicated CDR pavilion for the first time was considered a sign of growing visibility for CDR technologies (Carbon Gap, 2025).

3.3.2 Carbon Monetization

Carbon markets in Brazil remain highly uncertain. While the voluntary carbon markets lack stability and credibility, the regulated market is still under development, and its final design remains unclear. The difference between them is that the regulated market establishes emission limits, quotas, and mandatory participation for covered sectors, while the voluntary market, as the name suggests, allows companies to purchase credits to offset their emissions, usually to accomplish the companies' sustainability goals.

The voluntary market has experienced strong fluctuations in demand over the years and has not yet been established as a reliable and trustworthy system in Brazil. One of the main challenges is guaranteeing that issued credits represent real and additional emissions reductions, since it has no standardized methodologies, transparency, or consistent monitoring (Soares, 2024). In the past years, the carbon credits market has shrunk. Compared to 2020-2021, when it had a strong expansion, the market in 2023 went through a period of questioning and decline (Soares, 2024; Notícias Agrícolas, 2024). In 2023, there was a decrease of 89% in the volume of issued credits, reflecting the lack of confidence regarding the quality and integrity of voluntary credits (Notícias Agrícolas, 2024). Studies cited by (Soares, 2024) express that a significant share of credits currently available show low quality or high risk. Renewable energy projects represent a large portion of issued credits, but many of them no longer demonstrate real additionality, as these technologies are already established in the regime. Credit based on REDD+ also faced technical and reputational challenges.

Some companies are willing to pay more for credits of better quality, but the market is in transition and faces uncertainties regarding future demand (Soares, 2024). One interviewee highlighted that the carbon price required to make BECCS projects economically viable is significantly higher than current market prices (INT-02(C.2)). Even though BECCS credits are considered more reliable, companies are usually not willing to pay substantially more for fewer credits. This limits demand for BECCS-based credits and adds additional financial risk to such projects.

The regulated market was created to add economic value to emission reductions and incentivize the companies to mitigate and compensate for emissions through a compliance-based market (Paulo, 2025). In Brazil, the regulated market was sanctioned at the end of 2024 but will only be operational in 2030. Currently, there is no definition of how it will be designed, which creates uncertainties for companies to position their plans and investments and adapt their processes. What is known is that participation will initially be limited to high-emission industries, which may further pressure industrial sectors in an already deindustrialized economy.

According to some interviewees, CDR is expected to be included in regulated carbon markets. However, the interviewed energy expert believes that carbon prices in this market are likely to be low, as industries are already facing increasing decarbonization pressures and the government may be reluctant to impose additional economic burdens. Another point raised was the integration of the voluntary market into the regulated market (INT-04(C.4)). Given the current low prices of carbon credits, these prices may remain low. Therefore, it remains uncertain whether the carbon prices in the regulated markets will be enough to monetize CDR technologies and make them economically viable.

Another policy instrument in Brazil is RenovaBio, which incentivizes the production and consumption of biofuels. In theory, it works similarly to a carbon market, although it favors biofuels. It was better explained in subsection 3.1.1, and may also act as an indirect incentive for certain CDR technologies. In an interview with an ERW practitioner, it was emphasized that including ERW within RenovaBio was essential to the technology's viability (INT-01(C.1)). However, regarding BECCS, it was noted that CBio's current price is not high enough to make these projects viable. It is also uncertain whether CBio will be integrated into the future regulated carbon market. Ensuring that credits are not double-counted will be crucial to maintaining the integrity and reliability of Brazil's carbon governance framework.

3.4 Cultural shift

Another important factor influencing how innovations emerge and diffuse is the cultural system at the landscape level. Cultural change can occur for many reasons, such as questioning values and beliefs, changes in perspective, global dynamics, access to knowledge, and generational differences. One interviewee emphasized that cultural aspects are crucial for the diffusion of innovation and CDR technologies (INT-07(C.7)). It was specifically mentioned that the Brazilian market is not strongly engaged with causes that are not mandatory, such as sustainability goals or environmental protection. Businesses in Brazil tend to do only what is required for compliance, and environmental ethics are not embedded in corporate practices. This means that companies often do not adopt actions beyond legal obligations, even when they are technically or economically feasible. While there are exceptions, this view reflects a broader understanding of how the Brazilian market operates. And accordingly, the commitment to innovative climate solutions remains limited.

The interviewee argued that a stronger commitment to sustainable development would likely emerge only through generational change within company leadership (INT-07(C.7)). Young generations are perceived as having different priorities and a stronger sense of urgency regarding climate and environmental issues. Older generations tend to prioritize efficiency and profit. According to the interviewee, he/she feels that new generations are truly preoccupied with the climate and environment, and once this generation occupies the highest seats in the companies, that is when change will actually occur. Although this is a strong opinion, it aligns with the Brazilian context. Brazil is still a developing country, with industries that are still young, and many senior executives participated in the early stages of building these sectors. Their priority was economic growth and consolidation, whereas younger generations did not experience this phase of building industries from nothing, and are more focused on improving processes and doing it in a more sustainable way. As society has developed, concerns related to job quality, labor rights, and environmental protection have also evolved. Globalization and increased access to information have further reinforced the idea that productivity and efficiency can coexist with ESG practices, although this cultural shift remains slow and uneven.

3.5 Main Findings

In summary, the analysis of Brazil's governance and policy shows an increasing commitment to decarbonization and energy transition, with recent advances. The initiatives mentioned above demonstrate a desire to develop a net-zero future by promoting low-carbon innovations and integrating carbon management technologies across the industry. These policies create pressures on the regime level that can influence the direction of BECCS, biochar, and ERW diffusion, opening windows of opportunity. However, the regulations do not explicitly mention the technologies involved, and there is still implementation challenges and a lack of coordination, which limit systemic change.

At the same time, Brazil's macroeconomic conditions and market dynamics impose structural constraints on the diffusion of CDR technologies. Currency volatility, high interest rates, and dependence on imported capital goods raise the cost of innovation and favor short-term, low-risk investment strategies. Uncertainty surrounding carbon monetization and the instability and credibility challenges of voluntary carbon markets further reinforces these barriers. The undefinition of the design of the future carbon markets together with the expected low prices weakens economic incentives for diffusing CDR technologies to the socio-technical regime. RenovaBio also does not give guarantees regarding CDR technologies and CBios, resulting in even technically viable innovative technologies struggling to achieve financial feasibility at scale. Furthermore, Brazil shows a compliance-oriented business culture, where sustainable development is mainly driven by regulations rather than environmental ethics. A gradual cultural shift is emerging among the younger generation due to cultural shift, globalization, and ESG concern, but this transformation remains slow. But until then, proactive engagement with innovative and uncertain climate solutions such as CDR remains limited, mantaining regime stability.

Chapter 4

Socio-technical niche of BECCS, BCR and ERW

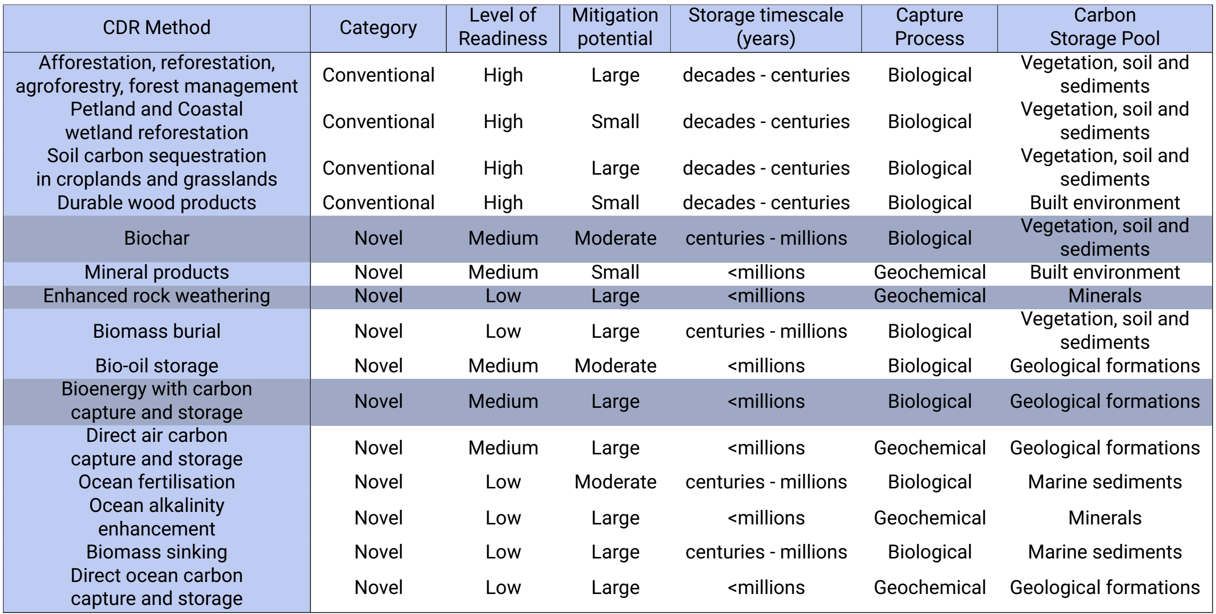
This chapter aims to answer the question: "How are the emerging socio-technical niches of CDR technologies developing in Brazil's sugar-energy sector?" and it focuses on the key technological characteristics of three carbon dioxide removal methods: BECCS, biochar, and enhanced rock weathering, with particular emphasis on BECCS and biochar, as both have energy generation potential. For instance, on BECCS, the carbon capture feature is integrated into the bioenergy power plant. At the same time, Biochar production also generates bio-oil and syngas as by-products, which are mainly used for energy generation, either within the same process or in other industries and sectors. ERW, in contrast, is a technology that aims to improve soil quality and capture CO_2. However, its production process remains highly energy-intensive and, unlike BECCS or biochar, it does not generate energy during operation.

The chapter also presents the technology phase of development, in which these CDR technologies are positioned within the multi-level perspective framework and the main stakeholders involved in their growth and diffusion. The chapter is structured into five sections, one dedicated to contextualizing CDR technologies, and the other three dedicated to each method. Each section provides an overview of the technology and explores how its technological niche is currently configured. The last section provides the main findings of the chapter.

4.1 Carbon Dioxide Removal

CDR refers to technologies and approaches designed to remove carbon dioxide (CO_2) from the atmosphere and store it for long periods of time. It includes direct air capture (DAC) together with long-term storage, expansion of carbon sequestration in plants and soils, biomass carbon removal and storage, enhanced mineralization, ocean-based CDR, and afforestation/reforestation (IPCC, n.d.). The State of Carbon Dioxide removal report (Smith et al., 2024) characterizes CDR with three key principles. Principle 1 says that the carbon captured must come from the atmosphere (not fossil sources). Principle 2 says that the storage of the captured CO_2 must be durable. Principle 3 states that the removal must result from human intervention, in addition to the earth's natural processes. Unlike CDR, Carbon Capture and Storage involves capturing CO_2 from industrial processes and storing it geologically. In this case, since the carbon captured comes from fossil fuels or minerals, it counts as an emission reduction, and not as carbon removal. On the other hand, Carbon Capture and Utilization (CCU) is part of ‘carbon recycling’ applications. Where the captured CO_2 is used directly or as ingredients in new products. The time of carbon offset in CCU depends greatly on how the sequestered carbon is used. Products such as fertilizers, fuels, or carbonated drinks store carbon only temporarily, while concrete and timber have longer storage periods.

Each CDR method can be viewed as a specific route through the Earth’s carbon cycle, capturing atmospheric carbon and transferring it to durable carbon sinks. These pools vary in how long they store carbon, each with its own timescale. Carbon captured can be stored in different pools or sinks, having different characterizations as well. They can be categorized by their level of readiness, where conventional CDRs are the methods well established and scaled, and novel CDRs are methods with a lower level of readiness and are applied at smaller scales. In Table 4.1, it is possible to see the capture process, carbon storage pool, category, level of readiness, mitigation potential, and storage timescale in years. All CDRs studied in this thesis are considered novel technologies, and with a medium to low level of readiness. ERW is the least ready for deployment, but that was expected since it is a newer field of study. Other characteristics of the technologies are in the table below.



CDR Method	Category	Level of Readiness	Mitigation potential	Storage timescale (years)	Capture Process	Carbon Storage Pool
Afforestation, reforestation, agroforestry, forest management	Conventional	High	Large	decades - centuries	Biological	Vegetation, soil and sediments
Petland and Coastal wetland reforestation	Conventional	High	Small	decades - centuries	Biological	Vegetation, soil and sediments
Soil carbon sequestration in croplands and grasslands	Conventional	High	Large	decades - centuries	Biological	Vegetation, soil and sediments
Durable wood products	Conventional	High	Small	decades - centuries	Biological	Built environment
Biochar	Novel	Medium	Moderate	centuries - millions	Biological	Vegetation, soil and sediments
Mineral products	Novel	Medium	Small	<millions	Geochemical	Built environment
Enhanced rock weathering	Novel	Low	Large	<millions	Geochemical	Minerals
Biomass burial	Novel	Low	Large	centuries - millions	Biological	Vegetation, soil and sediments
Bio-oil storage	Novel	Medium	Moderate	<millions	Biological	Geological formations
Bioenergy with carbon capture and storage	Novel	Medium	Large	<millions	Biological	Geological formations
Direct air carbon capture and storage	Novel	Medium	Large	<millions	Geochemical	Geological formations
Ocean fertilisation	Novel	Low	Moderate	centuries - millions	Biological	Marine sediments
Ocean alkalinity enhancement	Novel	Low	Large	<millions	Geochemical	Minerals
Biomass sinking	Novel	Low	Large	centuries - millions	Biological	Marine sediments
Direct ocean carbon capture and storage	Novel	Low	Large	<millions	Geochemical	Geological formations

Table 4.1: CDR Methods Categories (Smith et al., 2024)

CDR can play a key role in limiting global warming to below 1.5°C, and it is included in all modeled scenarios to meet the Paris Agreement goals and Nationally Determined Contributions (NDCs) (Smith et al., 2024). In the Net Zero 2050 scenario proposed by the NGFS (Network for Greening the Financial System) (NGFS, 2023), CDR is applied on a limited scale and combined with deeper reductions in fossil fuel emissions. Nevertheless, if CDR technologies are deployed effectively and made widely available, climate targets could be reached more quickly. The transition risk associated with CDR is twofold, since low levels of CDR increase transition costs, as gross emission reductions must be achieved through other means. While with a higher level of CDR, the success of the transition will depend on the timely availability and deployment of various CDR technologies, including long-term storage in soils, plants, and rocks.

4.2 Bioenergy with Carbon Capture and Storage (BECCS)

Bioenergy with Carbon Capture and Storage is a technology that combines energy production with carbon sequestration. It captures carbon released during combustion and conversion processes in biomass power plants, and after, carbon is stored underground, preventing this CO_2 from being released into the atmosphere (IEA, n.d.). BECCS is considered a negative-emission technology because the burned biomass has already captured carbon during its growth. The setup is similar to CCS, but CCS prevents new emissions, while BECCS can reduce atmospheric CO_2 levels (Hayat et al., 2024).

BECCS also produces energy, which differentiates this method from the other CDR technologies. Bioenergy can provide energy in different forms, as heat, electricity, and biofuels, positioning BECCS as a relevant technology, especially for decarbonizing hard-to-abate sectors (IEA, n.d.; Hayat et al., 2024). In the IEA's Net Zero Emissions by 2050 roadmap (NZE), BECCS is projected to contribute significantly to balancing residual emissions in sectors such as heavy industry, aviation, and trucking (IEA, n.d.). CO_2 capture in biofuels, biomethane, and biomass power plants occupies an important share, as they deliver large-scale negative emissions when paired with storage (Pelkmans et al., 2024).

Another advantage of BECCS is that many of the required technologies are already applied on a large scale. Centralized biomass power plants and biofuel plants are in operation worldwide, while CCS technologies are mature and are being deployed in fossil fuel power plants. In fact, CCS was originally developed to increase oil extraction rates in reservoirs through a process called Enhanced Oil Recovery (EOR). It involves using CO_2 from natural sources or, in some cases, captured CO_2 from gas reservoirs and injecting it back into the reservoirs, thereby increasing oil extraction. The climate benefits of this method are controversial; however, its development has provided technical knowledge and infrastructure, the necessary know-how to support the deployment of BEECS.

4.2.1 Technology map

In this section, the BECCS method is discussed, focusing on the technologies involved in the extraction, transportation, and storage of CO_2. A technology map can serve as a strategic blueprint, and in this study, it is intended to contextualize BECCS within the sugar-ethanol regime. Figure 4.1 shows the BECCS technology map, along with the steps description.

4.2.1.1 Biomass Conversion processes

Biomass can be converted into energy through thermochemical and biochemical processes, including combustion, gasification, pyrolysis, and fermentation (EIA, 2024; Gnanasekaran et al., 2023). Combustion is the most common method, where organic material is burned in the presence of oxygen to produce heat that can also be converted into electricity. Gasification and pyrolysis differ from combustion mainly in temperature and oxygen availability. While for pyrolysis, biomass is heated in the near absence of oxygen, producing biochar, bio-oil, and syngas (EIA, 2024; Gnanasekaran et al., 2023). And for gasification, the process occurs at higher temperatures with a controlled, limited amount of oxygen, producing syngas that can be used for power

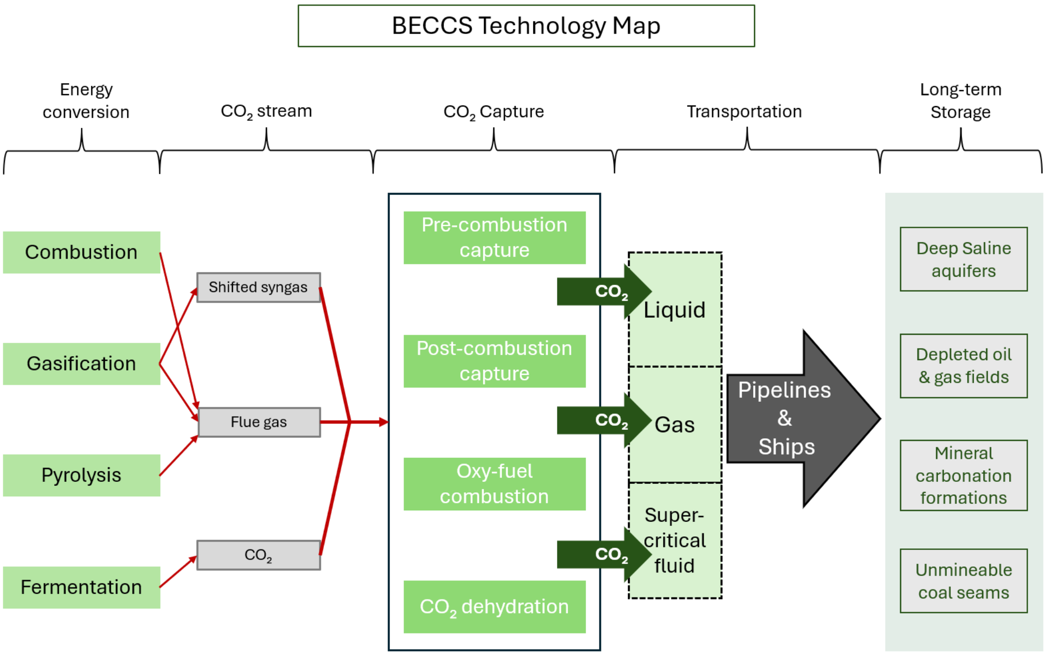


Figure 4.1: BECCS Technology Map

generation or as a chemical feedstock (EIA, 2024; Gnanasekaran et al., 2023). This study focuses specifically on the technological pathway of BECCS within ethanol production, following the scope of the study. Therefore, the focus is on fermentation, where CO_2 is released as a by-product, being then captured, transported, and stored.

Fermentation: Fermentation is the conversion method used to produce ethanol (C_2H_6O), and it starts with the pretreatment of the feedstock to release fermentable sugars. In sugar-based feedstocks like sugarcane juice, these sugars are directly available as sucrose and do not require a saccharification step (Manochio et al., 2017; Jenkins, 2014). The sugarcane juice is clarified, filtered, and concentrated before fermentation, and yeast is added to convert the sugars into ethanol and CO_2 in a 6–11 hours (Manochio et al., 2017) process. In the case of corn ethanol, it requires milling, hydration, gelatinization, and enzyme or acid hydrolysis to convert starch to glucose before fermentation. The process can be performed using dry or wet milling, where enzymes break down starch chains, and yeast ferments the resulting glucose over 30–40 hours under moderate temperatures (20-45 ^{o}C) (Manochio et al., 2017; Jenkins, 2014). During the fermentation stage, microorganisms [1] convert glucose ($C_6H_{12}O_6$) into ethanol and carbon dioxide, under anaerobic conditions. Beyond transportation, ethanol has also been studied and applied at smaller scales in industrial processes and power generation, where it acts as a renewable combustion fuel (Power Technology, 2013; Albioma, n.d.).

4.2.1.2 CO_2 Stream

A CO_2 stream is the mixture that results when carbon dioxide is emitted from an energy conversion source (European Parliament and Council, 2009), like a power plant or, in this case, an ethanol plant. It contains small amounts of other substances from the source or the capture process, as well as additives. CO_2 is directly released as a by-product of the fermentation process. The glucose is the fermentation process from

---

[1] Normally the yeast Saccharomyces cerevisiae is used

biomass, where the general reaction is shown in equation 4.1, yielding approximately 51% ethanol and 49% CO_2 by mass (Jenkins, 2014). Unlike CO_2 streams generated by other biomass conversion processes, glucose fermentation naturally produces carbon dioxide as a final product (Manochio et al., 2017), making the capture process simpler and more efficient than in other bioenergy pathways.

$$C_6H_{12}O_6 \longrightarrow 2\,C_2H_6O + 2\,CO_2 \tag{4.1}$$

Flue gas refers to the exhaust produced when fuel is burned, serving as the primary CO_2 stream in combustion systems. (Speight, 2019). The stream is composed of gases and impurities formed during the combustion process, such as dust, sulfur, nitrogen oxides, and carbon monoxide (Speight, 2019). The exact composition of the gas depends on the type of fuel used and the specific combustion conditions. **Syngas**, or synthesis gas, is a mixture of hydrogen (H_2) and carbon monoxide (CO) produced through the gasification or partial oxidation of carbon-based feedstocks such as coal, natural gas, or biomass. It serves as an important feedstock for the production of traditionally derived fuels and chemicals, and it is the main CO_2 stream generated in the gasification and pyrolysis processes (Speight, 2019; Basu, 2018). However, syngas generated by gasification or pyrolysis may also be used as a fuel for onsite heat production, in which case the main CO_2 will be in the flue gas.

4.2.1.3 CO_2 Capture Approaches

According to Shahbaz et al. (2021), there are three main CO_2 capture approaches known for fossil fuel power plants that can also be applied to bioenergy production. These are **pre-combustion**, **post-combustion,** and **oxy-fuel** combustion. The chosen approach for a power plant depends on the CO_2 concentration, the type of fuel burned, and the pressure of the gas stream. Post-combustion is a suitable method for cases with low CO_2 concentrations, while pre-combustion is more effective for high CO_2 concentration streams, above 20%. Post-combustion capture is also simpler to apply and allows for the retrofit of existing power plants, being the most mature of the three processes. In contrast, pre-combustion and oxy-fuel technologies can only be implemented in newly built facilities, and they require specific plant configurations. In the pre-combustion system, the fuel undergoes partial oxidation with a controlled amount of air, oxygen, or steam, producing syngas composed mainly of CO and H_2. The syngas then reacts with steam in a water–gas shift reaction, and it converts carbon monoxide into CO_2 and additional H_2. At this stage, the CO_2 is separated and captured, while the hydrogen can be used as an energy carrier in turbines, fuel cells, or other systems. The oxy-fuel process involves separating nitrogen (N_2) from oxygen (O_2) before combustion. This allows the resulting CO_2 to be separated from water without the need to remove NO_x components, producing a flue gas with a much higher CO_2 concentration (80–98%), which is the main advantage of this method. However, it is still the least developed option, as there are ongoing challenges related to its high energy intensity that must be overcome.

Inside each capture approach, different technologies can be applied to separate CO_2 from emission streams. Some of these technologies are already commercially mature, while others are still in the early stages of development and not yet ready for large-scale deployment. According to Shahbaz et al. (2021), chemical absorption is a widely used method that can be applied in both post- and pre-combustion processes. Other suitable options for post-combustion applications include membrane separation, cryogenic separation, vacuum swing adsorption, and adsorption using solid sorbents. In pre-combustion systems, physical solvent absorption is also considered a mature and proven technology. In the case of oxy-fuel combustion, three main methods are commonly discussed: chemical looping, combustion in pure oxygen, and chemical looping reforming.

However, as mentioned in section 4.2.1.2, in ethanol production, unlike in flue gas or syngas systems, the fermentation off-gas is already concentrated and composed almost entirely of CO_2 (Metz et al., 2005; Leal Silva et al., 2024; Kheshgi & Prince, 2005). Therefore, the capture process does not require separation methods such as chemical absorption or membrane separation. In this case, capturing CO_2 simply involves collecting the gas emitted during fermentation and then dehydrating it (Metz et al., 2005; Leal Silva et al., 2024). Depending on the level of ethanol impurities, the stream may also undergo a filtration step afterward. The concentration of CO_2 is not the same depending on the ethanol source, but it is higher than 90% for all sources (Kheshgi & Prince, 2005), while for sugarcane-based ethanol, the process is simpler, as the off-gas stream is nearly pure CO_2 (Metz et al., 2005).

4.2.1.4 Transportation

After CO_2 is captured from the fermentation process and dehydrated to remove possible traces of water vapor and ethanol (Doctor et al., 2005; Kheshgi & Prince, 2005), the gas, initially at atmospheric pressure (around 1 bar), must be compressed to be transported through pipelines specifically designed for carbon transport. CO_2 reaches supercritical conditions after being compressed in the range of 80 to 150 bar, behaving similarly to a liquid, although it is actually a supercritical fluid (Doctor et al., 2005; Shahbaz et al., 2021). There is also the possibility that the captured CO_2 is transported in the gas phase if the used network is retrofitted from an old natural gas network. The pipelines would not be able to handle CO_2 in the supercritical phase, making it easier to transport it in the gas state at pressures lower than 40 bar (Torbergsen, Leinum, & Røneid, 2025). Pipelines built for carbon transportation should follow the same regulations already used for oil and gas (Doctor et al., 2005), and they require CO_2 of high purity and minimal water content, since even small amounts of water can form carbonic acid and cause severe internal corrosion (Doctor et al., 2005; Torbergsen et al., 2025).

Another alternative to transport CO_2 is in liquid state by ships, where the pressure range is around 6 to 7 bar (Doctor et al., 2005; Geske et al., 2015). Transport costs represent a small fraction of total CCS costs but increase proportionally with distance, making short transport routes the most economical option (Geske et al., 2015; Doctor et al., 2005). Transporting carbon on ships is more viable when the distance is long, or offshore, and if the transportation volumes are medium-to-small (Geske et al., 2015). However, ship transportation adds CO_2 emissions due to oil combustion during navigation (Doctor et al., 2005), which reduces net CO_2 sequestration. Ideally, if the capture site is close to the storage location, the costs and environmental impacts associated with long transport distances will be reduced.

4.2.1.5 Long-term Storage

The captured and transported CO_2 now needs to be stored for a long period of time to complete the process of sequestration. Possible storage locations are **deep saline**

aquifers, **depleted oil and gas fields**, **mineral carbonation formations**, and **unmineable coal seams**. According to the Benson et al. (2005), these geological formations can securely retain CO_2 for thousands to millions of years through a combination of different mechanisms, such as physical, residual, solubility, and mineral trapping. Smith et al. (2024) also describes these reservoirs as the most reliable, stable, and long-lasting CO_2 storage options.

Deep Saline Aquifers: Saline aquifers are considered the most viable solution for the long-term storage of large amounts of CO_2. They have the most potential and a broad availability worldwide. It is estimated that saline aquifers can store 400 to 10,000 gigatonnes of CO_2 (Ringrose et al., 2021; Ismail & Gaganis, 2023; Izadpanahi et al., 2024; Worden, 2024). Before injecting captured carbon, these formations require thorough investigation to determine their geological features, including porosity and permeability. It is also important to verify the strength of the caprock, which is the rock layer above the reservoir that acts as a barrier for CO_2 and prevents it from escaping (Worden, 2024). Once in the reservoir, CO_2 is trapped underground through different mechanisms. It may be trapped beneath impermeable rock layers (structural and stratigraphic trapping), held in small rock pores (residual trapping), dissolved in salty water (solubility trapping), or react slowly with minerals, forming solid carbonates (mineral trapping) (Izadpanahi et al., 2024; Ringrose et al., 2021). Storage efficiency is relatively low (around 2–6% of the pore volume), because CO_2 is lighter and less viscous than brine, it tends to move unevenly through the rock, reaching only a portion of the available pore space. This irregular movement decreases the efficiency of CO_2 storage in saline aquifers (Ringrose et al., 2021; Worden, 2024). Pressure management can be employed to control pressure and protect the sealing rock, improving storage capacity and safety. Brine extraction is a technique to remove some of the water, creating space and lowering the pressure. Furthermore, alternating injections of water and CO_2 can facilitate a more uniform distribution of the gas (Ismail & Gaganis, 2023), a technique known as Water-alternating-gas (WAG) injection. Despite technical challenges, saline aquifers remain the foundation of long-term CO_2 storage, providing a safe and lasting way to keep carbon out of the atmosphere when properly managed.

Depleted oil and gas fields: Depleted oil and gas fields are considered an optimal option for CO_2. These locations have already proved they can contain hydrocarbons safely for geological timescales. Moreover, they have extensive pre-existing data and infrastructure due to the oil and gas industry, which reduces the cost and uncertainty of the projects (Z. Li et al., 2006; Hannis et al., 2017; Worden, 2024; Wei et al., 2023). It is estimated that these reservoirs can store approximately 700–900 gigatonnes of CO_2. Even though they have a smaller capacity than deep saline aquifers, the storage efficiency is higher, being around 60–80% of the available pore volume (Wei et al., 2023; Worden, 2024; Hannis et al., 2017). CO_2 can be injected safely at pressures below the original reservoir pressure, taking advantage of its naturally pressure-depleted conditions, which lowers the risk of caprock fracturing. However, the sealing capacity of caprocks must be re-evaluated before injection, since the contact between CO_2 and brine is less stable than that between hydrocarbons and brine, which can reduce the sealing strength of the caprock (Z. Li et al., 2006). To deal with that issue, experimental and field research were done with formations made of evaporites and shale seals and have shown that they are capable of maintaining secure CO_2 sequestration over long timescales (Z. Li et al., 2006). Therefore, depleted gas and oil fields represent a short-term, cost-effective solution that is ready for use, especially as a transition option. The necessary technology is already deployed and vastly used in the industry, allowing safe, large-scale sequestration of CO_2.

Mineral Carbonation Formations: Mineral carbonation is a process that captures CO_2 when reacting it with minerals rich in magnesium or calcium, such as olivine, serpentine, or basalt. In this reaction, CO_2 is sequestered in the form of a stable solid carbonate, magnesite, or calcite, for example. Water plays an important role in this method by dissolving CO_2, allowing it to reach the mineral surfaces where the reaction occurs. The process is an imitation of the natural weathering of rocks, but with conditions that happen faster than naturally. *In-situ carbonation* happens underground, having CO_2 injected into rock formations prone to reaction. *Ex-situ carbonation* is when the process happens above the ground, in controlled reactors using crushed minerals or industrial wastes (Olajire, 2013; Wang et al., 2018; Rashid et al., 2023). For the latter, reactors are needed to improve efficiency, with higher temperatures, pressures, and smaller particle sizes, but this also increases energy demand and costs. The global potential of this method is high. It is estimated that the sequestration potential of the technology is over 100 trillion tonnes of CO_2, with single regions, such as periodite formations in Oman, capable of holding around 30 trillion tonnes (Wang et al., 2018). However, this process is still not ready for large-scale applications. The chemistry, the safety, and long-term sequestration are well understood, but the technology is still evolving from laboratory to demonstration scale. CarbFix in Iceland is a project that applies this technology, and it has proven that in-situ mineralization can trap CO_2 underground in less than two years, but most mineral carbonation research remains at the pilot stage (Wang et al., 2018; Olajire, 2013).

Unmineable Coal Seams: Unmineable coal seams is a method where CO_2 captured is compressed and injected into deep coal formations, where it is adsorbed onto the internal surface of the coal. In this process, carbon substitutes for the methane trapped in the coal (Shi & Durucan, 2005; Jiang et al., 2022; Liu et al., 2025). It is estimated that the technology has a global potential to sequester 900-1000 gigatonnes of CO_2, mainly in China, United States, and Australia (Liu et al., 2025). Compared with saline aquifers, coal seams provides more secure, long-term trapping, but the capacity is smaller (Liu et al., 2025). Even though the mechanism is well understood, and pilot projects have proven technical feasibility, it is not yet deployed on a large-scale. Excessive injection pressure can cause the coal matrix to swell, which reduces permeability, decreasing the amount of CO_2 that could be injected efficiently. CO_2 storage in coal seams is considered to be at a pilot-to-demonstration stage of development. Future research focuses on enhancing injection efficiency, improving adsorption capacity with physical or chemical surface treatments, and predicting leakage risk and interactions between Co_2 and water (Liu et al., 2025).

4.2.2 Niche actors

Even though BECCS is a well-developed technology ready for large-scale deployment around the world, in Brazil there is only one project currently under development to capture CO_2 from an ethanol plant. The project is designed and developed by FS, the first ethanol company in Brazil to produce ethanol entirely from corn (FS Bioenergia, 2025). It is now awaiting the necessary documentation and approvals to begin the installation of the BECCS system at its facility in Lucas do Rio Verde, Mato Grosso (Novacana, 2025a). The operation is expected to start in July 2026. The company estimates that the system will capture around 423 kilotons of CO_2 per year, part of which has already been sold as carbon credits, although the prices per ton have not been disclosed to the public (Novacana, 2025a). Currently, the only ethanol plants operating with BECCS are located in the United States. This plant would therefore be the first outside the U.S. with the potential to achieve a negative carbon footprint (PR Newswire, 2024).

According to an industry interviewee (INT-02(C.2)), the strategic objective is to integrate BECCS as a structural component of ethanol production, rather than treating it as a marginal add-on. The project confirmed the geological feasibility of CO_2 storage after conducting studies approximately 2 km from the facility. They plan to inject the carbon at depths of around 800 m (PR Newswire, 2024), enabling pipeline-based CO_2 transport. Interviewees (INT-02(C.2), INT-04(C.4)) emphasized that this geographic advantage is not available to most ethanol producers, implying higher capital requirements for future BECCS projects that do not have this advantage. An industry practitioner noted that many incumbent firms in the sector are more risk-averse and would invest only once technical workflows and economic viability have been demonstrated (INT-02(C.2),INT-04(C.4)). Therefore, FS's project may serve as a reference case, with its outcomes likely to influence whether and how other ethanol producers engage with BECCS in Brazil.

According to an industry interviewee (INT-02(C.2)), the strategic objective is to integrate BECCS as a structural component of ethanol production, rather than treating it as a marginal add-on. The project confirmed the geological feasibility of CO_2 storage after conducting studies approximately 2 km from the facility. They plan to inject the carbon at depths of around 800 m (PR Newswire, 2024), enabling pipeline-based CO_2 transport. Interviewees (INT-02(C.2), INT-04(C.4)) emphasized that this geographic advantage is not available to most ethanol producers, implying higher capital requirements for future BECCS projects that do not have this advantage. An industry practitioner noted that many incumbent firms in the sector are more risk-averse and would invest only once technical workflows and economic viability have been demonstrated (INT-02(C.2), INT-04(C.4)). Therefore, FS's project may serve as a reference case, with its outcomes likely to influence whether and how other ethanol producers engage with BECCS in Brazil.

According to an industry interviewee (INT-02(C.2)), the strategic objective is to integrate BECCS as a structural component of ethanol production, rather than treating it as a marginal add-on. The project confirmed the geological feasibility of CO_2 storage after conducting studies approximately 2 km from the facility. They plan to inject the carbon at depths of around 800 m (PR Newswire, 2024), enabling pipeline-based CO_2 transport. Interviewees (INT-02(C.2), INT-04(C.4)) emphasized that this geographic advantage is not available to most ethanol producers, implying higher capital requirements for future BECCS projects that do not have this advantage. An industry practitioner noted that many incumbent firms in the sector are more risk-averse and would invest only once technical workflows and economic viability have been demonstrated (INT-02(C.2),INT-04(C.4)). Therefore, FS's project may serve as a reference case, with its outcomes likely to influence whether and how other ethanol producers engage with BECCS in Brazil.

4.2.3 Technology development phase

According to the development phases presented by Geels (2006, 2019) and briefly described in section 2.2.1, it can be said that BECCS in Brazil is positioned between technology development phases two and three. Phase two is characterized by small-scale demonstrations and protected niches for experimentation. The technology is in an early stabilization phase, where the expectations around its potential come from global decarbonization trends and the emergence of carbon markets. There is not yet industrial demand or a domestic policy that specifically protects BECCS; actually, the network that supports this technology in Brazil is limited to one actor, FS Bioenergia. The FS project is planned for large-scale deployment, but it remains a pilot initiative in Brazil and has not yet been consolidated as a phase-three technology. A significant barrier, aside from the project's capital cost, is specialized knowledge, which is mainly held by actors in the oil and gas industry. That creates not only economic barriers, but also barriers related to the knowledge and specialized know-how.

4.3 Biochar Carbon Removal (BCR)

Biochar is a carbon-rich microporous material that is made through the pyrolysis and carbonization of biomass (Chen et al., 2019). It is used as a soil amendment to improve soil health; however, its roots go back thousands of years. Original communities in the Amazon basin have been enriching their fields with charcoal and organic residue with evidence of this practice for more than 5000 years (Schmidt et al., 2023; Lehmann, 2009). This ancient technique is now called *Terra Preta de Índio*, or Amazonian Dark Earth (ADE), which, compared to nearby land, contains higher concentrations of carbon, phosphorus, calcium, manganese, and strontium (Schmidt et al., 2023). Its porous structure helps accumulate nutrients and beneficial microorganisms, stimulating plant growth (Chen et al., 2019). Biochar is not a fertilizer, but rather a soil conditioner that improves nutrient and water absorption in the soil; hence, it does not replace the need for a nutrient supply. As shown in Lehmann (2009), studies of ancient ADE prove that biochar can keep soils fertile for centuries or even millennia.

Nowadays, biochar can be produced by farmers, researchers, and industries using plant waste, such as sugarcane bagasse or wood scraps. The result is a porous carbon material that raises soil pH, locks away carbon, improves soil structure, and helps soil hold onto moisture and nutrients (Schmidt et al., 2023; Chen et al., 2019; L. Li et al., 2023). Due to its ability to store carbon for hundreds of years, biochar is now also being promoted as a natural means to help combat climate change. Furthermore, biochar is also considered a bioenergy technology, since its production through burning biomass also generates valuable co-products, i.e. syngas and bio-oil. These by-products can be used to generate heat, electricity, or liquid fuels, integrating biochar production into broader renewable energy systems and reinforcing biochar's circular-economy attributes. It can also be used as solid fuel, like charcoal, but its application as fuel limits its application as long-term carbon storage.

Depending on the feedstock used to produce biochar, its effectiveness and application may vary due to its final composition. On top of that, the temperature at which the biochar needs to be produced also needs to be adapted depending on the type of biomass used (L. Li et al., 2023; Zafeer et al., 2023), since different feedstocks thermally decompose at different temperatures (L. Li et al., 2023). For sugarcane bagasse, if the production method chosen is pyrolysis, the matter undergoes decomposition at temperatures above 300^{o}c (Zafeer et al., 2023).

4.3.1 Technology map

In this section, the same process done for Beccs is done for biochar. Focusing on the technology involved in the production, storage, distribution, and applications chain. The technology map can be used to contextualize biochar inside the sugar-energy regime. It is possible to see in figure 4.2 the technology map of Biochar together with the steps description below.

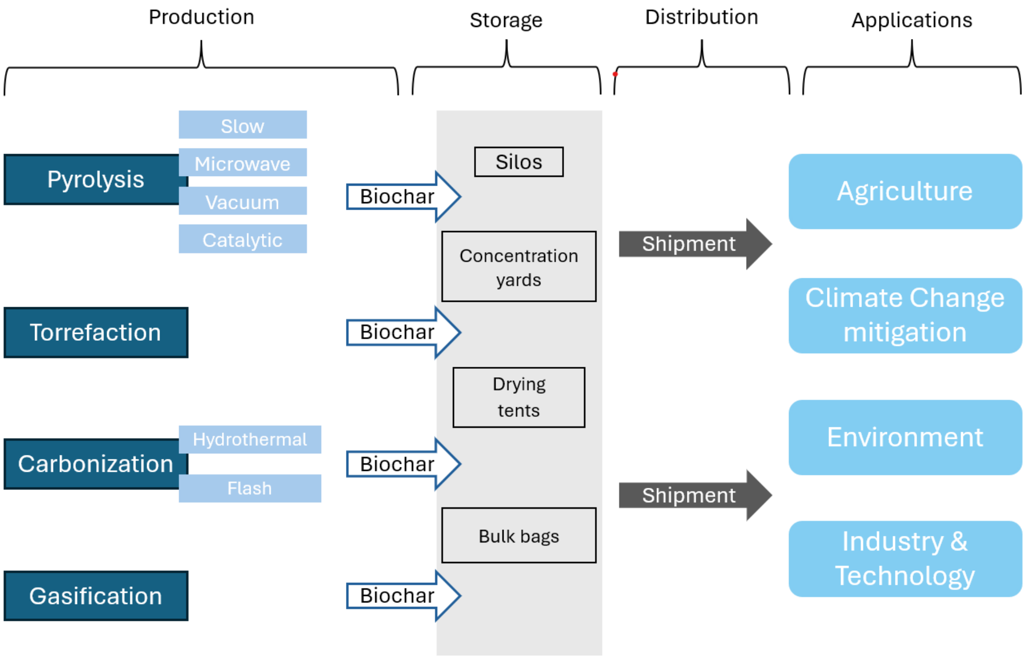


Figure 4.2: Biochar Technology Map

4.3.1.1 Production Technologies

Biochar can be made using different techniques, from traditional methods to more advanced and recently developed ones. Pyrolysis is the most traditional method, but the choice of method depends on factors such as region, feedstock, accessibility, and financial conditions (Singh et al., 2025). Furthermore, the methods considered here differ in their applications, processes, costs, and levels of technological readiness but also are physically distinguished by differences in temperature, heating rate, residence times for feedstock and vapors, char yield, carbon content, and carbon yield.

Pyrolysis: Pyrolysis is the main technique used to produce biochar. It is a method of chemical decomposition that occurs at high temperatures in the partial absence of oxygen, preventing combustion and allowing the organic matter to break down into smaller, simpler compounds, such as biochar, syngas, and bio-oils (Zafeer et al., 2023; Pereira et al., 2016; Al-Rumaihi et al., 2022). During the process, the main emissions are carbonaceous gases, hydrogen, and methane (Al-Rumaihi et al., 2022). The properties of the biomass used directly influence its composition and the byproducts produced. Another important factor affecting both the byproducts and their quality is the temperature and duration of the pyrolysis process (Pereira et al., 2016; L. Li et al., 2023). Moreover, biochar performance is determined by its properties, such as nutrient content, pH, and structural characteristics, which are also influenced by the pyrolysis method and feedstock used. The composition of biochar is critical for its effectiveness, whether as a climate change mitigator or as a soil amendment (L. Li et al., 2023). When temperature increases, the production of char decreases and more volatile matter is released; however, the char produced have better quality, having more carbon content in its composition (Carrier et al., 2011). That is the reason why not all pyrolysis methods are suitable for biochar production.

- **Slow Pyrolysis:** Slow pyrolysis, also known as *conventional pyrolysis*, is a method used since the 1900's and consists of heating the matter with lower temperatures (300–500 °C), slower heating rates ((0.1–1°C/s), and a maximum residence time of 2 h (Zafeer et al., 2023). The use of low heating rates and temperatures combined with extended residence times leads to a higher yield of high-quality char, up to 45%, while reducing the formation of liquid and gaseous byproducts (Zafeer et al., 2023; Al-Rumaihi et al., 2022). It is commonly used to convert lignocellulosic [2] and algal biomass, as well as food waste (Singh et al., 2025).
- **Microwave Pyrolysis:** Microwave heating is an energy transfer process that does not require contact and converts electromagnetic energy into thermal energy (J. Li et al., 2016). In biomass microwave pyrolysis, heat is produced within the core of the material due to the interaction between the microwaves and the biomass, resulting in a more efficient heat transfer (Foong et al., 2020). This results in higher heating rates and can provide selective, uniform heating, accelerating biomass pyrolysis and increasing energy efficiency, making it a more sustainable alternative to conventional pyrolysis (Lam et al., 2022; J. Li et al., 2016; Toscano Miranda et al., 2021). This method was initially studied for the production of bio-oil and gas, but, according to J. Li et al. (2016); Toscano Miranda et al. (2021), the biochar produced by microwave pyrolysis has been shown to be of higher quality than that generated by slow pyrolysis. The produced biochar has a higher surface area and pore volume, with micropores cleaner and more uniform.
- **Vacuum pyrolysis:** Vacuum pyrolysis is typically performed at moderate temperatures in a range of 400-600°C (Foong et al., 2020). It differs from conventional pyrolysis because it is carried out under low pressure, creating an oxygen-free environment that mimics an inert setting without the liberation of nonreactive gases (Foong et al., 2020; Carrier et al., 2011). The advantage of this method is its lower energy consumption, since there is no need to heat the inert gases. The production of bio-oil is increased in this method compared to slow pyrolysis Carrier et al. (2011) while the biochar production was decreased. However, the biochar produced is of higher quality, having a higher surface area and cleaner pores.
- **Catalytic Pyrolysis:** Catalytic pyrolysis is a thermochemical conversion technique that uses materials as catalysts to accelerate the pyrolytic process (Awodun et al., 2025; Choudhary et al., 2025). It provides better control over the process and by-products, enabling selective generation of products and emission of gases (Choudhary et al., 2025). It offers an alternative to conventional pyrolysis, which has limitations in product selectivity and high energy requirements. Catalytic pyrolysis enhances overall efficiency by reducing the reaction temperature and increasing reaction rates. It is a technology that improves bio-oil production, but depending on the catalyst used, it favors biochar yield over bio-oil.

---

[2] material of vegetal biomass

Torrefaction: Torrefaction is a thermochemical process that is also used for biochar production, and it operates at a temperature of 200-300°C in an environment with the presence of nitrogen and the absence of oxygen (Awodun et al., 2025; Singh et al., 2025; Singh Yadav et al., 2023). It has a high biochar yield of about 30-50%, but it also yields syngas and bio-oil (Singh et al., 2025). Compared to conventional pyrolysis, torrefaction enables higher biochar productivity and yield. It generates better quality biochar, i.e., lower moisture and ash levels, greater resistance to water, easier grinding, more uniform fuel properties, higher carbon content and energy density, and superior storage and transport characteristics (Awodun et al., 2025; Leong & Chang, 2023). Still, it is a high-energy-intensive process (Singh et al., 2025).

Carbonization: Carbonization can be characterized as a slow pyrolysis process (Ronsse et al., 2015). It is also a thermochemical process conducted under oxygen-limited conditions with long residence times, designed to maximize char yield. The resulting products include charcoal, torrefied biomass, activated carbon, and biochar.

- **Hydrothermal carbonization (HTC):** Hydrothermal carbonization, is a thermochemical process where biomass is decomposed in subcritical water [3] at low temperatures (180–250°C) and a pressure range of 2–10 MPa to produce hydrochar (Singh Yadav et al., 2023; Krysanova et al., 2022). Compared to pyrolysis, HTC happens in an aqueous medium, making it more suitable to use for wet biomass, e.g. algae, sewage sludge, and some agricultural residues (Czerwińska, Śliz, & Wilk, 2022; Krysanova et al., 2022; Petrović et al., 2024). The process involves a series of reactions yielding hydrochar, liquid, and gaseous by-products. Hydrochars produced through HTC achieve 40–70% solid yield, depending on feedstock and conditions (Singh Yadav et al., 2023). The resulting hydrochar has a higher energy density, reduced oxygen content, and improved fuel ratio compared to the raw feedstock; however it has lower surface area and porosity, which decreases adsorption capacity and turns hydrochar less stable and more biodegradable, leading to possible GHG emissions (Kambo & Dutta, 2015). According to Petrović et al. (2024), hydrochar can be further modified to improve its adsorption capacity and to be more stable for long-term carbon capture. Hydrothermal carbonization avoids predrying and does not generate direct gas emissions, making it one of the most cost-effective methods for producing biochar from moist feedstocks. Although the resulting process water contains dissolved organics that may be toxic and require treatment or reuse.
- **Flash Carbonization:** Flash carbonization is carried out at elevated pressures, up to 1 MPa, and with oxygen supplied to partially combust the feedstock (Ronsse et al., 2015). This process is described to achieve char yields close to thermodynamic equilibrium and generally higher than those obtained at atmospheric pressure, having 28-32% biochar yield and a short reaction time of around 30 min (Amalina et al., 2022). The technique uses an oxygen-blown pressurized kiln where biomass is ignited at the bottom, creating a flame front that moves upward through the bed, providing the heat needed for pyrolysis (Rosenbloom, 2019). Compared to other biochar production methods, there is little literature available on flash carbonization, which is explicable given that it is a more recent process and has not yet seen deployment on a large scale.

---

[3] Subcritical water is the liquid water maintained at 100–374°C under pressure, where it becomes less polar and more reactive (Petrović et al., 2024; Lorenzo et al., 2020).

Gasification: Gasification is a thermochemical process that happens in high temperature ranges from 600–1200°C. Biomass oxidizes partially, producing a gaseous mixture of CO, H_2, CO_2, and CH_4 or syngas (Kambo & Dutta, 2015; Qambrani, Rahman, Won, Shim, & Ra, 2017). Biochar is a smaller fraction byproduct of gasification, usually around 10% (Singh Yadav et al., 2023). This gasification-derived biochar differs from pyrolysis biochar not only in yield but also in properties because the harsher operating conditions and the oxidizing environment reduce carbon retention but can enhance surface reactivity (Akgül et al., 2024). The properties of the residual biochar depend on factors such as temperature, gasifying agent (air, oxygen, steam), and feedstock type. Higher temperatures generally lower yield but modify porosity and surface chemistry (Awodun et al., 2025). Although biochar is not the main product of gasification, it plays an important role in the process. The reactions between evolving gases and char in the reduction zone are essential for syngas formation (Awodun et al., 2025). Even though it produces less char compared to other methods, it is a relevant method to this study since it is usually utilized for industrial and large-scale applications, and the residual char can later be used as a carbon-rich material with potential applications in soil amendment, carbon sequestration, or as an industrial feedstock (Awodun et al., 2025; Singh et al., 2025).

4.3.1.2 Storage and Distribution

The storage and distribution of biochar are important steps of the supply chain of the material. The material can be stored as biomass itself, which is important to overcome the seasonality of the plantations, meaning biochar can be produced all year. Another possibility is to store biochar already made. Storing biochar brings some challenges, such as the degradation of the material over time, dust dispersion and accumulation, and spontaneous combustion of the raw material. Biochar is lightweight, porous, and fragile, which makes it a low-density product, challenging to handle. The fine particles are easy to disperse, and they can generate dust while handling. It also introduces explosion risks if biochar has not been properly cooled after production and are still active. Therefore, silos, concentration yards, drying tents, and container bags are possible storage units that help preserve product quality. Where high temperatures and direct sunlight should be avoided. The storage unit must be dry, helping to avoid humidity and mold (Anderson et al., 2016).

Storage of biochar is not only important to conserve the product and buffer feedstock availability fluctuation, but it also helps improve the efficiency of transportation, avoiding preprocessing activities such as sorting, drying, or screening. The best distribution method depends on how it was made. If it is in dust form, transportation also involves explosion risks, especially when transported in closed containers that can heat up, such as bulk. Transportation for large users can be handled by bulk shipments in bags, metal/plastic drums, or rail cars. For small users, transportation can be done with paper and plastic bags or bucket packaging, the same way soil amendment is transported (Anderson et al., 2016).

4.3.1.3 Application

Biochar is a very versatile bioproduct that has different applications in different sectors. For instance, the most well-known biochar application is in agriculture, which is part of the scope of this study. Since it has shown potential to improve soil fertility and crop productivity. Because of its structure, it is a lightweight and porous substance with high adsorption qualities, helping improve water retention. Due to the high presence of carbonates, biochar is alkaline, which helps neutralize soil pH and, because biochar is usually produced from biomass containing basic cations, it improves cation exchange in the soil by releasing these cations, improving productivity yield (Singh et al., 2025). The porous structure also helps improve water retention, and support nutrient cycling and microbial activity, with the strongest impacts observed in degraded, acidic, or sandy soils (Zilberman et al., 2022; Chen et al., 2019).

Another application of biochar addressed in this study is expectations for climate mitigation contributions. When produced, 10-50% of biomass carbon is converted into a stable aromatic carbon, which can remain in the soil for centuries (Anderson et al., 2016; Zilberman et al., 2022; Lehmann, 2009). This structure sequesters CO_2, contributing to the net reduction of GHG in the atmosphere both directly and indirectly. Carbon storage is an obvious direct effect, while avoiding methane and nitrous oxide emissions from biomass waste decomposition, improving soil processes, reducing fertilizer demand, increasing soil productivity, and displacing fossil fuels through coproducts (syngas and bio-oil) (Anderson et al., 2016) can be considered indirect contributions to climate mitigation. The assumptions taken about waste biomass management, soil dynamics, and market substitutions for inputs like fertilizer and fossil fuels (Anderson et al., 2016) are essential to quantify indirect climate benefits of biochar. Therefore, biochar systems are a technological method that supports national net-zero emission goals by integrating carbon sequestration, renewable energies, circular economy, and soil improvements.

Beyond the scope of this study, biochar also has applications in the environment, industry, and technology. In the environment, it can be used to immobilize heavy metals, microplastics, and capture organic pollutants (Singh et al., 2025; Zhou et al., 2025). In the industry it can be used, for example, in construction, incorporating it into composites to produce lightweight insulating and carbon-storing materials (Zhou et al., 2025; Singh et al., 2025). In the energy sector, biochar is also suitable for electrodes in batteries and supercapacitors due to its conductivity and porosity, which offer a sustainable and low-cost alternative to conventional carbon-based materials (Zhou et al., 2025; Singh et al., 2025).

4.3.2 Niche Actors

Even though biochar has good perspectives in Brazil, because of favorable conditions as abundant agricultural residues and a good harvesting climate, the industry remains underexplored. After research, it was found that there are small initiatives with biochar in Brazil. The biggest one is Net Zero, a French startup founded in 2021, is the leading private actor. According to their website (NetZero, n.d.), the company developed a large-scale biochar production model and has two plants in Brazil, located in Minas Gerais and Espírito Santo. The first plant is in Lajinha (Minas Gerais) and uses coffee husk from a cooperative of around 10,000 producers, generating about 4,000 tons of biochar per year. The produced biochar is sold back to cooperative members, reducing their fertilizer use. In 2024, a second plant was opened in Brejetuba (Espírito Santo), having the same production capacity but improved technology. In September of 2025, NetZero announced the construction of a new plant in Minas Gerais that will use the straw and juice of the sugarcane for the production of biochar (Novacana, 2025b). Net Zero sells biochar to farmers primarily as a soil amendment and has not yet been certified for carbon credits.

Another actor working with biochar is Aperam Bioenergia, which has one biochar project that has carbon credit certification issued by Puro.Earth (Carbonmark, 2025). The project is from 2023, and according to online information, it is still active and removing 50,000 tonnes of CO_2 per year. However, after this project, Aperam Bioenergy has not deployed any others. Another company with a biochar project in Brazil is Brasil Bioenergy (Brasil Biomassa, 2025); however, this project is still on paper. As a public actor, Embrapa (Empresa Brasileira de Pesquisa Agropecuária) [4] has supported research on biochar as part of its broader mission to promote sustainable agricultural innovation (Embrapa, n.d.). Despite Net Zero projects growing in scale, biochar deployment in Brazil remains limited, with existing projects concentrated in a small number of early commercial facilities.

4.3.3 Technology Development Phase

Differently from BECCS, biochar technology does not have large-scale projects in Brazil. Current activities are limited to pilot and local initiatives linked to government institutions, university research, and startups. Projects that could be considered large-scale and commercial are restricted to the startup Net Zero, which, from the public information, is not yet integrated into national carbon policies. Even though the Net Zero initiative has established clients and appears to be expanding its production and sales, the market remains limited and primarily focused on soil amendment rather than intentional CO_2 removal, despite the high potential for carbon sequestration. Therefore, the current focus of biochar in Brazil is still on learning, technological development, and building legitimacy within carbon markets. It is possible that once Net Zero consolidates its activities beyond soil improvement and begins to sell verified carbon credits, biochar could start transitioning towards phase three of development.

Across interviews, it is common sense that biochar is the most promising CDR technology to develop in the short term. This conclusion was based on the simplicity of the production method and the operational compatibility with the current process on the sugar plantation. Biochar can be produced on-site using relatively simple, well-established technology, pyrolysis. It allows the use of agricultural residues, and its application is similar to fertilization and soil conditioning processes. However, interviewees disagreed on how biochar should be primarily marketed. One energy expert believes that biochar could be economically viable even without revenues from carbon removal credits if sold only as a soil conditioner (Int-04(C.4)). In this view, biochar could reduce production costs by lowering dependence on imported fertilizers while also reducing emissions associated with fertilizer use and the decomposition of agricultural residues. However, other interviewees believe that biochar development and adherence would be accelerated if it were mainly sold as a carbon credit (INT-01(C.1), INT-03(C.3)). It was suggested that once a reliable MRV methodology is established for biochar and the credits are certified, that could represent a turning point for biochar development in Brazil.

Finally, it was also mentioned in the interviews that the sugar-energy sector has faced declining revenues from bioelectricity generation from bagasse because of increasing competition from wind and solar sources, which has driven electricity prices down (INT-04((C.4)). In this context, biochar production could offer an alternative destination for

---

[4] is a company from the Ministry of Agriculture of Brazil

bagasse, particularly for plants with expiring power purchase agreements, enabling the development of new business models aligned with decarbonization goals. That can also be a potential enabler of technology diffusion, but it needs further studies and economic viability assessments. However, it was also noted that, even with simple technologies, the method is still challenging to scale for large producers and plants with high processing capacity, due to the cost and availability of machinery.

4.4 Enhanced Rock Weathering (ERW)

Enhanced rock Weathering is a carbon removal technology that mimics the natural weathering process of rocks and minerals, but in an accelerated way (InPlanet, n.d.). That is done by applying finely ground rocks in the soil. The rocks used are usually basalt and other silicate minerals, which react with the CO_2 in the atmosphere when in contact with water (Sun et al., 2025; InPlanet, n.d.). Through this process, CO_2 is converted into dissolved bicarbonates that are transported hydrologically to rivers and eventually the oceans, where the carbon remains stored for geological timescales (Sun et al., 2025; InPlanet, n.d.; Ryan et al., 2024). It is a natural process, which makes it simple to scale and can be integrated into existing production chains, especially when added to already existing agricultural lands (Strefler et al., 2018). INT-01 (C.1) mentioned the operational compatibility of ERW with the current processes in Brazilian plantations, such as fertilizer and soil-conditioning spreading. ERW yields better results in tropical regions because weathering is accelerated by higher temperatures, abundant rainfall, and biologically active soils [5]. The hot and rainy characteristics of the tropics naturally favor rock weathering; therefore, tropical soils are already depleted of fresh minerals due to millennia of reaction with CO_2. ERW can be helpful in bringing back those minerals, through the addition of crushed rocks in the soil (Edwards et al., 2017; Strefler et al., 2018). The availability of plants and microbes makes the reaction with the added minerals more effective, since roots release acids and CO_2, which accelerate the breakdown of the added minerals. According to Strefler et al. (2018), at grain sizes around 20 μm, ERW could remove up to 4.9 Gt CO_2 per year with basalt and 95 Gt CO_2 per year with dunite globally, most of it in warm, humid regions.

Tropic conditions also influence the continuous growing season, which helps distribute rock dust and maintain contact between minerals, soils, and water (Edwards et al., 2017; Strefler et al., 2018). Enhanced rock weathering can also generate co-benefits in agricultural systems. The mineral, when applied to the soil, releases nutrients that can improve soil quality and crop productivity. As biochar, it can also serve as a soil amendment, reducing fertilizer and agricultural lime (Strefler et al., 2018; Edwards et al., 2017), thereby reducing emissions alone. Calcium, potassium, and magnesium are nutrients present in rocks commonly used for ERW that enhance soil, making it more attractive and more receptive to deployment on croplands. In Brazil, ERW also relies on the reuse of residues, although in this case, they originate from mining activities (INT-01(C.1)). Mining companies authorized to commercialize these materials must be certified by the Ministry of Agriculture, aligning ERW with circular economy principles. This also implies that the distance between residue sources and application sites, as well as associated logistics, is a critical factor when calculating net carbon removal, as noted by several interviewees.

---

[5] Microorganisms, plant roots, and soil fauna

Places where agriculture is an important part of the economy can share the space already used by plantations to capture carbon, along with decreasing the use of fertilizers. According to an interviewee (INT-01(C.1)), the sugar-energy sector is relatively technologically advanced and more open to organic soil management practices, which makes it more receptive to innovation. However, the technology still faces challenges in gaining acceptance among producers, largely due to past experiences with a similar product known as “rock dust,” which was marketed years ago as offering comparable benefits but was not properly processed and therefore failed to deliver the promised results. Furthermore, the technology has promising prospects; however, it is still an underexplored field compared to other CDR technologies, such as biochar. The empirical data available on the subject raise expectations but are still limited to a few large-scale applications. Its efficacy depends on multiple variables, including rock type, availability, particle-size distribution, local climate, and soil chemistry, which influence the weathering rate and, in turn, the practical quantity of carbon removed.

In Brazil, there is one startup, InPlanet, that works on enhanced rock weathering, and its first project was applying the technology to a 500 ha sugarcane plantation in São Paulo (InPlanet, n.d.). In December of 2024, the project calculated a net removal of 235 t CO_2 over the five years through the Isometric platform, a company that issues carbon credits (Isometric, n.d.). According to the interview INT-01(C.1), it was the first carbon removal project to be certified worldwide. An industry practitioner interviewed said that getting MRV certification and monetizing carbon credits was a turning point for ERW in Brazil(INT-01(C.1)); moreover, the technology also entered the RenovaBio policy, being eligible to issue CBios. ERW in Brazil is also in phase two of technological development, where the focus remains on pilot projects. Terradot is not a Brazilian company, but it has operations in Brazil, having investors as Google, Microsoft, and Cisco. During COP30 in November, the company announced its goal to expand its deployment by 5 times by the end of 2026 (Terradot, 2025). In September 2025, Future Climate [6] signed their first contract of ERW in the market (ESG Inside, 2025). In November of 2025, Verde Agritech and UNDO Carbon partnered to scale an ERW project and sell carbon credits to companies that want to offset their emissions (CarbonCredits.com, 2025).

However, ERW still lacks the institutional frameworks, market mechanisms, and large-scale projects that would characterize phase three. Therefore, it remains within the niche experimentation phase. The expectations around this technology are science-based, focusing on proving carbon removal effectiveness and the benefits for soil fertility. Market and policy expectations are in sight, and the actor network is emerging, dominated by InPlanet, the biggest actor in the field in the Brazilian context, but also with newly announced initiatives from other actors in the market. Another point of attention is that this niche is still dependent on foreign knowledge and voluntary carbon market success, deeply constraining this technology diffusion.

4.5 Main Findings

This chapter discussed three CDR technologies with potential integration in the sugar-energy sector. It explained their technological characteristics, applications, main actors, and diffusion stages. In the case of BECCS in ethanol production, the energy conversion technology for biomass and CO_2 capture are well established and well known. The main challenges are transporting CO_2 over long distances and storing

---

[6] Climate business platform that develops and intermediates carbon projects and carbon credits

it underground. These require high capital investments and specialized knowledge, at the same time that some methods of underground storage are also in the early stage of development. Therefore, the plant's location is a determinant of the project's viability. In Brazil, BECCS technology has not yet completed phase two of development, meaning it remains in the pilot stage, and niche developments depend on external changes. However, it already presents some characteristics of phase three, including large-scale projects and emerging institutional conditions that could enable broader adoption. The *Regulated Carbon Market*, which establishes a carbon market in Brazil for the coming years, represents a potential window of opportunity for BECCS, depending on the carbon prices that are still uncertain. The expertise around BECCS technology owned by the oil & gas industry may also support its future diffusion, but also creates a challenge, when extra expertise is needed in industries that were not needed before. Therefore, the learning process for the technology is mainly technical, focusing on capture, storage feasibility, geological assessment, and infrastructure integration. The absence of actors' coordination and long-term funding/incentives is also an important constraint.

Biochar is an ancient technology that can be produced using many methods, as shown in Figure 4.3.1, including well-established processes such as pyrolysis; however, it is still difficult to scale for large companies. It is noted that the existing methods of production differ significantly, indicating a significant effort to produce biochar of higher quality and efficiency. Some technologies are still experimental and not scalable, but the challenges are not technological in nature. Unlike BECCS, the main challenges of biochar are its production scalability and legitimacy among producers. The Biochar niche in Brazil is also in phase two of development, showing signs of niche stabilization, but the initiatives are still fragmented and small-scale. The advantage of biochar is its dual characteristic, serving as a soil amendment as well as a carbon removal. A small private organization and research efforts from public institutions dominate the network. Whether the technology is marketed as a soil amendment or a carbon removal method is not a significant issue. But the recognition and acceptance of it among smaller-to-medium producers is essential. It is easier to base its diffusion path on credibility through producers and its soil amendment characteristics than on carbon removal. However, it allows for a new business model and income for producers with excess biomass, where carbon removal certification, credit sales, and the evolution of Brazil's future regulated carbon market can play an important role.

ERW also remains in phase two of development, and its diffusion depends on the carbon value. It also has soil amendment and circularity properties similar to those of biochar. Still, the process is more energy-intensive and expensive, which constrains further development of a carbon market. While the issuance of ERW carbon credits marks a turning point, the technology continues to face the challenge of overcoming misconceptions created by earlier products that were inaccurately sold. Moreover, logistical barriers are significant for this technology, making it feasible only for plants located near the mineral residues. While the financial feasibility of CDR technologies is crucial for their successful diffusion, it is not the only variable. To access their potential, it is necessary to understand the broader socio-technical system into which they will be embedded and the power relations shaping their development. These dynamics are explored in the next chapter (5), which analyzes the regime level and the main actors influencing the diffusion of CDR technologies in Brazil.

Chapter 5

Brazilian Sugar-Energy Socio-Technical Regime

This chapter aims to answer the question: "*What are the existing institutional, political, and market structures and incumbent actors in the sugar-energy regime? And how do they influence the development and diffusion of CDR technologies?*". It focuses on the key characteristics of the socio-technical regime. It seeks to explain the political and market structures while outlining a stakeholder map that shows the interaction between actors and their influence on the technological development of CDR technologies in Brazil. The chapter is divided into two main parts. The first focuses on the regime's structural configuration and political role, while the second focuses on the actors and their influence within the regime. Both represent the meso-level of the MLP analysis, examining the structural and institutional dimensions that stabilize Brazil's sugar-energy system and mediate the diffusion of emerging CDR technologies.

5.1 Economic and Political Role of the Sugarcane and Ethanol Sector

5.1.1 Sugarcane

Sugarcane is a crop that thrives in tropical and subtropical regions (Cherlinka, 2025). It has an optimum temperature of 32 ^{o}C while growing. Cooler conditions also plays a role, limiting its growth and favoring the accumulation of sucrose in the plant. It requires a specific climatic pattern, areas with abundant precipitation, high solar activity, and fertile soils (Cherlinka, 2025). Brazil offers exceptionally favorable conditions for sugarcane cultivation. The Center-South of the country is the main sugarcane-producing region (São Paulo, Goiás, Minas Gerais, Mato Grosso do Sul, and Paraná), since it benefits from favorable weather, infrastructure, and industrial processing capacity. The Center-South region alone is responsible for around 87% of Brazil's total sugarcane production, with the State of São Paulo responsible for approximately 55% of that (Miranda & R. Martinho, 2020).

According to the study *Zoneamento Agroecológico da Cana-de-Açúcar (ZAE Cana)* (EMBRAPA, 2009), there were 64.7 million hectares of land suitable for sugarcane expansion in 2009, suggesting that land availability is not a limiting factor for the sector's expansion. In 2019, the expansion of sugarcane plantation area were of 1.263 million ha, indicating a growth of 14.3% (Miranda & R. Martinho, 2020), regarding 2009. Assuming an expansion of the same order between the years of 2019 and 2024, there are at least, yet 62 million hectares in Brazil that can be used for sugarcane expansion. Currently, sugarcane occupies a little over 1% of Brazil's national territory, highlighting the potential for scaling production without major land-use conflicts.

It stands out among other bioenergy crops due to its excellent energy balance, as it has high agricultural production, averaging 80 ton/ha (Raízen, 2023), with expectations to reach 100 ton/ha in 2030 (Neves et al., 2017). Each hectare of sugarcane can produce 6-8 m^3 of ethanol (Vian, 2022). Processing sugarcane also generates additional residual biomass that can be used to produce biofuels and bioenergy. These co-products can be used for bioelectricity, biogas, and biomethane production, further enhancing the crop's energy potential and its role in circular bioeconomy models (Raízen, 2023). These residues are bagasse, straw, vinasse, press mud, and molasse (Ungureanu et al., 2022).

The co-products of sugarcane represent a powerful and diverse platform for the development of multiple biofuels and renewable energy carriers. Beyond the well-established production of first-generation ethanol (E1G) and bioelectricity through cogeneration, sugarcane biomass offers promising routes for advanced technologies. There are other derivatives from sugarcane as second-generation ethanol (E2G) derived from lignocellulosic residues, biogas, and biomethane produced from vinasse and filter cake via anaerobic digestion. Emerging research and pilot projects also ecompasses hydrogen, sustainable aviation fuel (SAF), biochar, bio-oil, green diesel, and even methanol synthesis (Raízen, 2023; Ungureanu et al., 2022; Brasil, 2022), using various thermochemical and biochemical conversion pathways. Together, these products reinforce sugarcane's strategic role in a low-carbon economy, transforming it from a single-product crop into a cornerstone of the bioenergy and biorefinery transition.

5.1.2 Ethanol

Ethanol is a biofuel produced mainly from sugarcane in Brazil, but it can also be produced by corn and other crops. It is known for its relatively low carbon footprint compared to fossil fuels. Sugarcane ethanol has the world's lowest carbon footprint among other biofuels (Unica, 2024), and it is a key component of Brazil's energy matrix, playing a crucial role in reducing the country's greenhouse gas emissions from the transportation sector.

Two types of ethanol are used as fuel. Anhydrous ethanol contains less than 1% water and it is blended with gasoline at a mandatory proportion of 27% (E27) (Casa Civil, 2015), forming the standard gasoline sold at Brazilian gas stations. This percentage is likely to increase in the coming years, since studies realized by the government have indicate the technical viability to increase this blend to 30% anhydrous ethanol, 70% gasoline (Faria & Teixeira, 2025). Hydrated ethanol, on the other hand, contains about 5% water and is used as a standalone fuel in *flex-fuel vehicles* [1]. Brazil has around 31.5 million vehicles capable of running on any combination of gasoline and ethanol (Unica, n.d.). This dual ethanol system supports the country's flexible fuel strategy and contributes to its leadership in renewable transportation fuels. Sugarcane ethanol currently accounts for approximately 41.3% of the energy consumed by light-duty vehicles in the country (Unica, n.d.).

---

[1] Flex-fuel vehicles are capable of running on either pure ethanol, gasoline, or any mix of the two

According to a study by Copersucar [2], the consumption of hydrated ethanol in Brazil has significant growth potential in the coming decade, driven by the increasing demand for flexible fuel vehicles and the strategic shift toward inexpensive and readily available solutions for decarbonizing transportation. Even though over 83% of Brazil's light vehicle fleet is already flex-fuel, more than 70% of the fleet still uses gasoline instead of ethanol. It is expected that a strong public policy support for biofuels will drive a shift in consumer preference from gasoline to ethanol, avoiding millions of tons of CO_2 emissions and generating demand for billions of additional liters of renewable fuel (Copersurcar, 2024).

In a dynamic simulation conducted by Stellantis [3], a vehicle running on ethanol (E100) emitted only 25.79 kg of CO_2eq over a 240 km route, less than half the emissions of the same car running on gasoline (E27), which emitted 60.64kg of CO_2eq, and even lower than a battery electric vehicle (BEV) charged with electricity from the European grid (30,41 kg CO_2eq) (Stellantis, 2023). These results highlight the low-carbon potential of Brazil's energy matrix and demonstrate that ethanol, when considering full well-to-wheel emissions, can outperform even some electric vehicles in emissions reduction (Stellantis, 2023).

According to Unica (2024), since the flex vehicle technology was launched in the market in Brazil in 2003, the use of ethanol has prevented the emission of 660 million tons of CO_2eq until December of 2023. With global interest in low-carbon fuels increasing, Brazil sees potential to expand its ethanol exports and use bioethanol as a decarbonization strategy both domestically and internationally. The continued development of second-generation ethanol (produced from sugarcane residues) and potential integration with carbon capture technologies, such as BECCS, could further enhance ethanol's role in a low-carbon economy.

5.1.3 Economic Numbers and Political Influence

Sugarcane stands as Brazil's leading renewable energy source, accounting for 16.8% of the national energy mix, which is equivalent to 34.2% of the country's renewable energy supply (EPE, 2024). Highlighting the sector strategic and potential contribution to the renewable energy in the country, the bagasse of sugarcane can be used to generate electricity on-site for sugar mills and other processes, however, when there is a surplus [4], the electricity can be exported to Brazil's National Interconnected System (SIN), contributing to the national energy supply. In 2024, for example, sugarcane-based cogeneration supplied 21.2 GWh of bioelectricity to the SIN (Unica, 2025). With investments in efficiency improvements, it is possible to significantly increase the amount of electricity sold to the public grid, making sugarcane more relevant in the renewable power matrix in Brazil.

Additionally, the overall gross revenue of the sugar-energy chain exceeds US$100 billion, contributing approximately 2% of Brazil's GDP (Unica, n.d.). The sector generates around 730,000 formal jobs, reaching 2.2 million jobs when indirect employment is considered (Unica, n.d.). According to the document published by Unica (n.d.), Brazil produced approximately 716.4 million tons in the 2023/2024 harvest engaging approximately 1,200 municipalities and nearly 10 million hectares of cultivated land.

---

[2] Copersucar is a large sugar and ethanol trading company headquartered in Brazil.

[3] Stellantis is one of the world's leading automobile manufacturers and mobility providers.

[4] Higher energy generated than consumed

In the 2023/2024 cycle, sugar and ethanol exports generated around US$19.8 billion, making it the third-largest agribusiness export segment in Brazil, behind soy and meat (Unica, n.d.). Only the state of São Paulo generated 12.23 billion dollars in export revenue from sugar and ethanol. Sugarcane has the second biggest crop production in Brazil, in value, only behind soybeans, and ranking first in used land (Instituto Brasileiro de Geografia e Estatística, 2023). According to the portal Nova Cana, the country has a vast industrial network supporting this sector, with 433 processing plants currently in operation (NOVACANA, 2025).

Given its economic and energy significance, the sugar-energy sector exert considerable political influence, actively engaging in lobbying efforts to shape policies favorable to the industry's growth, especially through representatives from sugarcane-producing states. Brazil's sugar-energy sector has directly influenced national energy policies, firstly through RenovaBio (*LEI Nº 13.576*, 2017), aimed at expanding biofuel usage and meeting climate goals, and the Fuels of the Future law (*LEI Nº 14.993*, 2024). Politically, this industry maintains significant representation in the national legislature through powerful agribusiness caucuses, advocating policies beneficial to the sector. For example, in 2021 there was a shortage of anhydrous ethanol, the one added in the gasoline, and the attempts of the government to reduce the mandated percentage of ethanol blended in gasoline were effectively blocked due to strong lobbying efforts from sector representatives (Feldman, 2021). That was also confirmed across several interviews, which highlighted the significant political strength of the sector and its ability to influence policy discussion in Congress. Both interviews and the desk research indicate that this influence is mobilized for technologies aligned with the existing business models. However, the interviews also suggest that the sugar-energy sector currently shows limited interest in technologies such as Biochar and ERW, with attention concentrated in BECCS and future developments of the FS project (INT-03(C.3), INT-04(C.4)).

Its role in international trade negotiations underscores its diplomatic influence, particularly within Mercosur and bilateral trade agreements (Barros & Albuquerque, 2025; Datagro, 2024). At the regional level, the sugar-energy economy drives not only employment but also infrastructure and public service improvements, shaping political landscapes in key producing regions. Lastly, by framing sugarcane ethanol as a key sustainable solution, the sector actively shapes Brazil's broader environmental and climate strategies. Rather, the priority tends to be industry growth and increased profitability, with climate benefits arising as beneficial, yet secondary, outcomes (Silva, 2018; Escobar, 2019).

The economic and political facts mentioned above highlight the relevance of the sugarcane and ethanol sector in Brazil. From which, it can also be concluded that it represents a stable regime with strong institutional embeddedness, which makes it resistant to radical innovations. Since the system already operates efficiently, there is little motivation to incorporate new technologies or processes. Modifications are usually justified when they are intended to improve existing processes. Investments, policy frameworks, and research agendas in the sector follow the same logic, prioritizing innovations that enhance production or efficiency rather than those that do not directly contribute to it, which is the case with carbon dioxide removal technologies. This means that CDR technologies have more chances of being accepted and diffused if they are evaluated for their capacity to enhance productivity, hence profitability, than for their carbon removal potential.

Following the same forces, the political influence of the sector has shaped national programs that stimulate production and develop market stability, not including carbon removal potential and possibilities. In fact, this influence is historically being directed to support fuel decarbonization. This reinforces the sector's image as low-carbon but, at the same time, narrows the space for integrating CDR technologies, since they do not fit within the established regulatory and market frameworks of the sugarcane and ethanol industry. It is important to highlight that there are new political frameworks that may include CDR, such as the future carbon market (*LEI Nº 15.042*, 2024). Nevertheless, these technologies are still not included in the policy instruments specifically designed for the sugarcane and ethanol sector.

5.1.4 Important Considerations

It is important to consider that the sugar and ethanol sectors are part of a bigger system. They are analyzed here as a regime, but one that benefits from policies originally designed to stimulate and diffuse this technology. However, they follow the same rules of the national regulatory institution for fuels (ANP), interact in the same energy markets, and rely on production and distribution technologies that are tied to the national infrastructure. Therefore, it can be considered a sub-regime embedded within a larger one, the Brazilian energy regime. Even though it is an independent sector not directly controlled by the government, it is driven by private institutions and market mechanisms while remaining historically dependent on public policies. The combination of market autonomy with state-led incentives gives the sugar-energy sector both stability and strategic importance within Brazil's energy transition.

Like fossil fuels and other energy sources, ethanol is governed by market mechanisms. That means that its price is not constant but changes according to the availability of the fuel, following the law of supply and demand. In the case of ethanol, this availability depends on crop production, which is influenced by the crop's harvest and off-season cycles, the weather, and demand. But also depends on the price of gasoline. In periods when gasoline prices drop, consumers will be more likely to choose gasoline instead of ethanol, since ethanol has around 70% of gasoline's energy efficiency, and Brazil has a large fleet of flex-fuel cars that can run on both fuels. Therefore, the price of ethanol can be considered dependent on gasoline prices. When gasoline prices drop and the demand for ethanol decreases, the price of ethanol also tends to drop. And when gasoline prices increase, ethanol prices also rise, since the demand for ethanol becomes higher. However, this dependency is not directly proportional to the price variation. According to a study carried out by the Empresa de Pesquisa Energética (EPE, 2023), only 17.3% of flex-fuel car owners always make the price calculation before fueling up, while 47.6% never make this calculation. Both fuels tend to balance each other when the price of ethanol is proportional to the autonomy difference between them, i.e., around 70%.

Ethanol is a commodity, which means that the in- and off-season of the crops also influence its price, since during the harvest season, ethanol supply is higher, and prices tend to decrease. The opposite occurs in the off-season, since supply is limited, leading prices to increase. Weather conditions are also an important factor, as they affect crop yields during the harvest. When the climate is favorable, production and supply increase, lowering ethanol prices. In contrast, in years of poor yields due to unfavorable weather, ethanol prices rise. This dynamic reinforces that ethanol follows the same rules and mechanisms that govern other technologies within the embedded energy regime. That was also highlighted in the interview with a sector incumbent, because ethanol and sugar are commodities, there is limited margin to increase the product price due to innovations (INT-03 (C.3)).

Another common view across several of the interviews concerned the role of CDR technologies in the decarbonization strategies of the sector. For most interviewees, carbon dioxide removal was recognized as important for decarbonization, but it should not be assumed as the primary decarbonization effort. The priority is to mitigate emissions throughout the production process before considering CO_2 removal. Interviewees emphasized in fuel substitution, efficiency improvements, and costs reductions as the priorities in decarbonization (INT-04(C.4), INT-05(C.5), INT-06(C.6)). Regarding the sugar-energy sector, it was highlighted that reducing production costs would indirectly lead to emissions reductions, since the highest costs are associated with fertilizer use and soil conditioning. Optimizing these inputs improves economic performance but also lowers the carbon footprint of the product (INT-03(C.3)). It is important that these perspectives suggest that CDR technologies are not viewed as a justification for continued emissions, but as a complementary option to be considered once primary mitigation measures have already been addressed.

5.2 Stakeholders Analysis

This section aims to design a simplified version of the stakeholders involved in the development of Brazilian CDR technologies. They have been separated into 6 categories: Government & Policy Actors, Investors, Industry Incumbents, Civil Society, Knowledge & Research, and Niche Innovators. This classification was based in the Multi-Level Perspective, and the categories chosen represent actors in each level of the framework. Government & Policy represents the institutional and regulatory environment shaping the system belonging to the social-technical landscape. Industry Incumbents are the companies already established in the social-technological regime, while as the name suggests, Niche Innovators refers to actors working at the niche level. In this map, it is chosen to also have a category for niche actors, even though they are usually centered in the map. This decision was chosen because CDR is the object of the analysis, not an actor. To encompass the actors that are actively developing, testing, and operating CDR, the classification of Niche Innovators was added. In the Knowledge & Research category, there might be actors from all three levels of the MLP. It supports niche, regime, and landscape development and modifications. Civil Society, represents the socio-technical landscape in the form of societal pressure and legitimacy, while investors are important actors at the regime and niche level, with the power to influence the technologies that can scale.

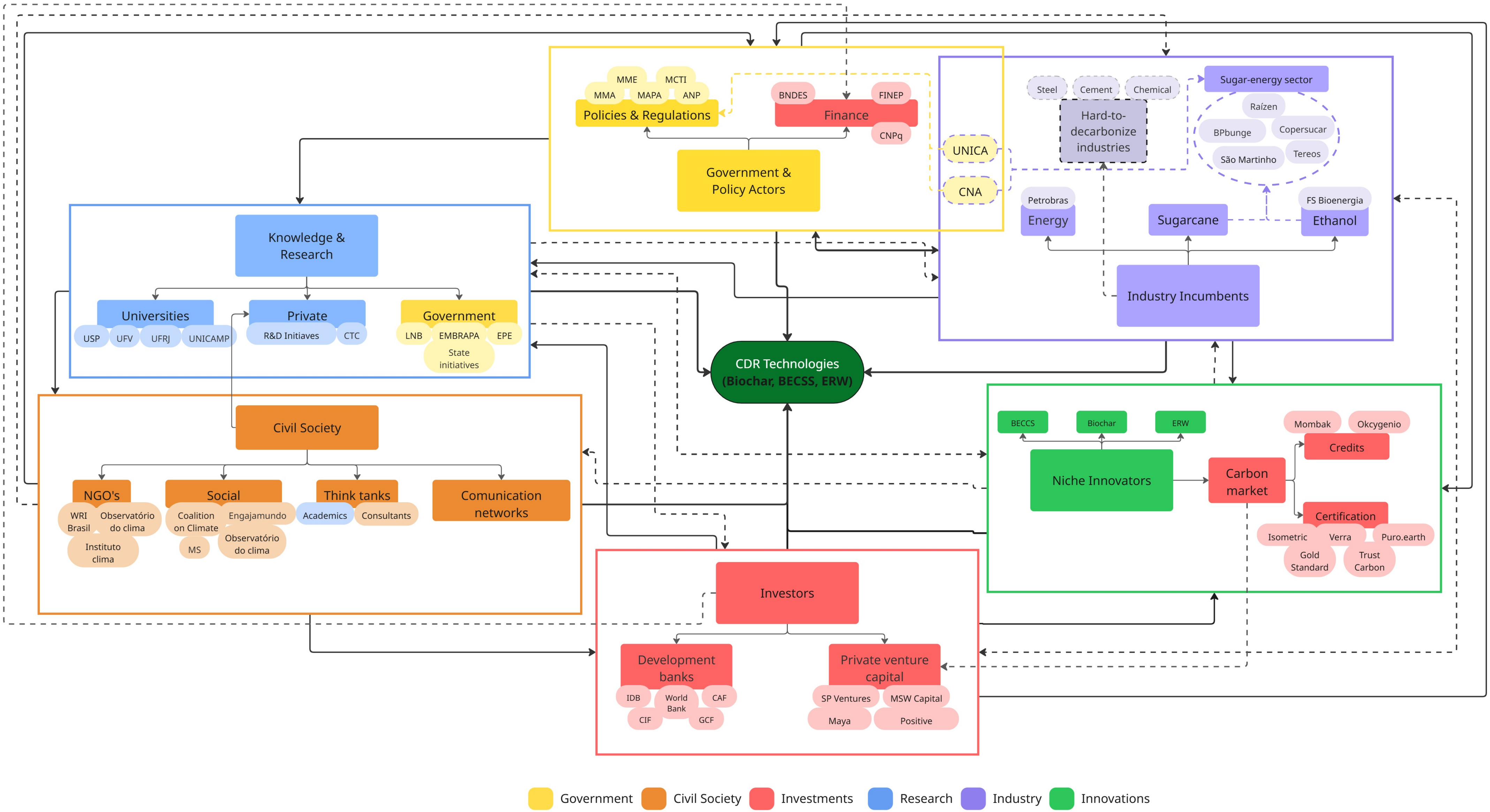


Figure 5.1: Stakeholder Map for CDR Technologies in Brazil

The Figure 5.1 highlights some of the most important relations between the stakeholders through arrows. The straight lines represent stronger and more direct influence, while the dashed lines represent weaker, though relevant connections. The direction of the arrows shows which group is exerting influence over another; however, in some cases, this influence is mutual. Most of the stakeholders are interconnected in other ways, but only the formal and most relevant connections are highlighted in this chapter for clarity of the analysis. The following sections give more detail on the different categories of stakeholders shown in the diagram and how they relate to each other. At the end of the section, it is possible to see a Power x Interest matrix that further studies the relations of these stakeholders with CDR technologies.

5.2.1 Government and Policies

This category refers to the public institutions that have national energy, climate, and agricultural strategies under their scope and control. These actors are responsible for regulating the sugar-energy-related guidelines, targets, and policies. They manage financial and research instruments that will enable or constrain innovation. Together, these governmental and policy actors shape the institutional conditions under which CDR technologies can emerge. Their priorities determine not only access to funding and regulatory incentives but also the legitimacy for diffusion of carbon removal within existing energy and agricultural frameworks.

The key ministries and agencies responsible for regulation and policies are the Ministry of Mines and Energy (MME), the Ministry of Environment and Climate Change (MMA), Ministry of Agriculture (MAPA), the Ministry of Science, Technology and Innovation (MCTI), and the National Petroleum Agency (ANP). The ministries' jurisdictions are literal as their names, and since they are related to CDR in all its different aspects, that can cause a lack of sync. Given that they work independently from each other, coordination challenges may be an issue. ANP is the government agency responsible for regulating petroleum and natural gas, but CCS regulations also fall under its control, which is important for BECCS.

Regarding investments in new technologies, there are some public institutions that play an important role. BNDES is the national development bank, a public bank with tools that enable financial help for innovation (BNDES, 2025). Finep is another public agency dedicated only for technological innovation and research funding. It aims to stimulate and strengthen the economic, technological, and social development through different financial programs (Finep, 2025). CNPq, on the other hand, is a program from the Ministry of Science, Technology, and Innovation that funds scholarships, research, and academic development (MCTI, 2025).

Regarding the Research branch, there are two government intitutions focused on producing knowledge and research that backs up new regulations and policies. They are Emprapa and EPE. EPE is the Energy Research Company, and it is responsible for energy modeling and long-term planning while researching the Brazilian profile and new technologies (EPE, 2025). Embrapa connects agricultural research to climate mitigation and soil management, also conducting research and managing policies (Embrapa, n.d.). Both institutions are an important backbone for the ministries to where to direct their attention, managing regulations and policies, adding new, or finalizing old-fashioned ones.

UNICA and CNA are sectoral associations that represent sugar-ethanol companies. They occupy both positions between policy and the industry. CNA is the Agriculture and Livestock Confederation, which represents the rural products in the congress (CNA, 2025). It is not part of the government, but it is an active participant in the discussion of policies and new guidelines, advocating for the needs of producers. UNICA is the Sugarcane Industry and Bioenergy Union. It is the representative for the main producers of sugar, ethanol, and bioelectricity of the center-south of Brazil, which is the region where the sugarcane plantations are clustered. Its goal is to promote the development of integrated food security and bioenergy solutions for Brazil (Unica, 2025).

From the MLP perspective, Government & Policies belong to the Socio-technical landscape, as explained in section 2.2.1. This means that macro-level dynamics, e.g. political arrangements, cultural shifts, policy frameworks, and international pressure, create a set of rules that guide the behavior of actors in the system. This category has direct relations with Knowledge & Research, Industry Incumbents, and Niche Innovators. It is also subject to pressures from incumbent firms already established in the regime, from Civil Society actors, which can influence political agendas and regulatory priorities and from Investors, which can influence policies and regulations through partnerships and co-financing projects. At the same time, Government & Policy actors exert influence on Industry Incumbents and Niche Innovators, as policy frameworks and regulatory mechanisms directly shape their opportunities and constraints. They also affect the direction of knowledge & Research production, since funding and institutional guidelines influence which technological pathways receive support. Figure 5.2 shows the government & policy actors connection with the other categoriess actors.

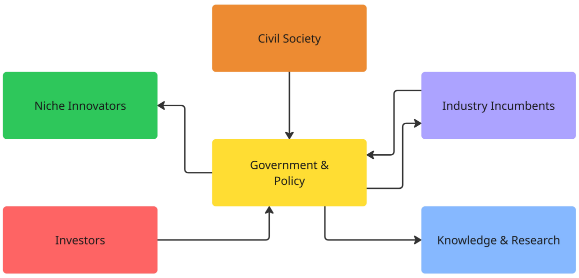


Figure 5.2: Influence Diagram - Government & Policy Actors

5.2.2 Industry Incumbents

This group includes big established firms and industrial associations within the sugar-energy and energy systems. These actors hold technical, financial, and political influence, being able to shape how emerging technologies may be integrated into production chains. Most of them are part of the socio-technical regime, with the exception of UNICA and CNA, which act more as representative and lobbying associations. They control the largest share of the Brazilian market related to their system, which gives them a central role in influencing technological pathway developments. Their position in the regime makes them important parts of the system, with the power to choose which innovations gain support and scale. They are relevant actors in the future of BECCS, biochar, and ERW, since their investment priorities and partnerships can help drive these technologies forward. As also discussed in the section 2.2.1, industry incumbents maintain strong ties with governmental institutions and financial agencies, having the power to influence policy design through lobbying and participation in advisory committees. At the same time, they might also have relations with niche innovators through R&D collaborations, pilot projects, and carbon credit agreements, contribuiting to the diffusion of CDR technologies. Incumbents do not fully determine technological pathways, but their strategies and investment decisions have significant power in shaping novel technologies moving beyond the niche level and being diffused into the mainstream sugar-energy regime.

As it was included in the Government & Policies group, UNICA and CNA are also part of the Industry Incumbents since they advocate for the sugar-energy sector interests, having also the power and influence to pass or stop new policies and lawsuits by the Congress. Sugar-ethanol companies are rarely just sugar or ethanol producers; the plants usually produce both by-products. FS Bioenery is an ethanol producer from corn, therefore it is part of the sugar-energy sector but only producing ethanol. For the sugar-energy sector, the biggest companies in the 24/25 harvest were put in the map to represent the many others that exist. In total there are 433 sugar-ethanol plants (NOVACANA, 2025), where Raízen, BP Bunge, Atvos, São Martinho and Tereos were the group with the highest production in the sector (Agroadvance, 2025). Interviews with industry representatives highlighted that large incumbent firms face structural limitations to have different products, since sugar and ethanol are highly commoditized with limited margin to have premium prices. This type of business model prioritize scale, standardization, and cost competitiveness (INT-03(C.3)). Therefore, niche products have little room to develop in large incumbent firms. This characteristic reinforces the priority of efficiency improvements over radical innovations, such as CDR technologies, which may increase production costs without generating a corresponding product price.

Energy incumbents, i.e. Petrobras, should also be included as stakeholders. Petrobras is a key fossil-based player, with CCS expertise and strong influence over national decarbonization strategies and policies. In addition, it is a public-private company while it holds an important share of the Brazilian energy market, and it is responsible for technical and knowledge development. That means it also has an important political and economic role, having the power to influence and lobby for new technologies and innovations. While hard-to-decarbonize industries also have a role in this system, they are in dashed line since they are not part of the same regime, although they can benefit from carbon credits generated by CDR technologies. It was also identified during the interviews that specially steel factories tend to have large areas of forest on their site, making biochar and ERW also a possibility for this sector (INT-04(C.4), INT-06). These industries contain significant companies, also embedded in their regime, with relevant power and influence to pressure for new technologies. Among these industries, the most critical are steel, cement, and chemicals.

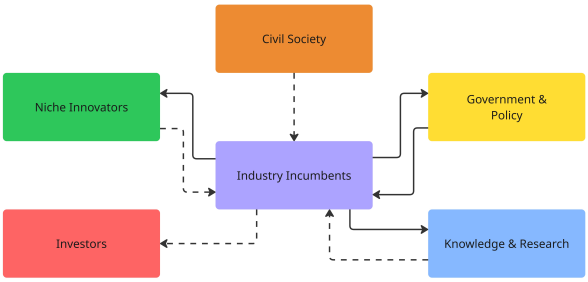


Figure 5.3: Influence Diagram - Industry Incumbents Actors

From the MLP perspective, industry incumbents are positioned at the core of the socio-technical regime and interact dynamically with other groups in the system. As previously said,Industry Incumbent firms are directly connected to Government & Policy actors through lobbying and regulatory negotiations, and to Niche Innovators through technological collaborations. However, these are not the only relations that it has. Civil Society also may shape incumbents' actions; even with limited power, companies are increasingly pressured to adopt more sustainable practices and to improve transparency in their environmental performance. This societal engagement encourage some firms to invest in low-carbon solutions and carbon markets as a way to maintain legitimacy and corporate reputation. At the same time, incumbents influence the Investment by shaping investor perceptions of risk and opportunity. They have size and visibility to attract investment flows and/or act as investors themselves in technological ventures. Incumbents also maintain connections with Knowledge & Research, they might sponsor researchers or conduct research themselves. According to the law (*LEI nº 9.478*, 1997) from ANP, oil and gas companies have to spend a percentage of their gross revenue in R&D (0.5-1%), which can be directed to new technologies as CDR alternatives. These interconnections are shown in figure 5.3, and they reinforce the incumbents' strategic position within the regime, as they mediate between societal expectations, financial dynamics, and the policy frameworks that guide innovation in the sugar-energy sector.

5.2.3 Niche Innovators

As the name suggests, niche innovators operate at the technological niche level. It is at this micro-dynamic level that experimentations, learning, and demonstration take place. One could argue that they might not appear in the stakeholders map, since they are the CDR technologies themselves, but they were included mainly for two reasons. The first is to visually demonstrate their relationship with other actors in the system. The second reason is to include in this category other niche actors that are not strictly CDR developers but are closely related to them, such as voluntary carbon markets actors. These actors have similar characteristics, including limited financial resources, uncertain regulations, low visibility, and legitimacy. They normally rely on government grants or partnership with incumbents, and lack defined standards, which is one of the main barriers for CDR. On one hand, they need credibility and certifications to sell their products, but on the other hand, they are still in early developments stages, where regulations and guidelines are not yet fully established.

The main companies currently working with CDR technologies in Brazil were already mentioned in chapter 4. Carbon markets have a larger number of initiatives, including international ones operating in Brazil. They can be divided into two main groups: credits and certifications. The credits group relates to the ones that only sell credits without participating in the certification process. The certification subcategory encompasses those involved in the certification process and MRV (measurement, reporting, and verification), some of whom also sell credits. In the first group, there are *Mombak* and *Okcygenio*. Mombak focuses on the reforestation of native vegetation and sells carbon credits (MOMBAK, 2025). Even though it does not work directly with the technologies discussed in this thesis, companies in this category could expand their portfolios to include biochar or ERW projects in the future. Their current influence remains limited, as the other niche innovators, but they are relevant stakeholders in the system. Okcygenio works with tokenized credits, functioning as a digital platform for selling certified carbon credits (Okcygenio, 2025), which is relevant for the future commercialization of biochar-, BECCS- and ERW-based credits.

Companies producingg biochar, ERW, and BECCS can also sell carbon credits, as long as their project are certified. Some of the organizations that work with carbon credit certification and MRV represented in the satakeholder map are *Trust Carbon*, *Puro.earth*, *Isometric*, *Verra*,and *Gold Standard* (Santos, 2024). InPlanet had its ERW certified by isometric (Isometric, n.d.). These companies are independent and have their own methodology for issuing certificates, without direct governmental regulation or legal enforcement. It is therefore important to highlight that they operate within the voluntary carbon market. Brazil has plans and an approved framework to apply a carbon market in the legislation, but that is not in operation yet (*LEI Nº 15.042*, 2024). For now, some companies with high emissions voluntarily purchase carbon credits to make their operations more sustainable, whether due to client pressure, corporate reputation, and/or environmental commitments.

The voluntary carbon markets are also a financial mechanism, since credible carbon credits can attract investments and partnerships, and are themselves a source of capital. The dependency of niche innovators with Government & Policy and Industry Incumbents was already explained in subsections 5.2.1 and 5.2.2. These new initiatives need funding, regulation, and literal inclusion on climate strategies, R&D cooperation, and infrastructure access in order to diffuse technologically. However ,they are also connected with Knowledge & Research, Investors, and Civil Society branches. Through egagement with research and society the new technologies gain legitimacy, while relationships with investors provide the capital needed to scale, initiate new projects, and

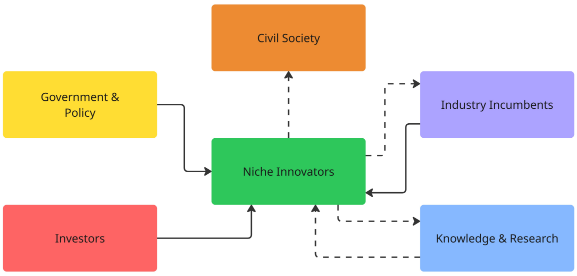


Figure 5.4: Influence Diagram - Niche Innovators Actors

enhance credibility. Niche innovators also influence research and academia through the diffusion of knowledge and practical experiences, which can be seen in figure 5.4.

5.2.4 Knowledge & Research

This category consists of universities, research centers, and technical institutes that produce scientific knowledge and technological development. It supports niche innovators and government policies with research in the development of up-to-date regulations and guidelines. It is therefore not a part of one socio-technical level of the multi-level perspective, but it is a tool for all three levels. It suggests development on the mesoscale, helping incumbent firms develop their products; it supports novel technologies and innovations on the microscale, and it also assists the macro-level in the design of policies.

Some of the organizations in this category are governmental institutions, such as LNBR, EPE, Embrapa, and some regional initiatives. EPE and Embrapa were already discussed in subsection 5.2.1. They are government institutions focusing their research on the energy and agriculture sectors, respectively. LNBR stands for Brazilian Biorenewables National Laboratory, and it is a non-profit private initiative financed by the Ministry of Science, Technology, and Innovation (LNBR, n.d.). It also aggregates a center of research in energy and materials. Some states have their own research institutes and funds. For example, the Agronomic Institute of Campinas (IAC), which is a research organization belonging to the São Paulo government (IAC, n.d.). It is an agricultural research institute where sugarcane is part of the research portfolio. Like that, other institutes and other states also have public organizations conducting studies in the field of energy, decarbonization, and agriculture. Universities can also be recognized as a part of government since the ones leading research are public, but often they have private investments in their research, which is the main reason why they are separate in the stakeholders map. USP and UNICAMP are universities in the state of São Paulo. As discussed, São Paulo is the state with the most sugarcane production in Brazil, and these universities also lead research in this field.

Private institutions also have their research centers to develop their products and improve the efficiency of their production chain. A major example is the Sugarcane Technological Center (CTC), which is a private organization focused on sugarcane. It is an R&D institution that develops sugarcane breeding programs, industrial process innovations, and biotechnological research for ethanol, sugar, and bioenergy (CTC, n.d.-b). It has as shareholders sugarcane companies, e.g., Raízen, São Martinho, Copersurcar, BP bioenergy, and Tereos, but also the Brazilian development bank (BNDES) (CTC, n.d.-a). Private R&D are also realized by the companies themselves, as well as companies with high carbon emissions, which are obligated by law to invest a percentage of their gross revenue in R&D.

Research institutions contribute to the legitimacy of emerging CDR and new technology pathways, providing independent data and technical validation. They function as

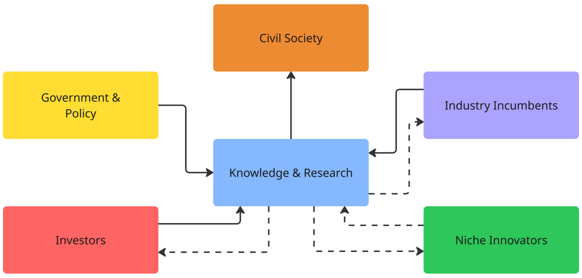


Figure 5.5: Influence Diagram - Knowledge & Research Actors

mediators between innovation and policy, and they support incumbents' technological development, playing a central role in connecting scientific knowledge with practical applications. These characteristics also position this category as playing a significant role in the discussion of the low-carbon transition in Brazil. Despite their importance, research institutions face several challenges, including dependence on public funding, independent research agendas, and limited coordination between energy and agricultural programs. The study's scope is limited since their activities are also strongly influenced by national policy priorities and funding agencies. Collaboration with industry incumbents and niche innovators is crucial for testing new technologies and facilitating knowledge transfer. Research actors' interconnections can be seen in figure 5.5.

5.2.5 Civil Society

When categorizing Civil Society, it is understood to include non-governmental organizations (NGO's), social movements, think tanks, and communication networks. They are important in shaping the discourse around climate change, sustainability, and technological innovations. They are an important part of the socio-technical landscape. These kinds of institutions advocate and fight for environmental integrity and transparency while helping monitor corporate and government actions, which contributes to legitimizing or contesting emerging CDR. The economic relevance is significantly lower than big companies and the government itself, but their pressure, when in unison, can be a bothersome resistance to government and companies' actions, at the same time that they can be an important voice advocating for ideologies and novel technologies.

There are many NGO's acting in Brazil in favor of sustainable development, fewer emissions, and fair social conditions. Some of the well-known ones are Observatório do Clima, World Resources Institute (WRI) Brasil, and Instituto Clima e Sociedade (iCS). Observatório do Clima was the first network of the Brazilian civil society acting on the climate agenda. It was formed at FGV [5] and now reunites 133 members, including environmental associations, research institutes, and social movements (Observatório do Clima, n.d.). WRI Brazil, for instance is an organization with the mission to promote sustainable development, focusing on social equity and ecosystem conservation through science-based, innovative low-carbon solutions, land use, and agriculture programs. They realize research on the topics and local projects (WRI Brasil, n.d.). iCS is a philanthropic institution that focuses on the fight against climate change (iCS, n.d.). There are many other non-governmental organizations in Brazil working in this field; the three added here are just relevant examples. As well as many social movements, i.e., Brazilian coalition on Climate, MST, Engajamundo, and also Observatório do clima. These social movements focus in diferent causes, but they all have in common the mission of social and sustainable development, and fighting climate change

Think tanks, media, and communication networks also have a role in the system. Think tanks are research organizations that generate policy-relevant analysis on political, economic, and social issues, producing reports and policy briefs (Oxford

---

[5] Fundação Getúlio Vargas- private higher education institution in Brazil

University Careers Service, 2025). It is a diverse group of people consisting of expertes and consultants, scholars and academics, policymakers, and journalists. Media and communication networks include TV shows, social media, journals, and any other means of communication. Through both these categories, noise can be made regarding climate concerns, and boycotts and protests can be organized. They have the power to engage society in issues and subjects that were not being discussed.

These organizations exert pressure on both government and industry incumbents to adopt cleaner technologies and align with Brazil's climate commitments. They also can contribute to the legitimacy of emerging CDR technologies by bridging scientific knowledge with public awareness and by supporting initiatives that combine environmental and social benefits. Although they have limited direct decision-making power, their influence on public perception and policy priorities confirms they are an important party in the development and diffusion of new technologies and climate/social regulations. By setting climate management and sustainability as a core societal expectation, civil society helps create the normative environment necessary for the diffusion of carbon removal technologies. The relation of civil society actors, can be visualized in figure 5.6. Through societal pressure and awareness, Civil Society influences not only Government & Policies and Industry Incumbents, but also direct shapes Investors' movements and has a partial influence on Niche Innovators. Knowledge & Research influences and endorses Civil Society questioning.

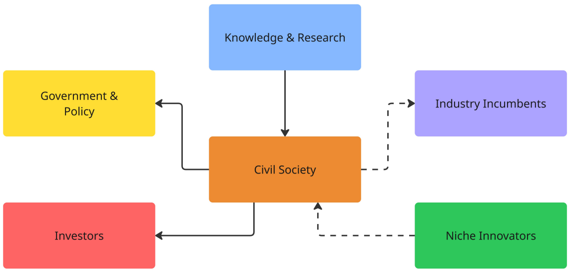


Figure 5.6: Influence Diagram - Civil Society Actors

5.2.6 Investors

The Investors category represents financial institutions, development banks, private funds and also carbon markets. It encompasses all organizations that provide capital for technological innovation and climate projects. Their role is to allocate capital, manage risks, and shape market incentives for innovation. They are influenced by global trends, such as ESG, carbon emissions, and carbon pricing. They influence both social-technical regime and niche levels by choosing which technologies or companies will receive funding and market endorsement.

Several development banks operating at regional and international levels can act as potential stakeholders in financing new technologies in Brazil. The main ones are BNDES, IDB, CAF, and the World Bank. BNDES is Brazil's national development bank, as discussed in subsection 5.2.1. However, interviews indicate that access to these concessional financing conditions is often bureaucratic and uneven (INT-07(C.7)). In practice, projects may be required to operate through intermediary financial institutions, which can significantly increase effective interest rates. Moreover, access to BNDES financing tends to favor large incumbent firms and well-connected actors with greater administrative capacity and political leverage. As a result, niche innovators remain structurally constrained, frequently relying on partnerships with incumbents or on international capital to finance new technologies.

CAF[6] and IDB[7] are regional development banks for Latin America and the Caribbean, aiming to provide financing and technical knowledge to improve development in the region. The World Bank has a similar purpose but operates globally. CIF[8] and GCF[9] are climate funds through which developed countries finance climate initiatives in developing nations (Green Climate Fund, n.d.; CIF, n.d.). Finep and CNPq, also discussed in subsection 5.2.1, are Brazilian government programs that fund and finance research and innovation projects. Private venture capital funds also play an important role in supporting new technologies and startups. The ones represented in the map are just a small example of the many that exist. Regarding carbon markets, their relation to CDR technologies was already explained in subsection 5.2.3. In short, when carbon removed from the atmosphere through CDR projects is certified and commercialized in carbon markets, it becomes an additional source of investment and an incentive for other investors, as it adds credibility and reduces uncertainty about future financial returns.

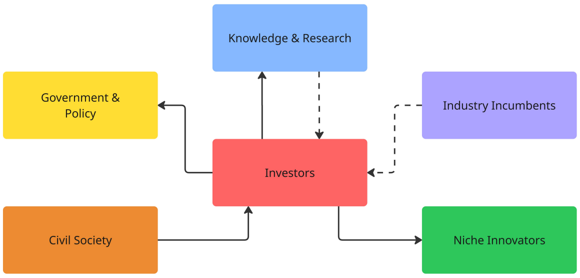


Figure 5.7: Influence Diagram - Investors Actors

Investors influence both regime and niche dynamics by determining which technologies receive financial support and by shaping the perceived risk of emerging markets like carbon removal. However, investment in CDR remains limited by regulatory uncertainty, high technological risk, and limited short-term profitability. Beyond the connection of Investors with Industry Incumbents and Niche Innovators, they also influence public funding priorities through co-financing models, partnerships, and lobbying for favorable investment conditions. In turn, Investors are increasingly influenced by Civil Society and global market trends, while it also influences Knowledge & Research by financing and funding researches as can be seen in figure 5.7. As regulatory frameworks evolve and carbon markets expand, investor engagement will be crucial for scaling up Brazil's CDR technologies and diffusing them into the sugar-ethanol social-technical regime. Investors can be considered a bridge between economic interests and sustainability goals.

5.2.7 Power x Interest Matrix

This section aims to present and explain the Power versus Interest Matrix, which is part of the analysis of the stakeholders. It can be visualized in Figure 5.8, where the reasoning behind the actors' positions in the diagram is also detailed. The grid was designed based on the relationships presented in this chapter, with actors positioned according to their power and interest within the system. However, it is important to note that this grid is not static, as changes in the landscape, niche, or regime levels can significantly shift these positions. For this analysis, the political and economic power of each actor, their current interest in the topic, and their efforts towards decarbonization were taken into consideration. The grid is divided into four quadrants according to each actor's (or set of actors) power and interest in CDR technologies. The theory

---

[6] Development Bank of Latin America
[7] Inter-American Development Bank
[8] Climate Investment Fund
[9] Green Climate Fund

behind it is better explained in subsection 2.2.1.2.

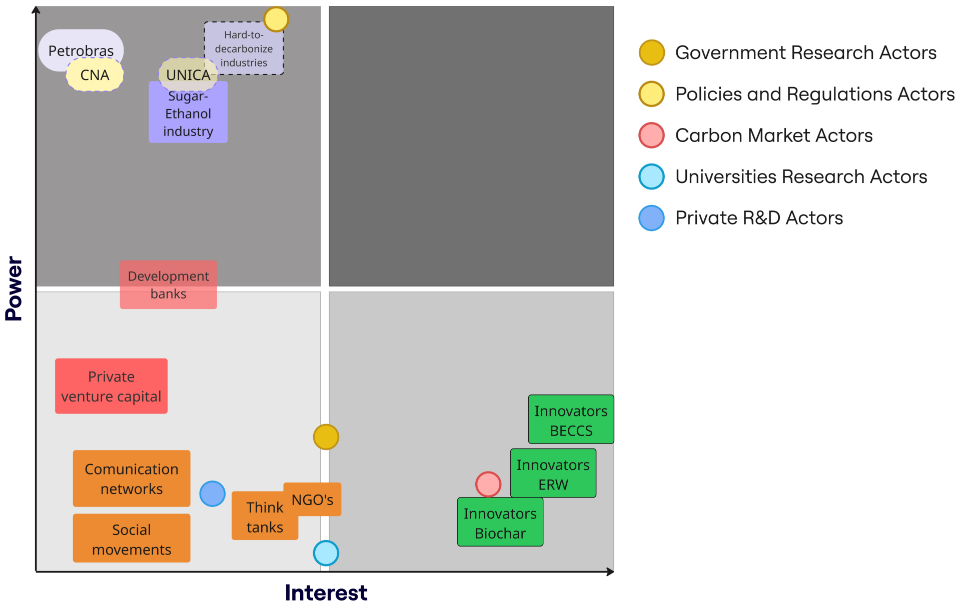


Figure 5.8: Power X Interest Grid

High Power-Low Interest:

In this quadrant, the actors with high power and low interest are positioned. Petrobras is positioned here due to its significant political and economic influence, as it is the largest oil and gas producer in Brazil and has the Brazilian government as its controlling shareholder. However, the diffusion of CDR technologies does not seem appealing to this company or similar companies in this category, since CDR technologies do not offer an increase in productivity or profitability in their operations. Unless there are changes in the socio-technical landscape in the future regarding policies and regulations, this position is unlikely to change.

In the sugar-energy sector, companies also hold strong political and economic power, as discussed in Section 5.1, but they have not yet demonstrated clear interest in the diffusion of CDR technologies. There are few, if any, projects or research initiatives idealized by actors in the sector. The only exception is FS, which is currently building a BECCS unit for its ethanol plant (Novacana, 2025a). The results and success of this project may influence the sector's perception and interest in the future, but that is not yet the case. Unica is the representative of the sugar-ethanol sector in the congress, and it holds a similar position to the sector itself, but with slightly more power due to its political influence. CNA is also a representative of the Sugarcan sector, but they also represent a broader range of agricultural activities, decreasing their interest since their focus on the topic is more limited.

Policy and regulatory actors are positioned with the highest level of power, as they design new guidelines and legal frameworks. Their interest level is higher than the previous actors because they are involved in climate regulations, the recent approval of Brazil's carbon market, and other political milestones discussed in chapter 3. Lastly, the hard-to-decarbonize industries are located more to the right than sugar-energy incumbents, mainly based on perceptions during the interviews (INT-05(C.5), INT-06(C.6)). These sectors will need to implement more stringent decarbonization requirements in the near future due to their high-emission-intensity processes and limited mitigation options. Therefore, these industries are already putting more effort into transition and decarbonization measures than the sugar-energy sector, which currently faces less immediate regulatory pressure. Like Petrobras and the sugar-ethanol sector, they have economic and market relevance, as well as representation in Congress. Their interest is higher because they could benefit from carbon credits acquired through carbon dioxide removal technologies. If these credits gain credibility and value, these actors could become key players in the system.

Low Power-Low Interest:
This quadrant shows actors with both low power and low interest. Among them are social movements, communication networks, think tanks, NGO's, private ventures, researchers, and development banks. Development banks are positioned higher in power due to their economic relevance and sustainability-oriented guidelines. Government and university research institutions occupy a middle ground between low and moderate interest, as research on CDR exists but is not yet a primary focus. The other actors have straightforward positions in the grid, given that CDR technologies are still incipient technologies and not yet widely discussed. Although interest in the topic is growing, it has not yet reached the center of public debate, which explains why most civil society actors remain in this quadrant. The interviews also revealed limited knowledge and public debate surrounding CDR technologies. Awareness of these technologies appears to be largely confined to experts and specialized actors, while broader societal understanding remains low.

Low Power-High Interest:
Actors in this quadrant are the niche innovators (5.2.3). All CDR-related actors share a high level of interest, but not equally, and they do not have the same power and influence. BECCS innovators are positioned with a slightly higher level of power and higher interest, since the company leading this initiative operates within the ethanol sector, which increases its visibility and networking capacity, and it is a technology created with the sole intention to remove CO_2 from the atmosphere. Biochar and ERW have similar levels of influence, though InPlanet, which is a startup of ERW, has additional credibility and economic strength after having its carbon credits certified by Isometric (Isometric, n.d.).

The difference in interest between the three technologies lies in the main benefit of each. Biochar is sold primarily as a soil amendment and, as a consequence, helps mitigate carbon, but it is not yet certified as a carbon removal technology, and questions remain about this feature. ERW is certified and has a methodology to calculate the amount of carbon it removes from the atmosphere. However, it still has another benefit, which is still the primary one, that is soil amendment. On the other hand, BECCS has one purpose: removing carbon from the atmosphere, which positions the actors working with this technology as having a greater interest than others. Carbon markets fall within the same range of power, but with lower interest, since their portfolios are diversified. While they are interested in expanding to new credit types, CDR technologies are not yet their core focus, and the demand for these specific types of credits is still low, which may also be linked to the low engagement of civil society.

High Power-High Interest:
This quadrant represents actors with both high power and high interest, those most capable of systemic change. If there are multiple players with high power and high interest, the likelihood of a technological innovation emerging from niche to regime increases. In this analysis, no actor has yet reached the position of key player. Some have the potential to become, but that would require changes in the regime and landscape levels. Given that CDR technologies are in an early stage of development, it is understandable that the interest in them is still limited, despite their potential for future growth and relevance.

5.3 Actors' narratives on innovation and carbon removal

The previous subsections mapped actors by their position and influence within the socio-technical system. This section explores the interviews and synthesizes how innovation and carbon removal are framed among actor groups. These interviews help understand how priorities are constructed, responsibilities are allocated, and CDR technologies are positioned within broader decarbonization strategies. The interviews' summaries are displayed in Appendix C.

Across interviews, innovation was mainly described as incremental and profit-oriented. For industry actors, innovation tends to mean improving efficiency, reducing cost, and optimizing existing processes, rather than introducing new production models and inputs. This view was not limited to the sugar-energy sector, but was also shared by practitioners from other energy-intensive industries. In these contexts, decarbonization is largely approached through measures that fit within established operations, such as gradual fuel switching or process improvements. In some companies, the circular economy could also be included as an established operation. Technologies that do not clearly contribute to operational performance or short-term competitiveness struggle to gain attention and be prioritized inside the companies. In the case of carbon removal technologies, they were not totally dismissed, but they were also not seen as an immediate priority. Instead, interviewees across different sectors described CDR as something that might become relevant later, once emissions reduction efforts have been developed or become more expensive than applying CDR technologies in the process. Many actors expressed the view that "doing the homework" of reducing emissions within their own processes should come first, with carbon removal considered only as a complementary option in the future. This way of thinking places CDR outside core investment decisions, even when its long-term importance for climate targets is acknowledged.

Another theme that was mentioned in some of the interviews was that the engagement with CDR technologies (and innovations) is conditional on external factors outside of the actors' control. Such as clearer regulation, higher and more stable carbon prices, or stronger market demand for low-carbon products. The responsibility for advancing CDR was frequently shifted between actors: some actors emphasized the role of government frameworks and incentives, while others highlighted the importance of private investment and market mechanisms. That results in CDR technologies having increasing attention from the market but remaining cautious when investing or making commitments to their resources and processes. The Economic factor strongly shapes how CDR technologies and innovations are developed. Interviewees stresses that decarbonization measures must make economic sense, particularly in sectors where products such as sugar and ethanol are highly commoditized, and profit margins are tight. Capital-intensive options like BECCS were often described as technically promising but financially difficult, especially under current policy and market conditions. Although carbon markets were seen as potentially supportive, many interviewees also doubted that existing or emerging markets would generate prices high enough to justify large investments in carbon removal on their own, especially for BEECS operations where carbon credit prices are high.

Differences in the three CDR technologies were also clear during the interviews. In most of the interviews, BECCS was seen as the option with the greatest potential to deliver large emissions impacts, but also as the most complex and risky, with high capital investment needed. Other challenges were the lack of regulatory clarity and the necessity of expertise outside the traditional competencies of the sugar-energy sector. Biochar and enhanced rock weathering were described as easier to integrate into agricultural practices, but more dependent on demonstrating concrete co-benefits, such as improvements in soil quality or productivity. Moreover, it was perceived that changing inputs from normal processes, in large-scale incumbent firms, is operationally not simple and may face regime resistance. In this context, carbon removal tends to be valued not only for its climate contribution but also for its ability to align with existing business logics and deliver additional and efficiency benefits.

5.4 Main Takeaways

The results of this chapter indicate that the sugar-energy sector constitutes a highly stable and influential socio-technical regime within Brazil's energy system, owing to its strong economic importance, broad territorial presence, potential for expansion, and political representation. The regime benefits from public programs and regulatory frameworks, such as Proálcool and RenovaBio, while maintaining market autonomy by allowing private investment and competition. However, this same structure also makes the system resistant to radical innovations by creating technological and institutional lock-ins. Innovation within the regime is considered if gradual and if aimed at making the system more efficient, with productivity and profitability increase rather than transforming it structurally. The probability of carbon dioxide removal technologies being incorporated in the regime is higher when they fit within existing production systems or make the sector more environmentally friendly while increasing profit, rather than when they require big changes in the institutions or infrastructure.

The stakeholder analysis makes it easier to understand where the key actors fit within the socio-technical system and how they interact and influence one another. Niche Innovators are part of the technological niche level, as the name suggests, and they work by experimenting with new ideas and technologies related to CDR. Government & Policy actors and Civil Society are positioned at the landscape level, where broader rules and pressures that influence the regime are shaped. The Industry Incumbents form the regime's core, representing the embedded firms and the structural lock-ins they maintain. Investors and Knowledge & Research institutions work at both the regime and niche levels, although investors have a bigger impact on the niche because their funding decisions directly affect the diffusion of new technologies, and Knowledge & Research also form connections at the landscape level. It is clear that some players have broader and more direct power over other players, but the decision of one set of actors, or the shift in a system variable, can change the perception and actions of all other actors, since they are all interconnected.

The Power–Interest Matrix highlights an imbalance between the power actors have and their level of involvement in CDR development. Most powerful actors, such as policymakers, Petrobras, and large sugar-energy companies, still show limited interest in supporting or promoting CDR technologies. Research institutions play an essential role in creating new knowledge, yet show moderate interest, whereas niche innovators are the most involved but continue to face power and funding constraints. Regime actors retain decision-making power within the sector, but currently do not prioritize CDR technologies, while niche actors show strong interest in these technologies, yet remain constrained by limited power and influence. This setup indicates that the progress of CDR technologies depends heavily on external drivers (or potential windows of opportunity), such as regulatory change, market incentives, and public awareness. If visibility and societal engagement increase, the balance of interest and power among stakeholders could shift, creating a more favorable environment for CDR development in Brazil.

The interview narratives help explain why carbon removal remains a secondary strategy in the sugar-energy sector. CDR technologies do not face direct opposition, but are weakened by regime practices that prioritize efficiency and condition engagement on external developments. The interviews show that regime stability is maintained not only through formal rules and market structures, but also through shared interpretations of what counts as feasible and necessary in the present, or in the short-term.

Chapter 6

Discussion: Cross-Level Dynamics Shaping CDR Technologies Diffusion

The chapters above examined the niche, regime, and landscape levels, focusing on their structure, main characteristics, and dynamics from a multi-level perspective. This chapter connects these three levels, focusing on how they interact and shape the diffusion of the CDR technologies in Brazil's sugar energy sector. The intention is to deepen the analysis of cross-level dynamics. This chapter explores *barriers*, *internal drivers*, and *window of opportunities*, which are important elements that influence technology diffusion as cited in Geels (2006). This is important to connect the levels and understand how they interplay. Through the research, it was identified that the barriers play a more prominent role than potential internal drivers and windows of opportunities; hence, the chapter is structured by first discussing the main barriers identified across niche, regime, and landscape levels. It then examines potential internal drivers and windows of opportunity that could support future diffusion. The third subsection synthesizes these findings by explicitly discussing how interactions across socio-technical levels shape current constraints and future possibilities for CDR technologies in the sugar-energy sector. After, the chapter discusses the implications of the diffusion of CDR technologies. Lastly, the chapter shows a reflection on the study and the scientific contributions of this thesis.

The information in this chapter is based on the empirical findings made throughout this study, with the research and the interviews with actors. Barriers are factors that constrain or slow down the diffusion of technologies from the niche to the regime level. On the other hand, internal drivers and a window of opportunity represent potential forces that could push CDR technologies toward wider adoption. According to the MLP framework (Geels, 2006), internal drivers emerge from modifications and development, such as performance improvements, learning processes, or actors' alignment. A window of opportunity emerges from changes at the regime and landscape levels, such as policy changes, market reconfiguration, cultural shifts, or other external pressures, that open space for niche innovations. As discussed in Section 2.2.1, internal drivers and windows of opportunity are elements within the third phase of technology development, when technologies are diffusing in the established regime. However, the three CDR technologies analyzed in this thesis (BECCS, biochar, and ERW) are still in the second phase of development. As a result, there are no clear internal drivers or concrete windows of opportunity. Nevertheless, this chapter identifies emerging dynamics that could potentially act as future drivers or opportunities, helping to understand how diffusion pathways could manifest.

6.1 Barriers

Through the research and interviews, some barriers were identified for the CDR technologies studied. One aspect that stood out, especially during the interviews, is that the actors do not perceive the three technologies as competing for market space (INT-01(C.1), INT-02(C.2)). The niche actors mentioned the ”infinite” availability of the market for these technologies and other innovations to come. The demand would be bigger than the offer for some time to come, and it was noted that the development of one CDR technology can mean the development of the others as well. However, despite this shared optimism, niche actors do not appear to be in close communication or actively joining forces. It was concluded by the interviews that actors tend to operate in parallel and not collaboratively, with limited coordination or collective strategies. This fragmentation represents a potential barrier to the diffusion of CDR technologies, or at least makes the process longer and slower, weakening the niche's capacity to influence regime actors and policy development.

Another barrier highlighted by INT-03, representing the sugar-energy sector, was related to market structures and cost considerations. It is particularly difficult for large companies to adopt tailor-made, higher-cost solutions in a context where sugarcane and ethanol are highly commoditized products. For larger firms, it is economically unattractive to produce differentiated, low-carbon products with higher costs. The interviewee mentioned that some clients express interest in lower-carbon products, but they do not specify how much more they would be willing to pay for these products (INT-03(C.3)). Having this in mind, the priority is to aim for cost reduction in production, which would indirectly reduce emissions through high productivity or reduced use of lime and fertilizer. In fact, several interviewees mentioned that before considering CDR technologies, the priority is to reduce emissions within their own production chains (INT-03(C.3), INT-04(C.4), INT-06(C.6)). CDR technologies are generally viewed as a solution of last resort, to be adopted only when there are no cheaper mitigation options available. Therefore, the lack of government support and insufficient economic incentives are also common barriers for all three technologies. One interviewee (INT-03(C.3)) mentioned the difficulty of investing in innovations in Brazil due to high import taxes on specialized machinery. The machinery is essential for the deployment of new technologies and is often not produced domestically.

In the case of BECCS, the main barrier is the storage availability. Although this is not an issue for the FS project, not all sugar-energy plants are located near geologically suitable CO_2 storage sites. Long distances increase capital and operational costs, limiting broad application. On that subject, the geological knowledge also represents a technical barrier, since historically, subsurface storage expertise has been developed within the oil and gas sector, and sugar-energy companies often lack this knowledge. That means BECCS projects rely on partnerships with oil and gas actors, increasing the project complexity and costs. Regulatory uncertainty further reinforces these challenges. Although the National Agency of Petroleum, Natural Gas and Biofuels has been assigned responsibility for CCS regulation, an interviewee noted that the regulatory framework is still under development, which highlights the need for close interaction between niche actors, regulators, and policymakers (INT-02(C.2)). Moreover, the integration of BECCS requires significant modifications to existing production processes, which increases project complexity and reduces acceptance. As mentioned in the interviews, most actors are risk-averse and are only willing to invest in BECCS once they have a clear workflow and the project's technical feasibility and profitability are clear (INT-02(C.2), INT-03(C.3), INT-04(C.4)). In this sense, the outcomes of the FS BECCS project may act either as a driver or a barrier for the technology diffusion.

In addition, two interviewees raised concerns regarding the potential price levels in a future regulated carbon market in Brazil. According to these interviewees, the incorporation of existing voluntary carbon markets into the regulated system may limit carbon prices, preventing them from reaching levels high enough to adequately monetize CDR technologies (INT-02(C.2), INT-04(C.4)). This was seen as particularly problematic for BECCS, which already faces difficulties in voluntary markets due to the relatively high cost of its carbon credits. Interviewees noted that companies often allocate their carbon budgets across cheaper mitigation or removal options, such as forestry and

REDD+, rather than concentrating resources on fewer, higher-cost credits, even when these represent higher-quality and more durable carbon removals (INT-04(C.4)). As a result, there are high possibilities that BECCS may remain economically unattractive under both voluntary and regulated market structures if price signals do not reflect removal quality and permanence, with carbon prices remaining low. However, these are still speculations since the Brazilian regulated carbon market is still being designed, and there are latent uncertainties surrounding it.

Biochar is seen as the most promising technology in the short term, but the barriers are also significant. While biochar is easier to operate than BECCS and does not require modifications to existing processes in the sugar-energy sector, scaling up production for large plants is still a challenge. One interviewee mentioned difficulties finding a pyrolysis reactor for their operations, implying there was no infrastructure in the market, even though the technology is simple and ancient (INT-03INT-04(C.3)). That is a significant barrier for large companies. Another technical barrier relates to MRV and certification methodologies, which are not consistent across all projects. As a result, the carbon removal function of biochar is not yet a main feature of the technology, limiting its potential to be marketed explicitly as a CDR technology. The acceptance and acknowledgement of the technology by farmers also represents a relevant barrier. Although biochar is well known by industry actors, it is not yet a widespread common sense. Changing plantation inputs requires long-term engagement and trust-building with farmers, who tend to rely on practices they already know to be effective. It was emphasized in the interviews that Brazilian agriculture is demand-driven, and the farmers tend to resist changes in plantation inputs and remain with the ones already known to work (INT-07(C.7)). Moreover, climate concerns are not a primary priority for producers. Similar dynamics apply to ERW, but it is easier to convince them about biochar, as an organic matter, than the application of rock-based materials, which remains a more abstract concept.

In the case of enhanced rock weathering, an additional barrier relates to misconceptions resulting from past experiences. According to an actor in the field (INT-01(C.1)), some years ago, a product marketed as ”rock dust” was introduced in the market; conceptually, it should work similarly to ERW, but mining companies were primarily worried with disposing of residues and monetizing them. As a result, the product was not adequately milled and processed, and the promised agronomic benefits did not take place. That happened because the weathering process was not accelerated due to the size and diameter of the rocks. Nowadays, this persists in the industry and continues to influence perceptions among farmers. The actors in the sector are well connected and actively share information, which can be a barrier or a driver, and negative experiences spread quickly. Since then, the Ministry of Agriculture (MAPA) has certified mining companies authorized to commercialize ERW materials that meet technical parameters, which will accelerate weathering and improve soil quality. Beyond the acceptance challenges, ERW also faces logistical and technical barriers. Even though the material utilizes residues that would once go to waste, the production process to get rocks to a sufficiently small particle size is energy-intensive, which needs to be accounted for in the costs and emissions. Moreover, another issue is the transport and distribution of large volumes of the final material. Depending on the distance from mining sites to the plants, transport costs and emissions may not be economically and environmentally viable option. Therefore, in the BECCS case, the plant’s location is an important factor when considering enhanced rock weathering.

6.1.1 Enabling factor

The analysis of the barriers highlights that barriers are still strong forces preventing the technologies from developing and diffusing into the regime level. However, together with these barriers, it is possible to identify emerging factors that could potentially function as internal drivers and windows of opportunity for the CDR technologies. These are

Barriers	MLP level	Potential internal driver/ window of opportunity
Lack of coordination among niche actors	Niche	**Collective platforms, joint advocacy, shared projects**
Low willingness to pay for CDR	Regime	Regulated carbon market with quality-based pricing
Insufficient government support and economic incentives	Landscape	**Integration of CDR into existing policy instruments**
Uncertain carbon market price signals	Regime-landscape	**Regulated carbon market with price signals that support CDR viability**
BECCS high costs and uncertainty	Regime	**Economical and technical success of the FS BECCS project**
Regulatory uncertainty for CCS and BECCS	Landscape	ANP standardizes CCS regulations in Brazil
Lack of standardized MRV and certification for biochar	Niche	Issue of carbon credit certification for biochar
Farmer resistance to ERW and biochar	Regime	**Extend services, agronomic trials, proof of effectiveness by EMBRAPA**

Table 6.1: Main barriers and potential enabling factors

dynamics that indicate conditions under which CDR technologies could gain traction if the key constraints were addressed. These enabling factors could be named *potential internal drivers* and potential *windows of opportunity*, as the technologies are not in the third phase of development yet. Table 6.1 summarizes the main barriers and their relationship to potential enabling developments across socio-technological levels. The factors in bold letters in the ”Potential internal driver/window of opportunity” column represent the enabling dynamics with particularly strong potential to influence innovation diffusion, based on the empirical material in the thesis.

6.2 Interplay Between Socio-Technical Levels

Through this study, it was identified that the socio-technical levels are connected, forces and dominant structures in the regime are essential dynamics in the diffusion of innovative CDR technologies in Brazil's sugar-energy sector, where actors play a central role.The technological options that receive attention, resources, and political support are influenced by how incumbent actors exercise power within it and the regime structure. Incumbent actors keep close communication with policymakers and are well-positioned to influence advocacy and regulatory agendas. However, policymakers are one group of actors with limited influence to reshape regime structures or the broader landscape dynamics. They are able to introduce new policies and investment frameworks, which is an important factor from a niche perspective, but financial dependencies further reinforce these cross-level dynamics.

CDR technologies innovators often depend on large incumbents or international investors to access capital and scale their operations. Partnerships like that can enable pilot projects and early experimentation, but they also constrain the strategic autonomy of niche actors. Through that structure, novel CDR innovations are limited in their scaling capacity, and niches lose forces to challenge dominant rules, maintaining existing power asymmetries in the regime. As a result, weak niche pressure contributes further to regime stability, slowing deeper socio-technical change. Therefore, CDR niche innovations require more than access to financing, in fact, they need a genuine strategic commitment from regime actors. There is a clear difference between partnerships that support pilot projects and those that reflect a willingness to integrate these technologies into existing production processes. It is when incumbents move to actual adoption of the technology that regime actors can influence diffusion. Based on the material, such a shift still appears distant.

The interactions between niche, regime, and landscape levels also determine how political attention within the sector is selective. Enhanced rock weathering and biochar are not yet receiving much attention from regime actors, even though they have technical potential. This narrow engagement results in weak political support, constraining their visibility in political debates and regulatory agendas, keeping the technologies confined to niche operations. In contrast, BECCS attracts more attention, with lobbying efforts due to its alignment with incumbent interests. Even though the BECCS project still needs to prove effective when operational, big sugar-energy companies are considering it as a future possibility. But also, oil and gas companies have interest on more projects containing CCS technology. With this power strategy, the socio-technical regime level minimizes disruption to established production structures. Consequently, changes within the regime remain selective instead of transformative. Despite the increasing decarbonization pressures at the landscape level, this selective dynamic contributes to the stabilization of socio-technical configurations in the regime.

Moreover, the sugar and ethanol being commodities also reinforces regime stability, as the sector operates under small margins and price competition. The focus is on cost-minimization strategies that discourage risky investments. The way the sugar-energy sector perceives its environmental performance also shapes cross-level dynamics. The sector not only benefits from an associated ”green” image, but it also understands itself as such. Especially with regard to the role of ethanol and electric energy from sugarcane bagasse in Brazil’s long-standing energy transition narrative. This self-perception reduces the perceived urgency for further decarbonization efforts, reinforcing the view that current practices are already sufficient. Furthermore, this image has historically been driven by economic development goals rather than by environmental or sustainability considerations. Therefore, economic performance remains the primary priority, while decarbonization measures alone are often seen as secondary, even though there is room for deeper emission reductions and carbon removal within the sector. The agricultural sector is also not expected to be included in the future Brazilian regulated carbon market, which further weakens the sense of responsibility to contribute to decarbonization efforts. While Brazil’s climate commitments are ambitious, sustainability and decarbonization are not yet central organizing principles for the sugar-energy regime.

These dynamics help explain why stronger regulatory or international pressures may be necessary to shift current trajectories. As Brazil seeks to expand ethanol exports, international demand for low-carbon fuels could create new pressures and opportunities, and more sustainable production processes may enhance competitiveness. It was mentioned that reducing fertilizer and soil-conditioning costs is an effective way to lower emissions, where biochar, or ERW, could substitute conventional inputs, but they are not yet perceived as such by regime incumbents. Regime-level market structures favor technologies that require minimal changes to existing production systems, creating a selective environment for innovation. These cross-level interactions help explain why CDR technologies remain marginal, despite their technical potential and alignment with broader decarbonization goals.

6.3 Implications for the Diffusion of CDR Technologies in the Sugar-Energy Sector

Up to this point, this thesis examined the conditions shaping the diffusion of CDR technologies within the sugar-energy regime. However, this analysis rises a central question: should these technologies be diffused? This is not a simple nor a direct question, and it does not allow for a yes-or-no answer. It is more a question of understanding how, where, and for what purpose they would diffuse. As demonstrated through the analysis, diffusion is conditional and can be assessed from different perspectives.

From the climate mitigation perspective, all three technologies can offer strategic relevance to the sector. BECCS, biochar, and ERW are compatible with hard-to-abate emissions, net-zero and net-negative scenarios, and they are land-based mitigation in an economy highly dependent on bioenergy systems. However, this relevance can be argued to be sector-specific and not necessarily universal, and in this thesis, their potential contribution must be assessed in relation to the characteristics and challenges of the sugar-energy sector itself. Beyond climate mitigation, these technologies may offer additional contributions that deserve further attention and research, especially in relation to the substitution or reduction of agricultural inputs. Fertilizers, soil conditioners, and agricultural lime are essential inputs in agriculture, but they contribute to GHG emissions, and in Brazil, they are imported and can be costly. ERW has the potential to partially substitute agricultural lime, and biochar contributes to soil conditioning, nutrient retention, and reduced fertilizer demand. These benefits may align with existing sectoral challenges, to reduce production costs and emission reductions. The quantitative comparison of these solutions needs to be further investigated, but if these benefits are proven to be economically feasible, ERW and biochar would not need to rely exclusively on carbon markets to justify their integration in the sector's chain of production. Moreover, they also align with production narratives in the sector, such as the use of nature-based solutions and potential efficiency gains. This way, CDR becomes justifiable when carbon removal is a co-benefit but not the sole value proposition.

Another argument for the diffusion of CDR technologies, such as biochar, is the potential to create new uses for existing residues in the sugar-energy sector. Producing biochar from surplus bagasse can generate additional income and offer an alternative option for plants that are losing energy contracts in the near future. This allows value to remain within the sector and provides firms with more flexibility to deal with uncertainty in future market and policy conditions. Regarding environmental concerns, many of the potential negative impacts are more closely linked to the structural characteristics of the sugar-energy sector than to the technologies themselves. Issues such as land-use dynamics, resource intensity, and power concentration predate CDR and may persist if these technologies are introduced without appropriate governance frameworks. From a strategic perspective, even if the technologies are not economically attractive under current market conditions, early experimentation allows for learning, and organizational readiness. Therefore, engagement with CDR technologies creates options for firms and policymakers to deal with future regulatory, market, and climate-policy changes. For this to occur, technologies must be sufficiently understood and tested to be ready later if scale and economic value are proven under future conditions.

Nevertheless, diffusion is not automatically desirable. Risks and barriers need to be taken into account and balanced out against their benefits. Economic and market-related uncertainties are a significant constraint. If the value of CDR technologies is primarily based on carbon removal, current carbon credit prices are still volatile and insufficient to support large-scale deployment, and even in the future, if CDR becomes standard practice, credits will lose further scarcity value, and revenue expectations also may collapse, as happened with wind and solar energy carbon credits. Moreover, diffusion raises concerns if it crowds out alternative mitigation pathways or if it is used as a legitimacy mechanism without bigger structural change, therefore reinforcing incumbent dominance.

In conclusion, this thesis does not argue for unconditional diffusion of BECCS, biochar, or ERW in Brazil, but suggests that diffusion and development of these technologies may be justified under specific conditions. Such as when they deliver co-benefits to the sector, contribute to broader sustainability goals, and are embedded within wider governance and structural reforms. CDR technologies are not a stand-alone climate solution. They can complement other climate mitigation strategies, but they cannot substitute for emissions reductions nor justify the continuation of high-emission practices in other sectors.

6.4 Reflections

This section reflects on the study's scope and implications related to niche innovations and the sugar-energy regime. While the sugar-energy sector is pictured as a strategic element of Brazil's low-carbon energy transition, it is important to recognize that it is also associated with socio-environmental controversies. The sector includes actors with rooted practices, expressed mainly in organizational and cultural patterns that privilege continuity over experimentation. Among smaller producers, production decisions are often embedded in family-based entrepreneurship, conservative decision-making, and strong dependence on demand-driven structures. These characteristics tend to favor proven practices and low-risk investments, thereby reducing the attractiveness of engaging with novel and uncertain technologies. Similar to other agricultural sectors in Brazil, the sugar-energy sector also faces concerns related to deforestation, land-use competition, water use, labor conditions, and pollution that cannot be ignored.

The potential expansion of the sugar-energy sector raises legitimate concerns regarding land-use competition and deforestation, it is difficult to make a direct connection, but these concerns emphasize the need for effective regulation and monitoring, especially in Brazil with the vast territory it has. Zoning studies discussed in Section 5.1 indicate that land availability for sugarcane cultivation remains significant, and therefore, currently, food production does not compete with energy crops. This is opposed to the European context, where land-use competition is a central concern when the subject is bioenergy and the cultivation of crops for energy generation, due to land scarcity and climatic constraints. Nevertheless, the climate vulnerability of the sugar-energy sector also introduces uncertainty regarding its future role, and these uncertainties limit long-term projections and indicate the unpredictability of the future of the sector.

Another reflection involves the scope of this study and the diffusion potential of CDR technologies beyond the sugar-energy regime. While this thesis focuses on CDR diffusion within the Brazilian sugar-energy sector, it is clear that technologies such as biochar and enhanced rock weathering may diffuse through other regimes, such as agriculture. Several initiatives already apply these technologies in other crops, such as coffee and citrus plantations. The sugar-energy sector remains one of the most powerful and technologically advanced agricultural regimes in Brazil and is often perceived as relatively open to innovation. However, other agricultural sectors may face stronger pressures to adopt decarbonization measures, since they do not have a similar "green" image. At the same time, there are indications that the agriculture sector as whole will not be complied to enter the regulated carbon market in Brazil, which may not encourage the adoption of other decarbonization measurements.

Interviews also highlighted alternative pathways for diffusion, such as deployment through the steel sector, where existing forestry operations could support the use of biochar and ERW (INT-04(C.4)). In that sense, biochar and enhanced rock weathering technologies could also diffuse through the pulp and paper system, which is also a huge industry in Brazil, with the country being the first exporter of pulp in the world and the second producer (EPE et al., 2022). However, BECCS is not as adaptable to other regimes due to its infrastructure and storage limitations, and the capture process is always associated to a bioenergy plant. BECCS may be applicable in other bioenergy plants contexts beyond ethanol and sugar-cane-based productions. Therefore, the diffusion of CDR technologies can follow multiple pathways, and it is not sector-specific.

The role of CDR technologies in climate mitigation strategies should be understood as a complement to emission reductions, rather than being a substitution. This distinction is crucial for the credibility of CDR technologies and for ensuring that their diffusion contributes to structural transformation and does not be an enabler for continued emissions growth. Several interviews emphasized that emission reductions within production chains should be priorities before carbon removal. At the same time, to achieve ambitious climate targets, the integration of carbon removal together with other mitigation efforts may be needed. This dual role underscores both the potential and the limits of CDR technologies within the decarbonization pathways.

Finally, an important reflection that goes beyond CDR technologies is how sustainability is organized within the companies. During the process of contacting actors for the interviews, it was noticed that large companies often have sustainability as a separate area in the company, which can be seen as an institutional recognition of sustainability matters, but it also can create the perception that the responsibility for sustainability lies with a limited group of people, rather than being shared across the whole organization. This separation may reduce accountability from operational and production departments, which may not see decarbonization as part of their core responsibilities, making the implementation of new processes or the substitution of inputs more difficult, particularly when changes affect established routines. Sustainability within the companies is running the risk of being confined to reporting or compliance functions, rather than driving substantive operational change.

6.5 Scientific Contributions

This study addressed a critical and yet underexplored dimension of Brazil's climate mitigation strategies: the influence of incumbent firms and regime-level actors on the diffusion of carbon dioxide removal technologies in the sugarcane and ethanol sector. By adopting this perspective, the thesis contributes to the scientific understanding not only of the technical characteristics of BECCS, Biochar Carbon Removal, and Enhanced Rock Weathering, but emphasizing on the socio-political conditions shaping their diffusion into existing systems. The use of the Multi-level Perspective framework provides a comprehensive socio-technical analysis, but explicitly centers the discussion on the role of actors, power relations, and political dynamics in technological development. This responds to a strong criticism of the MLP, which argues that the framework tends to focus on structural dynamics over agency, defined here as the capacity of actors to intentionally influence socio-technical change through strategic action and power relations (Geels, 2011). As a result, conflicts and intentional strategies of key actors may be underrepresented in transition analyses.

This thesis shows that the MLP can be applied in an actor-centered way to capture these dynamics, even without explicitly theorizing power, political economy, or strategic behavior in its core structure. This thesis made use of the MLP framework and semi-structured interviews, which adds empirical knowledge to show how incumbent strategies, institutional interests, and political positioning have the power to shape the diffusion of emerging CDR technologies. This study, therefore, extends the application of the MLP in an actor- and politics-oriented direction. This is not the first study that enriches the MLP with actor-centered or power-sensitive approaches in other transition contexts (Benvenutti et al., 2023); however, to the current knowledge, this thesis is the first to apply an analysis for CDR technologies within the sugar-energy regime in Brazil. The findings illustrate that regime stability or change is not only structurally constrained but also politically and strategically produced through the actions of powerful incumbents and regime actors.

Another scientific contribution of this thesis is the comparative socio-technical analysis of multiple CDR technologies within the Brazilian sugar energy sector. MLP-based studies mainly focus specifically on one technology; however, this comparative design does not examine a single technological method, but it analyses BECCS, biochar, and ERW side-by-side in the same regime and national context. By maintaining the same regime and institutional context, the analysis demonstrates that differences in technological development and diffusion are not only technical but also shaped by political and institutional dynamics. That reveals a selective engagement and strategic positioning by incumbents, showing how and why incumbents engage with different technologies under shared regime conditions. And further exemplifies how incumbents engage in ways that avoids deep structural changes in the system. This approach, therefore, contributes comparative insights that extend beyond descriptive case analyses.

Lastly, this thesis also contributes to the empirical analysis of bioenergy as a central socio-technical and political regime in Brazil, leading the country in its climate mitigation strategies and goals. The study demonstrates how the sugarcane and ethanol sector plays a strategically important role in the Brazilian economy, energy systems, and political landscapes, and how it has the power to shape national climate mitigation pathways and influence the diffusion of CDR technologies. By studying innovation technologies within the sugar-energy regime, the thesis highlights the differences between the market configuration in Brazil to the European context, where bionenergy occupies a more contested position in the energy transition. The findings show that in Brazil, bioenergy incumbents, as sugar-ethanol actors, exert influence over technological and political agendas. These findings may be extended to a Global South context and configuration that challenges assumptions derived from European energy transition studies. It shows the importance of accounting for country-specific political and economic configurations when analyzing the feasibility and governance of GHG emission reductions and climate mitigation pathways.

6.6 Research Limitations

Reflection on the limitations of the research is important for contextualizing the final work findings and informing future studies. Firstly, the chosen methodology approach for the research is based on qualitative methods, which allows in-depth interpretation of actors' perspectives and insights into socio-political and technical dynamics. It would be interesting to be able to compare the costs of ERW and biochar with fertilizers and soil conditioning. Such a comparison could provide a better understanding of the competitiveness and commercial viability of CDR technologies, but the lack of a quantitative approach hinders comparisons among the technologies and constrains the analysis of economic feasibility. Without this kind of data, it is difficult to draw conclusions about economic barriers that remain indicative and biased toward the interviewees' perceptions.

Secondly, the final findings are also limited by the number of interviews conducted, and although the interviews provided valuable insights, the initial intention was to interview a wider range of actors. In some cases, one representative from a group was interviewed, which may limit how findings can be generalized to the entire sector. Unfortunately, this study does not include interviews with policymakers and representatives from the biochar industry, which could also have influenced the interpretation of governance and market dynamics due to the restricted diversity of perspectives.

BECCS, biochar, and ERW are currently situated in the second phase of niche development, which is characterized by experimentation and early demonstration. In the second phase of development, changes occur rapidly, with new projects, partnerships, and policy discussions emerging frequently. As a result, some aspects of the analysis can become outdated over time. During the research process, it was necessary to revise sections to incorporate newly available information, indicating how the subject is dynamic. This reflects the relevance and momentum of CDR technologies, but it also limits the stability of the findings. Furthermore, given the early stage of deployment, the study cannot assess performance, permanence, or socio-environmental impacts of CDR technologies on the long-term.

Moreover, the findings are case-specific for the Brazilian sugar-energy sector and cannot be directly applied to other sectors or contexts with different institutional and market conditions. The results may be more promising or more negative depending on the case applied, since each system has different forces, pressures, and structures that dictate how innovations are perceived and developed. However, the study contains a structured analysis of cross-level dynamics shaping CDR, and the research limitations can be used as improvements in future research.

6.7 Summary

This chapter examined how interactions across niche, regime, and landscape levels shape the diffusion of CDR technologies in Brazil's sugar-energy sector. It also discussed the main barriers identified through the research and explored cross-level dynamics and power relations influencing technology diffusion. Furthermore, it also reflected on broader implications related to the sector, organizational practices, and the role of CDR in decarbonization strategies. Lastly, the chapter addressed the scientific contributions and limitations of the study, providing context for the interpretation of the findings. The conclusion is in the next chapter, with the research questions and recommendations for actors and future research.

Chapter 7

Conclusion

This thesis investigated the development of three carbon dioxide technologies in the socio-technical and political context of the sugar-energy regime in Brazil. The purpose of this study was not only to make technological evaluations regarding CDR but also to reach a deeper understanding of how climate solutions unfold within complex political economies and how actors can/cannot influence the diffusion of CDR technologies. The study used qualitative methods and semi-structured interviews, with the multi-level perspective framework as the main analytical framework. The theory of MLP framework allows the thesis to investigate the political, institutional, and socio-economic conditions under which CDR may be diffused or not in Brazil's existing sugar-energy regime. This chapter provides answers to the research questions and offers recommendations for actors and for future studies.

7.1 Answer to the Research Questions

To answer the main research question of this study, ***"What role do sugar-energy incumbents play in shaping the diffusion of BECCS, BCR, and ERW in Brazil's low-carbon transition?"*** three subquestions were proposed to help picture the structure and dynamics of the three socio-technical levels of the multi-level perspective (niche, regime, and landscape). This section aims to answer all these questions.

7.1.1 Sub-RQ-1: What global and national trends influence the development of CDR technologies in Brazil's sugar-energy sector?

This question was made to understand the socio-technical landscape that shape the diffusion of these technologies. It considers the Brazilian climate governance and policy landscape, Brazil's Nationally Determined Contribution under the Paris Agreement, market dynamics, and cultural shifts. Dynamics and pressures create opportunities or barriers for the diffusion of the technologies. The analysis indicated that Brazil is showing an increasing commitment to decarbonization, with ambitious climate and emissions goals submitted as NDCs, which is reflected in the new climate policies recently sanctioned by Congress. The one that attracts the most attention is the law that establishes a regulated carbon market in Brazil. These initiatives show the willingness of the country to develop towards a net-zero future and to pressure the regime level for change.

However, these pressures are not yet sufficient to create windows of opportunity for CDR technology to diffuse from the niche to the regime level. For instance, the studied technologies are not specifically mentioned in the climate and agricultural policies, since the policies generally focus on low-carbon technologies, meaning other initiatives and projects can also benefit from these incentives and regulations. The uncertainty around carbon monetization is also a concern, especially in the voluntary carbon markets, which are unstable and face credibility issues, and in the regulated carbon market, which is still undefined and carries expectations of low carbon prices, weakening a possible incentive for CDR technologies. Furthermore, The high interest rates, currency volatility, and dependence on imported capital goods favor short-term, low-risk investment strategies, which do not apply to CDR technologies, where investment costs are high. In the Brazilian business culture, sustainable development is primary driven by regulations and not environmental ethics. There is an expectation that a gradual cultural shift will occur as new generations assume management and power positions, but this is still a slow transformation. Therefore, the country is creating a landscape that provides initial legitimacy but does not yet offer the stable rules, incentives, or norms needed for large-scale diffusion. Within this context, even though it is a favorable environment for the diffusion of CDR technologies in Brazil's sugar-energy sector, they remain limited to protected and experimental spaces.

7.1.2 Sub-RQ-2: How are the emerging socio-technical niches of CDR technologies developing in Brazil's sugar-energy sector?

This research question was developed to understand how the socio-technical niches of Biochar, Enhanced Rock Weathering, and BECCS are configured, focusing on their technological design, actor networks, and phase of development. Based on the technology map that was drawn, the interview data, and the analysis of existing and planned projects in Brazil, it can be concluded that BECCS, biochar, and ERW are in the second phase of niche development. They are still characterized by pilot projects, experimental initiatives, and early commercial applications, indicating that none of the technologies has yet reached a stable diffusion phase, which also means that in this phase, the barriers are more present than the enablers for the innovations.

Even though they share a similar development stage, the niche configurations of the three technologies are very different. In the case of BECCS for ethanol production, the energy conversion and CO_2 capture technologies are well-established and mature, as can be seen in Figure 4.2.1; however, BECCS diffusion is constrained by challenges in CO_2 transportation and long-term geological storage. These challenges are associated with high capital costs, the need for specialized expertise dominated by the oil & gas sector, and the geological dependence of storage availability. In that sense, the plant location is a decisive factor for project economic feasibility. As a result, learning processes in the BECCS niche are more focused on the technical and infrastructure part, and its development remains dependent on long-term investments and external changes at the regime level, such as the establishment of a regulated carbon market with sufficiently high and stable carbon prices.

In contrast, the main challenges faced by Biochar and ERW are more related to scalability, legitimacy, and market acceptance, and less to technological feasibility. Biochar is produced through well-established processes such as pyrolysis, with a diversity of production methods, as shown in the Figure 4.3.1. This diversity of production methods indicates an intention to optimize the production process and the product quality. For large companies, the difficulty of standardizing the products creates barriers for the pricing differentiation of low-carbon products, such as ethanol and sugar produced using biochar, and limits large-scale applications. Biochar's niche environment is fragmented and dominated by small private initiatives and research institutions, with application dependent on credibility among sugarcane producers and on recognition of its dual role as a soil amendment and a carbon removal technology. ERW shares similar soil and circularity benefits as biochar, both derived from residues. However, ERW faces additional constraints due to its higher energy intensity and logistical barriers, limiting its feasibility to locations near mineral residues. At the same time, the recent certification of ERW carbon credits represents a turning point for the technology and an important strength factor, increasing its economic attractiveness and legitimacy as a carbon dioxide removal technology.

ERW requires less direct technological engagement from producers, as the production process is externalized to specialized mineral processing companies. Biochar also fits relatively well within existing sugarcane and ethanol production chains, especially if biomass residues are available. And BECCS demands infrastructure changes and the incorporation of expertise not traditionally present in the sugar-energy sector. Overall, the analysis shows that while financial viability and carbon pricing are important for all three technologies, their diffusion cannot be explained solely by technological factors. As seen in this chapter, their development is shaped by broader socio-technical dynamics, including actor coordination, legitimacy, and alignment with regime-level institutions and policies.

7.1.3 Sub-RQ-3:What are the existing institutional, political, and market structures and incumbent actors in the sugar-energy regime? And how do they influence the development and diffusion of CDR technologies?

This research question was made to understand the Brazilian sugar-energy regime by identifying existing institutional, political, and market structures, the roles of incumbent actors, and how these elements influence the diffusion of carbon dioxide removal technologies. The analysis indicates that the sugar-energy sector is a stable and powerful socio-technical regime. It has a strong economic relevance, historical policy support, and established institutional and infrastructural arrangements. Proálcool, RenovaBio, and Fuels of the Future are examples of public programs and regulatory frameworks that historically support the sector's expansion, guaranteeing market autonomy and competitiveness, as well as contributing to a system that prioritizes productivity and profitability.

The establishment of regime configuration creates a structural resistance to change towards innovation. Innovations need significant modifications to infrastructure, production processes, or new institutional arrangements. Therefore, technological change is more readily accepted when it aligns with or adds to existing practices, or enhancing economic performance or improving environmental indicators without disrupting the core business model. As a result, the incorporation of CDR technologies into the regime is more likely when they can improve efficiency, enhance, or complement current operations. However, when innovations require high capital investments or systemic transformation in the absence of strong incentives, they are likely to be resisted, which is the case for CDR tcehnologies in the currently stage.

The stakeholder (Figure 5.1) and power-interest (Figure 5.8) analyses show how the interactions between actors are complex within the studied socio-technical system. Industry incumbents are the core of the regime and exert strong influence over technological pathways. On the other hand, policymakers, investors, and research institutions shape the broader conditions and pressures where innovation occurs. The analysis shows that the incumbents and political actors hold significant power in their decisions, but most of them show little to no interest in promoting CDR technologies, creating an imbalance in the power-interest matrix. As shown in Figure 5.8, actors more interested in CDR development are the niche actors, which have the least power and resources, while actors with more power and capital, the incumbent actors, have little interest in CDR technology innovation. This imbalance contributes to a hostile regime context for CDR diffusion, where innovation remains fragmented and dependent on external pressures.

However, it is important to mention that the analysis also shows that no actor alone has the power to determine the trajectory of technological change, which means that a shift in one variable, such as regulatory frameworks, carbon pricing, or public legitimacy, can influence the strategies and perceptions of multiple actors, which can reorient the regime over time. Therefore, the current regime configuration constrains CDR development, but it also remains sensitive to coordinated changes across political, market, and institutional dimensions. Without stronger incentives, clearer policy signals, and broader societal engagement, the sugar-energy regime will probably continue favoring technologies that reinforce existing structures rather than enabling the large-scale diffusion of CDR technologies.

7.1.4 Research Question: What role do sugar-energy incumbents play in shaping the diffusion of BECCS, BCR, and ERW in Brazil's low-carbon transition?

This research question examined the role of sugar-energy incumbents in shaping the diffusion of BECCS, biochar Carbon Removal, and enhanced rock weathering within Brazil's low-carbon transition. It is found that incumbents do not determine technological pathways unilaterally, but their strategic decisions, investment capacity, and political influence puts them in a central role position, enabling or constraining the diffusion of CDR technologies from protected niches into the dominant sugar-energy regime. Incumbent firms hold the highest concentration of power within the socio-technical system. They control capital-intensive assets, operate large-scale infrastructure, maintain close connections with policymakers, and can influence which innovations are prioritized for experimentation. Therefore, they can invest in pilot projects and experimentation with new technologies; however, experimentation only becomes meaningful for diffusion when coupled with a clear intention to integrate innovations into their core production processes. While CDR technologies remain limited to isolated investments or small commercialization, they are unlikely to diffuse beyond the niche level and reach the third development phase.

Even though biochar and ERW are technically simpler and less capital-intensive, the established regime is characterized by system lock-ins that favor BECCS over the other two technologies. Biochar and ERW are more structurally disruptive, since they require a more decentralized application, changes in agricultural inputs, and closer engagement with producers, which challenge dominant routines and operational logics. In contrast, BECCS is more easily aligned with large incumbents' production models, with the inputs remaining unchanged, which is the key difference. Large sugar-energy firms are characterized by standardized products and price competition, which discourage product differentiation and limit the development of premium-priced products that internalize environmental value. The innovations that incumbents tend to prioritize improve efficiency or reduce cost without altering product characteristics and disrupting existing production chains. The market structure contributes to caution toward technologies that introduce uncertainty or new value propositions, even if they offer environmental benefits. These dynamics help explain why incumbents currently show limited interest in Biochar and ERW, although their potential is recognized, but show some interest to BECCS. Large-scale adoption has not yet occurred, but incumbents are closely monitoring the outcomes of the FS BECCS project. It was suggested in the interviews that this project could be a reference case if this initiative demonstrates a viable operational workflow and economic feasibility, encouraging other firms to consider BECCS as a possibility for them too. Therefore, while biochar and ERW lack direct institutional access on their own, greater alignment among actors across different CDR technologies may strengthen their collective visibility and credibility in policy spaces. In this context, BECCS occupies a strategic position due to its stronger institutional embeddedness, although in a conditional and non-leading role.

Small and medium-sized producers, on the other hand, seem more open to Biochar and ERW, especially after recent harvests that didn't produce as much as they had hoped. For small producers, modifying the inputs used in farming can seem like a low-risk way to boost production and soil quality, especially when compared to the disruption that changing inputs can cause in large firms. For many producers, especially those with family-based, conservative production profiles, carbon credits are still abstract and ambiguous. On the other hand, productivity improvements and agronomic benefits are more concrete and convincing. When sold as an extra way to make money instead of the main reason for adoption, carbon credit revenues are more appealing to these groups. This is especially important when producers have too much biomass waste or bagasse because they lost contracts to sell energy, which puts pressure on them to find other uses and ways to make money. In these cases, making biochar and using ERW can offer both waste valorization and economic diversification, strengthening their legitimacy at the niche level. The interplay of governance, market, and cultural dynamics creates a landscape that provides initial legitimacy to CDR technologies, but it still lacks stable rules, incentives, or norms necessary for large-scale diffusion. In this context, CDR technologies remain limited to protected and experimental environments, which reinforces incumbents' cautious strategies and their hesitance to commit to structural changes without definitive regulatory or market indicators. These niche-level dynamics are therefore not isolated, but may generate experiential knowledge, credibility, and public legitimacy that gradually feed back into regime-level evaluations of CDR technologies.

Overall, incumbents play an essential but conditional role in the diffusion of CDR technologies. Without the engagement with the incumbent firms, large-scale integration into the sugar-energy regime is unlikely, especially for technologies that need infrastructural alignment and long-term investment commitments. At the same time, diffusion pathways should not depend exclusively on incumbent adoption. The implementation of the technologies among small and medium-sized producers is essential for creating legitimacy, credibility, and experiential knowledge for biochar and ERW. The dynamics within these niches may eventually create an environment in which established players evaluate integrating these technologies into their standardized production systems. Thus, incumbents do not completely block or actively promote the diffusion of CDR technologies, but they can facilitate pathways that correspond with current regime structures, thereby reinforcing gradual and regime-compatible transition dynamics rather than transformative change.

7.2 Recommendation for Actors

The findings of this study show that the diffusion of carbon dioxide removal technologies in Brazil's sugar-energy regime is shaped by the interaction between powerful incumbent actors, emerging niche initiatives, and state institutions, with diffusion remaining limited in the absence of clear coordination and commitment from regime incumbents. It was also concluded that the system is misaligned between power, interest, and institutional support. Therefore, some recommendations will be shared with the intention of helping address structural barriers while enabling conditions for BECCS, biochar, and enhanced rock weathering.

7.2.1 Recommendations for sugar-energy incumbents

First, it is important that incumbents do more than exploratory experimentation and start considering pathways to scale successful pilots, especially when CDR technologies align with existing infrastructure and productivity goals. Experiments with the substitution of fertilizer by Biochar and ERW would allow firms to evaluate agronomic and economic benefits without disrupting the system.

Dedicate efforts to promote Ethanol internationally. The success of ethanol is important for new technologies to emerge in the regime, especially with BEECS, which can further differentiate the Brazilian ethanol in global markets. Initiatives like that will not change the characteristics in the system, but can enhance the value of negative-emission ethanol and drive the technology to bigger developments.

7.2.2 Recommendations for policymakers and government institutions

The CDR technologies are not mentioned explicitly in national climate instruments. Therefore, it is important that policymakers explicitly recognize CDR technologies in policies and legal frameworks. A clear inclusion can enhance legitimacy and reduce uncertainty for private actors.

It is important to have a clear design of the regulated carbon market. As long as this mechanism stays unclear, uncertainties and instability will continue for CDR technologies. Long-term policy signaling is crucial to mitigate incumbents' risk aversion and facilitate investment planning. Moreover, carbon pricing mechanisms need to reflect the real costs and permanence requirements of CDR technologies, ensuring that market incentives correspond with the reality of the technologies.

Government institutions such as Embrapa could play a key role in legitimizing CDR technologies, especially for Biochar and ERW, by providing technical validation, agronomic guarantees, and independent performance assessments. Reducing import taxes on specific equipment for CDR deployment could lower entry barriers and decrease the needed initial investments.

Responsibilities related to CDR encompass agriculture, energy, environment, and industry, and the coordination across all these ministries remains a critical challenge. There is a necessity for more cohesive governance mechanisms to mitigate policy fragmentation and guarantee consistency within institutional mandates. The communication between ministries needs to be collaborative.

7.2.3 Recommendations for public financing bodies and development banks

Public financial institutions and development banks could develop dedicated financial instruments specifically for early-stage CDR deployment, since now all projects compete together for funding. Creating a quota system between different low-carbon projects categories could be interesting.

Through ANP and their R&D compliance program, projects of CDR could be targeted, supporting learning processes and lower technological uncertainty. That means, instead leaving the companies to choose in which topic they will invest their R&D money, institutions could indicate the topics in need of development and knowledge.

7.2.4 Recommendations for niche actors and innovators

It is encouraged that niche actors developing biochar, ERW, and BECCS strengthen their contact and enhance coordination and collaboration, instead of operating in isolation. Being together can improve knowledge sharing, reduce duplication of efforts, and enhance bargaining power in interactions with incumbents and policymakers. Collective representation in policy discussions could help ensure that niche perspectives are better reflected and communicated in emerging regulatory frameworks, particularly as Brazil's regulated carbon market is still not designed.

7.3 Recommendation for Future Research

This research adopted a qualitative, socio-technical perspective to analyze the diffusion of carbon dioxide removal technologies in Brazil's sugar-energy sector. While this approach provided insights into actor dynamics, institutional configurations, and regime–niche interactions, the study's limitations indicate various paths for future research. Addressing these research gaps could enhance the understanding of how CDR technologies may transition from experimental niches to scalable elements of Brazil's long-term climate mitigation strategy.

First, future research could explore the economic viability of BECCS, biochar, and enhanced rock weathering using a quantitative approach, such as techno-economic assessments, cost–benefit analyses, and scenario modeling. This could be useful to complement the qualitative insights of this thesis by evaluating investment requirements, operational costs, revenue streams, and sensitivity to carbon pricing. These can be further valuable to understand under which market and policy conditions these technologies could become competitive within the sugar-energy regime.

Second, more investigative and large-sample research involving a wider range of stakeholders to identify patterns in perceptions, expectations, and levels of recognition of CDR technologies. More interviewees and a wider diversity could help check whether the dynamics observed in this study reflect systemic trends or context-specific configurations, especially among sugar-energy incumbents, policymakers, financial institutions, and civil society actors.

Third, future studies could also incorporate oil and gas incumbents into the analysis. These actors may play a significant role in shaping BECCS diffusion pathways, since they have technological expertise in CO_2 capture, transport, and storage, as well as their growing involvement in carbon management strategies. Examining cross-sectoral interactions between the oil and gas industry and the sugar-energy sector can offer valuable insights into knowledge transfer, power dynamics, and competing transition narratives.

Finally, further research is needed on the circularity potential of biochar and enhanced rock weathering. Investigating whether these technologies could be embedded within broader circular economy strategies, could increase their value proposition beyond carbon removal alone, and clarify their role in integrated sustainability transitions in agriculture and bioenergy systems.

References

Agroadvance. (2025). *15 maiores grupos do setor sucroalcooleiro no brasil em 2024/25.* `https://https://agroadvance.com.br/blog-maiores-grupos-do-setor-sucroalcooleiro/.` (Accessed: 2025-11-07)

Agência Senado. (2024, Dec). *Sancionada lei que regula mercado de carbono no brasil.* Retrieved from `https://www12.senado.leg.br/noticias/materias/2024/12/12/sancionada-lei-que-regula-mercado-de-carbono-no-brasil` (Accessed: 26/05/2025)

Akgül, A., Şener Akın, S., Güleç, F., & Kazanç, F. (2024). Biochar gasification: Insights from pyrolysis atmospheres and gasification heating rates. *Fuel*, *360*, 130469. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0016236123030831` doi: https://doi.org/10.1016/j.fuel.2023.130469

Albioma. (n.d.). *Saint-pierre power plant.* `https://www.albioma.com/en/site/reunion-island/saint-pierre/#:~:text=The%20first%20power%20plant%20in,the%20R%C3%A9union%20Island%20power%20grid.` (Accessed: 04/10/2025)

Al-Rumaihi, A., Shahbaz, M., Mckay, G., Mackey, H., & Al-Ansari, T. (2022). A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar yield. *Renewable and Sustainable Energy Reviews*, *167*, 112715. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1364032122006049` doi: https://doi.org/10.1016/j.rser.2022.112715

Amalina, F., Syukor Abd Razak, A., Krishnan, S., Sulaiman, H., Zularisam, A., & Nasrullah, M. (2022). Advanced techniques in the production of biochar from lignocellulosic biomass and environmental applications. *Cleaner Materials*, *6*, 100137. Retrieved from `https://www.sciencedirect.com/science/article/pii/S2772397622000971` doi: https://doi.org/10.1016/j.clema.2022.100137

Anderson, N. M., Bergman, R. D., & Page-Dumroese, D. S. (2016). *A supply chain approach to biochar systems* (No. chapter 2). Cambridge Press London, UK.

ANP. (2024, Aug). *Renovabio.* Retrieved from `SobreoRenovaBio` (Accessed: 28/05/2025)

Awodun, K., He, Y., Wu, C., & Masoudi Soltani, S. (2025). Catalytic pyrolysis of bio-waste in synthesis of value-added products: A systematic review. *Fuel Processing Technology*, *275*, 108258. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0378382025000827` doi: https://doi.org/10.1016/j.fuproc.2025.108258

Barros, M. L., & Albuquerque, M. (2025, Jan). *Mercosur-eu deal to open brazil ethanol flows.* Retrieved from `https://www.argusmedia.com/en/news-and-insights/latest-market-news/2646064-mercosur-eu-deal-to-open-brazil-ethanol-flows` (Accessed: 02/06/2025)

Basu, P. (2018). Chapter 12 - production of synthetic fuels and chemicals from biomass. In P. Basu (Ed.), *Biomass gasification, pyrolysis and torrefaction (third edition)* (Third Edition ed., p. 415-443). Academic Press. Retrieved from `https://www.sciencedirect.com/science/article/pii/B9780128129920000121` doi: https://doi.org/10.1016/B978-0-12-812992-0.00012-1

Benson, S., Cook, P., Anderson, J., Bachu, S., Nimir, H. B., Basu, B., … Zhou, D. (2005). Underground geological storage. In B. Metz, O. Davidson, H. de Coninck, M. Loos, & L. Meyer (Eds.), *Ipcc special report on carbon dioxide capture and storage* (pp. 195–276). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Retrieved from `https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter5-1.pdf` (Accessed:07/10/2025)

Benvenutti, L. M. M., de Souza Campos, L. M., Vazquez-Brust, D., & Liston-Heyes, C. (2023). The changing roles of actors in 'fortuitous' sustainability transitions: An analysis of brazil's passenger vehicles fuel technology from 1970 to 2020. *Technological Forecasting and Social Change*, *192*, 122584. Retrieved from `https://www.sciencedirect.com/science/article/pii/S004016252300269X` doi: https://doi.org/10.1016/j.techfore.2023.122584

BNDES. (2025). *Bndes mais inovação.* `https://www.bndes.gov.br/wps/portal/site/home/financiamento/produto/programa-bndes-mais-inovacao`. (Accessed: 2025-11-05)

Bonetto, A. (2025, jul). *Tendências de ESG em 2025: sustentabilidade como vantagem competitiva.* Mundo Corporativo. Retrieved from `https://mundocorporativo.com.br/tendencias-de-esg-em-2025-sustentabilidade-como-vantagem-competitiva/` (Accessed: 2025-12-26)

Brasil, M. (2022, Oct). *Pesquisadores avaliam produção conjunta de biocombustíveis para preservar áreas de cultivo.* Retrieved from `https://eixos.com.br/hidrogenio/pesquisadores-avaliam-producao-conjunta-de-biocombustiveis-para-preservar-areas-de-cultivo/` (Accessed: 28/05/2025)

Brasil Biomassa. (2025). *Planta Industrial Biochar – Industrial Biochar Plant.* Retrieved from `https://www.brasilbiomassa.com/plantaindustrialbiochar?lang=en` (Accessed: 2025-12-20)

Brazilian Government. (2024). *Brazil's ndc- national determination to contribute and transform.* Retrieved from `https://unfccc.int/sites/default/files/2024-11/Brazil_Second%20Nationally%20Determined%20Contribution%20%28NDC%29_November2024.pdf`

Carbon Gap. (2025, nov 25). *Visibility for carbon removal at COP30: limited progress, rising momentum.* Carbon Gap Blog. Retrieved from `https://carbongap.org/cop30-takeaways/` (Accessed: 2025-12-26)

CarbonCredits.com. (2025). *Verde AgriTech and UNDO Carbon Partner to Scale Enhanced Rock Weathering.* Retrieved from `https://carboncredits.com/verde-agritech-and-undo-carbon-partner-to-scale-enhanced-rock-weathering/?utm_source=chatgpt.com` (Accessed: 2025-12-20)

Carbonmark. (2025). *PUR-175613 | Aperam BioEnergia.* Retrieved from `https://app.carbonmark.com/projects/PUR-175613` (Accessed: 2025-12-20)

Carrier, M., Hugo, T., Gorgens, J., & Knoetze, H. (2011). Comparison of slow and vacuum pyrolysis of sugar cane bagasse. *Journal of Analytical and Applied Pyrolysis*, *90*(1), 18-26. Retrieved from `https://www.sciencedirect.com/science/article/pii/S016523701000135X` doi: https://doi.org/10.1016/j.jaap.2010.10.001

Casa Civil. (2015, Apr). *Governo anuncia elevação da mistura de etanol na gasolina a 27%.* Retrieved from `https://www.gov.br/casacivil/pt-br/assuntos/noticias/2015/marco/mistura-de-etanol-na-gasolina-sera-de-27-a-partir-de-16-de-marco` (Accessed: 02/06/2025)

Chen, W., Meng, J., Han, X., Lan, Y., & Zhang, W. (2019, 04). Past, present, and future of biochar. *Biochar*, *1*. doi: 10.1007/s42773-019-00008-3

Cherlinka, V. (2025, Feb). *How to grow sugar cane: Planting and optimum conditions.* Retrieved from `https://eos.com/blog/how-to-grow-sugar-cane/` (Accessed: 30/05/2025)

Choudhary, P., Pandey, V. K., & Pathak, A. (2025). Process innovations in catalytic pyrolysis of lignocellulosic biomass for sustainable conversion: A review on economical approach. *Biomass and Bioenergy*, *201*, 108073. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0961953425004842` doi: https://doi.org/10.1016/j.biombioe.2025.108073

CIF. (n.d.). *Cif-website.* `https://www.cif.org/`. (Accessed: 2025-11-09)

CNA. (2025). *Cna.* `https://www.cnabrasil.org.br/cna`. (Accessed: 2025-11-05)

Comissão de Valores Mobiliários. (2025, fev). *Relatório perfil e comportamento dos investidores 2024* (Tech. Rep.). Gerência de Educação e Inclusão Financeira (GEIF) / SOI. Retrieved from `https://www.gov.br/investidor/pt-br/educacional/publicacoes-educacionais/pesquisas/relatorio-perfil-e-comportamento-do-investidor-2024.pdf`

Copersurcar. (2024). *Mobilidade: Consumo de etanol hidratado tem potencial para crescer no brasil.* Retrieved from `https://www.copersucar.com.br/website/wp-content/uploads/2025/03/Estudo-Mobilidade.pdf` (Accessed: 10/06/2025)

CTC. (n.d.-a). *Shareholding composition.* `https://ri.ctc.com.br/en/corporate-governance/shareholding-composition/`. (Accessed: 2025-11-09)

CTC. (n.d.-b). *Who we are.* `https://ctc.com.br/en/who-we-are/`. (Accessed: 2025-11-09)

Czerwińska, K., Śliz, M., & Wilk, M. (2022). Hydrothermal carbonization process: Fundamentals, main parameter characteristics and possible applications including an effective method of sars-cov-2 mitigation in sewage sludge. a review. *Renewable and Sustainable Energy Reviews*, *154*, 111873. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1364032121011400` doi: https://doi.org/10.1016/j.rser.2021.111873

Datagro. (2024, Sep). *Mercosur-eu agreement opens opportunities for brazilian sugar and ethanol, says unica.* Retrieved from `https://portal.datagro.com/en/12/agribusiness/917031/mercosur-eu-agreement-opens-opportunities-for-brazilian-sugar-and-ethanol-says-unica` (Accessed: 02/06/2025)

Doctor, R., Palmer, A., Coleman, D., Davison, J., Hendriks, C., Kaarstad, O., & Ozaki, M. (2005). Transport of CO⊠. In B. Metz, O. Davidson, H. C. de Coninck, M. Loos, & L. A. Meyer (Eds.), *Ipcc special report on carbon dioxide capture and storage.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Retrieved from `https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter4-1.pdf` (Accessed: 06/10/2025)

Edwards, D. P., Lim, F., James, R. H., Pearce, C. R., Scholes, J., Freckleton, R. P., & Beerling, D. J. (2017). Climate change mitigation: potential benefits and pitfalls of enhanced rock weathering in tropical agriculture. *Biology Letters*, *13*(4), 20160715. Retrieved from `https://royalsocietypublishing.org/doi/abs/10.1098/rsbl.2016.0715` doi: 10.1098/rsbl.2016.0715

EIA. (2024, April). *Biomass explained.* `https://www.eia.gov/energyexplained/biomass/`. (Accessed: 04/10/2025)

Embrapa. (n.d.). *Embrapa- site oficial.* `https://www.embrapa.br/sobre-a-embrapa`. (Accessed: 17/09/2025)

EMBRAPA. (2009). *Zoneamento agroecológico da cana-de-açúcar (zae cana).* (Accessed: 30/05/2025)

EPE. (n.d.). *Combustível do futuro.* Retrieved from `https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/combustivel-do-futuro` (Accessed: 22/05/2025)

EPE. (2023). *Pesquisa de variáveis e fatores do processo de escolha do consumidor quanto ao combustível.* PowerPoint presentation. Retrieved from `https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-792/CA-EPE-DPG-SDB-2023-09_Prefer%C3%AAncia%20do%20consumidor_ve%C3%ADculo%20flex.pdf` (Accessed: 2025-10-27)

EPE. (2024). *Balanço energético nacional 2024: Ano base 2023.* Ministério de Minas e Energia. Retrieved from `https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-819/topico-723/BEN2024.pdf` (Accessed: 28/05/2025)

EPE. (2025). *Who we are.* `https://www.epe.gov.br/en/about-epe/who-we-are`. (Accessed: 2025-11-07)

EPE, IEA, & IBA. (2022, jan). *A indústria de papel e celulose no brasil e no mundo* (Relatório Técnico). Empresa de Pesquisa Energética (EPE) / International Energy Agency (IEA). Retrieved from `https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-650/Pulp%20and%20paper_EPE+IEA_Português_2022_01_25_IBA.pdf` (Accessed: 2026-01-02)

Equipe GNPW Group. (2025, nov 28). *Brasil pós-cop30: por que o país virou o hotspot de investimentos em energia limpa.* GNPW Group Blog. Retrieved from `https://www.gnpw.com.br/cop-30/brasil-pos%e2%80%91cop30-por-que-o-pais-virou-o-hotspot-de-investimentos-em-energia-limpa/` (Accessed: 2025-12-26)

Escobar, H. (2019, Nov). *Liberação da cana na amazônia É "desnecessária e perigosa", alerta professor da usp.* Retrieved from `https://jornal.usp.br/ciencias/ciencias-ambientais/liberacao-da-cana-na-amazonia-e-desnecessaria-e-perigosa-diz-professor-da-usp/` (Accessed: 02/06/2025)

ESG Inside. (2025). *Future Climate assina o primeiro contrato de ERW no mercado de carbono.* Retrieved from `https://esginside.com.br/2025/09/23/future-climate-assina-o-primeiro-contrato-de-erw-no-mercado-de-carbono/?utm_source=chatgpt.com` (Accessed: 2025-12-20)

European Parliament and Council. (2009). *Directive 2009/31/ec of the european parliament and of the council of 23 april 2009 on the geological storage of carbon dioxide and amending council directives 85/337/eec, 2000/60/ec, 2001/80/ec, 2004/35/ec, 2006/12/ec, 2008/1/ec and regulation (ec) no 1013/2006.* `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0031`. (Official Journal of the European Union, L 140, 5.6.2009, p. 114–135)

Faria, A., & Teixeira, R. (2025, Mar). *Dedo de prosa: Etanol na gasolina deve passar de 27% para 30%.* Retrieved from `https://www12.senado.leg.br/radio/1/conexao-senado/2025/03/21/dedo-de-prosa-etanol-na-gasolina-deve-passar-de-27-para-30` (Accessed: 02/06/2025)

Feldman, B. (2021, Jun). *Lobby não permite reduzir etanol na gasolina.* Retrieved from `https://autopapo.com.br/blog-do-boris/lobby-etanol-na-gasolina/` (Accessed: 02/06/2025)

Finep. (2025). *O que apoiamos.* `http://www.finep.gov.br/apoio-e-financiamento-externa/o-que-apoiamos`. (Accessed: 2025-11-05)

Foong, S. Y., Liew, R. K., Yang, Y., Cheng, Y. W., Yek, P. N. Y., Wan Mahari, W. A., … Lam, S. S. (2020). Valorization of biomass waste to engineered activated biochar by microwave pyrolysis: Progress, challenges, and future directions. *Chemical Engineering Journal*, *389*, 124401. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1385894720303922` doi:

https://doi.org/10.1016/j.cej.2020.124401

FS Bioenergia. (2025). *Fs bioenergia -site oficial*. `https://www.fs.agr.br/`. (Accessed: 2025-10-15)

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy*, *31*(8), 1257-1274. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0048733302000628` (NELSON + WINTER + 20) doi: https://doi.org/10.1016/S0048-7333(02)00062-8

Geels, F. W. (2006). Multi-level perspective on system innovation: Relevance for industrial transformation. In X. Olsthoorn & A. J. Wieczorek (Eds.), *Understanding industrial transformation: Views from different disciplines* (pp. 163–186). Dordrecht: Springer Netherlands. Retrieved from `https://doi.org/10.1007/1-4020-4418-6_9` doi: 10.1007/1-4020-4418-6_9

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions*, *1*(1), 24-40. Retrieved from `https://www.sciencedirect.com/science/article/pii/S2210422411000050` doi: https://doi.org/10.1016/j.eist.2011.02.002

Geels, F. W. (2014, 08). Regime resistance against low-carbon transitions: Introducing politics and power into the multi-level perspective. *Theory, Culture Society*, *31*, 21-40. doi: 10.1177/0263276414531627

Geels, F. W. (2019). Socio-technical transitions to sustainability: a review of criticisms and elaborations of the multi-level perspective. *Current Opinion in Environmental Sustainability*, *39*, 187-201. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1877343519300375` (Open Issue 2019) doi: https://doi.org/10.1016/j.cosust.2019.06.009

Geske, J., Berghout, N., & van den Broek, M. (2015). Cost-effective balance between co2 vessel and pipeline transport. part i – impact of optimally sized vessels and fleets. *International Journal of Greenhouse Gas Control*, *36*, 175-188. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1750583615000729` doi: https://doi.org/10.1016/j.ijggc.2015.01.026

Gnanasekaran, L., Priya, A., Thanigaivel, S., Hoang, T. K., & Soto-Moscoso, M. (2023). The conversion of biomass to fuels via cutting-edge technologies: Explorations from natural utilization systems. *Fuel*, *331*, 125668. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0016236122024978` doi: https://doi.org/10.1016/j.fuel.2022.125668

Green Climate Fund. (n.d.). *Gcf-website*. `https://www.greenclimate.fund/`. (Accessed: 2025-11-09)

Gregorio, R. (2025). *Em um ano apertado para as usinas, Citi aponta quem deve sofrer menos*. Retrieved from `https://www.theagribiz.com/empresas/usinas/em-um-ano-apertado-para-as-usinas-citi-aponta-quem-deve-sofrer-menos/` (Accessed: 2025-12-26)

Hannis, S., Lu, J., Chadwick, A., Hovorka, S., Kirk, K., Romanak, K., & Pearce, J. (2017). Co2 storage in depleted or depleting oil and gas fields: What can we learn from existing projects? *Energy Procedia*, *114*, 5680-5690. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1876610217319082` (13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland) doi: https://doi.org/10.1016/j.egypro.2017.03.1707

Hayat, M. A., Alhadhrami, K., & Elshurafa, A. M. (2024). Which bioenergy with carbon capture and storage (beccs) pathways can provide net-negative emissions? *International Journal of Greenhouse Gas Control*, *135*, 104164. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1750583624001075` doi: https://doi.org/10.1016/j.ijggc.2024.104164

IAC. (n.d.). *Conheça o instituto agronômo (iac), de campinas*. `https://www.iac.sp.gov.br/areadoinstituto/instituto/`. (Accessed: 2025-11-09)

iCS. (n.d.). *Who we are*. `https://climaesociedade.org/en/who-we-are/`. (Accessed: 2025-11-09)

IEA. (n.d.). *Bioenergy with carbon capture and storage*. `https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage`. (Accessed: 25/09/2025)

InPlanet. (n.d.). Retrieved from `https://inplanet.earth/` (Accessed: 18/11/2024)

Instituto Brasileiro de Geografia e Estatística. (2023). *Produção agropecuária*. Retrieved from `https://www.ibge.gov.br/explica/producao-agropecuaria/` (Accessed: 01/06/2025)

IPCC. (n.d.). *Carbon dioxide removal*. Retrieved from `https://www.ipcc.ch/report/ar6/wg3/downloads/outreach/IPCC_AR6_WGIII_Factsheet_CDR.pdf` (Accessed: 15/04/2025)

Ismail, A., & Gaganis, V. (2023). Carbon capture, utilization, and storage in saline aquifers: Subsurface policies, development plans, well control strategies and optimization approaches—a review. *Clean Technologies*, *5*(2), 292–314. Retrieved from `https://doi.org/10.3390/cleantechnol5020031` doi: 10.3390/cleantechnol5020031

Isometric. (n.d.). *Project serra da mantiqueira.* https://registry.isometric.com/project/prj_1J7NQMR9V1S04P0D#project-documentation. (Accessed: 24/09/2025)

Izadpanahi, A., Blunt, M. J., Kumar, N., Ali, M., Gaeta Tassinari, C. C., & Sampaio, M. A. (2024). A review of carbon storage in saline aquifers: Mechanisms, prerequisites, and key considerations. *Fuel*, *369*, 131744. Retrieved from https://www.sciencedirect.com/science/article/pii/S0016236124008925 doi: https://doi.org/10.1016/j.fuel.2024.131744

Jenkins, B. (2014). Global agriculture: Industrial feedstocks for energy and materials. In N. K. Van Alfen (Ed.), *Encyclopedia of agriculture and food systems* (p. 461-498). Oxford: Academic Press. Retrieved from https://www.sciencedirect.com/science/article/pii/B978044452512300156X doi: https://doi.org/10.1016/B978-0-444-52512-3.00156-X

Jiang, L., Chen, Z., Farouq Ali, S., Zhang, J., Chen, Y., & Chen, S. (2022). Storing carbon dioxide in deep unmineable coal seams for centuries following underground coal gasification. *Journal of Cleaner Production*, *378*, 134565. Retrieved from https://www.sciencedirect.com/science/article/pii/S0959652622041373 doi: https://doi.org/10.1016/j.jclepro.2022.134565

Kambo, H. S., & Dutta, A. (2015). A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. *Renewable and Sustainable Energy Reviews*, *45*, 359-378. Retrieved from https://www.sciencedirect.com/science/article/pii/S136403211500060X doi: https://doi.org/10.1016/j.rser.2015.01.050

Kheshgi, H. S., & Prince, R. C. (2005). Sequestration of fermentation co2 from ethanol production. *Energy*, *30*(10), 1865-1871. Retrieved from https://www.sciencedirect.com/science/article/pii/S0360544204004888 doi: https://doi.org/10.1016/j.energy.2004.11.004

Krysanova, K., Krylova, A., Kulikova, M., Kulikov, A., & Rusakova, O. (2022). Biochar characteristics produced via hydrothermal carbonization and torrefaction of peat and sawdust. *Fuel*, *328*, 125220. Retrieved from https://www.sciencedirect.com/science/article/pii/S0016236122020580 doi: https://doi.org/10.1016/j.fuel.2022.125220

Lam, S. S., Yek, P. N. Y., Cheng, W. Y., Liew, R. K., Tabatabaei, M., & Aghbashlo, M. (2022). Chapter 25 - production of biochar using sustainable microwave pyrolysis approach. , 323-332. Retrieved from https://www.sciencedirect.com/science/article/pii/B978032385343900015X doi: https://doi.org/10.1016/B978-0-323-85343-9.00015-X

Leal Silva, J. F., Souza, G. M., Maciel Filho, R., Yang, Y., & Li, F. (2024, December). *Case studies of CO▯ utilization in the production of ethanol: Overview of costs and greenhouse gas emissions* (Tech. Rep.). Paris, France: IEA Bioenergy Task 39. Retrieved from https://www.ieabioenergy.com/wp-content/uploads/2025/02/Case-studies-of-CO2-utilization-in-the-production-of-ethanol.pdf (Accessed: 06/10/2025)

Lehmann, J. (2009). Terra preta nova – where to from here? In W. I. Woods, W. G. Teixeira, J. Lehmann, C. Steiner, A. WinklerPrins, & L. Rebellato (Eds.), *Amazonian dark earths: Wim sombroek's vision* (pp. 473–486). Dordrecht: Springer Netherlands. Retrieved from https://doi.org/10.1007/978-1-4020-9031-8_28 doi: 10.1007/978-1-4020-9031-8_28

Lei nº 13.576. (2017, Dec). LEI Nº 13.576. Retrieved from https://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/l13576.htm (Accessed: 28/05/2025)

Lei nº 14.993. (2024, Oct). LEI Nº 14.993. Retrieved from https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2024/lei/L14993.htm (Accessed: 22/05/2025)

Lei nº 15.042. (2024, Dec). LEI Nº 15.042. Retrieved from https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2024/lei/L15042.htm (Accessed: 26/05/2025)

Lei nº 15.103. (2025, Jan). LEI Nº 15.103. Retrieved from https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2025/lei/L15103.htm (Accessed: 21/05/2025)

Lei nº 9.478. (1997, Aug). LEI nº 9.478. Retrieved from https://www.planalto.gov.br/ccivil_03/Leis/L9478.htm (Accessed: 2025-11-07)

Leong, Y. K., & Chang, J.-S. (2023). Microalgae-based biochar production and applications: A comprehensive review. *Bioresource Technology*, *389*, 129782. Retrieved from https://www.sciencedirect.com/science/article/pii/S0960852423012105 doi: https://doi.org/10.1016/j.biortech.2023.129782

Li, J., Dai, J., Liu, G., Zhang, H., Gao, Z., Fu, J., … Huang, Y. (2016). Biochar from microwave pyrolysis of biomass: A review. *Biomass and Bioenergy*, *94*, 228-244. Retrieved from https://www.sciencedirect.com/science/article/pii/S0961953416303002 doi: https://doi.org/10.1016/j.biombioe.2016.09.010

Li, L., Long, A., Fossum, B., & Kaiser, M. (2023). Effects of pyrolysis temperature and feedstock type on biochar characteristics pertinent to soil carbon and soil health: A meta-analysis. *Soil Use and*

Management, *39*(1), 43-52. Retrieved from `https://bsssjournals.onlinelibrary.wiley.com/doi/abs/10.1111/sum.12848` doi: https://doi.org/10.1111/sum.12848

Li, Z., Dong, M., Li, S., & Huang, S. (2006). Co2 sequestration in depleted oil and gas reservoirs—caprock characterization and storage capacity. *Energy Conversion and Management*, *47*(11), 1372-1382. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0196890405002098` doi: https://doi.org/10.1016/j.enconman.2005.08.023

Liu, X., Zhang, B., Fu, X., Lu, J., Huang, M., & Zeng, F. B. (2025). Potential, efficiency, and leakage risk of co2 sequestration in coal: A review. *Processes*, *13*(6). Retrieved from `https://www.mdpi.com/2227-9717/13/6/1680` doi: 10.3390/pr13061680

LNBR. (n.d.). *Lnbr overview.* `https://lnbr.cnpem.br/en/overview/`. (Accessed: 2025-11-09)

Lorenzo, J. M., Putnik, P., Bursać Kovačević, D., Petrović, M., Munekata, P. E., Gómez, B., … Barba, F. J. (2020). Chapter 4 - silymarin compounds: Chemistry, innovative extraction techniques and synthesis. In Atta-Ur-Rahman (Ed.), *Bioactive natural products* (Vol. 64, p. 111-130). Elsevier. Retrieved from `https://www.sciencedirect.com/science/article/pii/B9780128179031000048` doi: https://doi.org/10.1016/B978-0-12-817903-1.00004-8

Manochio, C., Andrade, B., Rodriguez, R., & Moraes, B. (2017). Ethanol from biomass: A comparative overview. *Renewable and Sustainable Energy Reviews*, *80*, 743-755. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1364032117307001` doi: https://doi.org/10.1016/j.rser.2017.05.063

MCTI. (2025). *Conselho nacional de desenvolvimento científico e tecnológico.* `https://www.gov.br/cnpq/pt-br`. (Accessed: 2025-11-05)

Metz, B., Davidson, O., de Coninck, H., Loos, M., & Meyer, L. (2005). Capture of CO□. In B. Metz, O. Davidson, H. de Coninck, M. Loos, & L. Meyer (Eds.), *Ipcc special report on carbon dioxide capture and storage* (pp. 107–182). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Retrieved from `https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter3-1.pdf` (Accessed: 06/10/2025)

Ministério de Minas e Energia. (n.d.). *Política nacional de transição energética.* Retrieved from `https://www.gov.br/mme/pt-br/assuntos/secretarias/sntep/dte/cgate/pnte` (Accessed: 21/05/2025)

Ministério de Minas e Energia. (2024, Nov). *Pnte norteará a estratégia para transição energética justa e inclusiva.* Retrieved from `https://www.gov.br/mme/pt-br/assuntos/noticias/pnte-norteara-a-estrategia-para-transicao-energetica-justa-e-inclusiva/` (Accessed: 21/05/2025)

Ministério de Minas e Energia. (2025, Jan). *Programa de aceleração da transição energética foi sancionado nesta quarta-feira.* Retrieved from `https://www.gov.br/mme/pt-br/assuntos/noticias/programa-de-aceleracao-da-transicao-energetica-foi-sancionado-nesta-quarta-feira` (Accessed: 21/05/2025)

Miranda, E., & R. Martinho, P. (2020). *Territorial dimension and trends of sugarcane between 2009 and 2020.* Revista Opiniões. Retrieved from `https://sucroenergetico.revistaopinioes.com.br/en/revista/detalhes/3-dimensao-territorial-e-tendencias-da-cana-de-acu/` (Accessed: 30/05/2025)

MOMBAK. (2025). *We remove carbon, tons of it.* `https://mombak.com/what/`. (Accessed: 2025-11-07)

NetZero. (n.d.). Retrieved from `https://netzero.green/pt/` (Accessed: 17/09/2024)

Neves, M., Gerardi, F., Kalaki, R., & Gali, R. (2017). *O setor sucroenergético em 2030: Dimensões, investimentos e uma agenda estratégica* (Tech. Rep.). Confederação Nacional da Indústria.

NGFS. (2023, Nov). *Ngfs climate scenarios technical documentation.* Author. (Accessed: 15/04/2025)

Notícias Agrícolas. (2024). *Mercado voluntário de carbono no brasil foi 10 vezes menor no ano passado ante 2021, segundo observatório de bioeconomia da fgv.* Retrieved from `https://www.noticiasagricolas.com.br/noticias/meio-ambiente/381488-mercado-voluntario-de-carbono-no-brasil-foi-10-vezes-menor-no-ano-passado-ante-2021-segundo-observatorio-de-bioeconomia-da-fgv.html` (Accessed: 2025-12-26)

NOVACANA. (2025). *As usinas de açúcar e etanol do brasi.* `https://www.novacana.com/usinas_brasil`. (Accessed: 2025-11-07)

Novacana. (2025a, Sep). *Fs anuncia primeiras transações de créditos de carbono beccs no brasil.* `https://www.novacana.com/noticias/fs-anuncia-primeiras-transacoes-creditos-carbono-beccs-brasil-010925`. (Accessed: 2025-10-15)

Novacana. (2025b, Sep). *Netzero fará biochar a partir da palha e do bagaço da cana-de-açúcar.* `https://www.novacana.com/noticias/netzero-biochar-partir-palha-bagaco-cana-de-acucar-160925`. (Accessed: 2025-11-10)

Observatório do Clima. (n.d.). *O observatório do clima.* `https://www.oc.eco.br/o-observatorio-do-clima/`. (Accessed: 2025-11-09)

Okcygenio. (2025). *Selling carbon credits with efficiency and legal security.* `https://www.okcygenio.com/en/carbon-credits/`. (Accessed: 2025-11-07)

Olajire, A. A. (2013). A review of mineral carbonation technology in sequestration of co2. *Journal of Petroleum Science and Engineering*, *109*, 364-392. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0920410513000673` doi: https://doi.org/10.1016/j.petrol.2013.03.013

Olander, S., & Landin, A. (2005). Evaluation of stakeholder influence in the implementation of construction projects. *International Journal of Project Management*, *23*(4), 321-328. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0263786305000232` doi: https://doi.org/10.1016/j.ijproman.2005.02.002

OpenAI. (2025, December). *Digital illustration of sugarcane and ethanol production with biochar and enhanced rock weathering.* Image generated with DALL·E via ChatGPT. (Prompt by the user; generated using model GPT-5.1 with image generation tool)

Oxford University Careers Service. (2025). *Think tanks.* `https://www.careers.ox.ac.uk/think-tanks`. (Accessed: 2025-11-09)

Paulo, P. P. (2025). *O que é e como funciona o mercado de carbono.* Retrieved from `https://g1.globo.com/meio-ambiente/cop-30/noticia/2025/08/30/o-que-e-e-como-funciona-o-mercado-de-carbono.ghtml` (Accessed: 2025-12-26)

Pelkmans, L., Cowie, A., & Berndes, G. (2024). *The role of bioenergy in the energy transition* (Commentary No. IEA Bioenergy Task 45). IEA Bioenergy, International Energy Agency. Retrieved from `https://www.iea.org/articles/what-does-net-zero-emissions-by-2050-mean-for-bioenergy-and-land-use` (Published: December 2024)

Pereira, L. L., Zubiolo, C., Nascimento, J. d. S., Freitas, L. d. S., Ruzene, D. S., & Silva, D. P. (2016). *produção de biochar a partir da pirólise de resíduos agroindustriais.* Retrieved from `https://ri.ufs.br/bitstream/riufs/7658/2/ProducaoBiocharPirolise.pdf` (Accessed: 05/09/2025)

Petrović, J., Ercegović, M., Simić, M., Koprivica, M., Dimitrijević, J., Jovanović, A., & Janković Pantić, J. (2024). Hydrothermal carbonization of waste biomass: A review of hydrochar preparation and environmental application. *Processes*, *12*(1). Retrieved from `https://www.mdpi.com/2227-9717/12/1/207` doi: 10.3390/pr12010207

Power Technology. (2013, March). *Ethanol power plant, minas gerais.* `https://www.power-technology.com/projects/ethanol-power-plant/`. (Accessed: 04/10/2025)

PR Newswire. (2024, jul). *Fs confirms geological feasibility of beccs project and will be able to produce the world's first carbon-negative ethanol.* `https://www.prnewswire.com/news-releases/fs-confirms-geological-feasibility-of-beccs-project-and-will-be-able-to-produce-the-worlds-first-carbon-negative-ethanol-302158599.html`. (Accessed: 2025-10-15)

Qambrani, N. A., Rahman, M. M., Won, S., Shim, S., & Ra, C. (2017). Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: A review. *Renewable and Sustainable Energy Reviews*, *79*, 255-273. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1364032117306937` doi: https://doi.org/10.1016/j.rser.2017.05.057

Rashid, M. I., Yaqoob, Z., Mujtaba, M., Fayaz, H., & Saleel, C. A. (2023). Developments in mineral carbonation for carbon sequestration. *Heliyon*, *9*(11), e21796. Retrieved from `https://www.sciencedirect.com/science/article/pii/S2405844023090047` doi: https://doi.org/10.1016/j.heliyon.2023.e21796

Raízen. (2023). *Cana-de-açúcar: Entenda o potencial da cana na transição energética.* Times de Etanol, Açúcar e Bioenergia e Sustentabilidade e Comunicação Corporativa da Raízen. Retrieved from `https://www.raizen.com.br/blog/potencial-da-cana-de-acucar` (Accessed: 27/05/2025)

Ringrose, P., Furre, A.-K., Gilfillan, S., Krevor, S., Landro, M., Leslie, R., … Zahid, A. (2021, 06). Storage of carbon dioxide in saline aquifers: Physicochemical processes, key constraints, and scale-up potential. *Annual Review of Chemical and Biomolecular Engineering*, *12*. doi: 10.1146/annurev-chembioeng-093020-091447

Ronsse, F., Nachenius, R. W., & Prins, W. (2015). Chapter 11 - carbonization of biomass. In A. Pandey, T. Bhaskar, M. Stöcker, & R. K. Sukumaran (Eds.), *Recent advances in thermo-chemical conversion of biomass* (p. 293-324). Boston: Elsevier. Retrieved from `https://www.sciencedirect.com/science/article/pii/B9780444632890000119` doi: https://doi.org/10.1016/B978-0-444-63289-0.00011-9

Rosenbloom, D. (2019). A clash of socio-technical systems: Exploring actor interactions around electrification and electricity trade in unfolding low-carbon pathways for ontario. *Energy Research Social Science*, *49*, 219-232. Retrieved from `https://www.sciencedirect.com/science/article/pii/S2214629618307266` doi: https://doi.org/10.1016/j.erss.2018.10.015

Ryan, P., Santis, A., Vanderkloot, E., Bhatti, M., Caddle, S., Ellis, M., … Wright, S. (2024). The potential for carbon dioxide removal by enhanced rock weathering in the tropics: An evaluation of costa rica. *Science of The Total Environment*, *927*, 172053. Retrieved from `https://www.sciencedirect.com/science/article/pii/S004896972402196X` doi: https://doi.org/10.1016/j.scitotenv.2024.172053

Salomão, I. C. (2024). O plano real. *Economia & História: Difusão de ideias econômicas*.

Santos, L. F. (2024, feb). *Certificadoras brasileiras de créditos de carbono buscam espaço em mercado dominado por estrangeiras.* Terra. Retrieved from `https://www.terra.com.br/economia/certificadoras-brasileiras-de-creditos-de-carbono-buscam-espaco-em-mercado-dominado-por-estrangeiras,2c4dfce1a9e015977f9ee18ca8365d2erj9zjpya.html` (Accessed: 2025-11-07)

Sawaya, R. R. (2024). Plano real, neoliberalismo e transformação estrutural. *Revista NECAT - Revista do Núcleo de Estudos de Economia Catarinense*, *13*(26), 56–75. Retrieved from `https://ojs.sites.ufsc.br/index.php/revistanecat/article/view/6463`

Schmidt, M. J., Goldberg, S. L., Heckenberger, M., Fausto, C., Franchetto, B., Watling, J., … Perron, J. T. (2023). Intentional creation of carbon-rich dark earth soils in the amazon. *Science Advances*, *9*(38), eadh8499. Retrieved from `https://www.science.org/doi/abs/10.1126/sciadv.adh8499` doi: 10.1126/sciadv.adh8499

Shahbaz, M., AlNouss, A., Ghiat, I., Mckay, G., Mackey, H., Elkhalifa, S., & Al-Ansari, T. (2021). A comprehensive review of biomass based thermochemical conversion technologies integrated with co2 capture and utilisation within beccs networks. *Resources, Conservation and Recycling*, *173*, 105734. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0921344921003438` doi: https://doi.org/10.1016/j.resconrec.2021.105734

Shi, J., & Durucan, S. (2005). Co2 storage in deep unminable coal seams. *Oil & gas science and technology*, *60*(3), 547–558.

Silva, A. C. (2018, Mar). Retrieved from `https://www.ihu.unisinos.br/categorias/188-noticias-2018/577480-cana-de-acucar-da-amazonia-uma-ameaca-a-floresta` (Accessed: 02/06/2025)

Singh, R., Goyal, A., & Sinha, S. (2025). Global insights into biochar: Production, sustainable applications, and market dynamics. *Biomass and Bioenergy*, *194*, 107663. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0961953425000741` doi: https://doi.org/10.1016/j.biombioe.2025.107663

Singh Yadav, S. P., Bhandari, S., Bhatta, D., Poudel, A., Bhattarai, S., Yadav, P., … Oli, B. (2023). Biochar application: A sustainable approach to improve soil health. *Journal of Agriculture and Food Research*, *11*, 100498. Retrieved from `https://www.sciencedirect.com/science/article/pii/S2666154323000054` doi: https://doi.org/10.1016/j.jafr.2023.100498

Siqueira, C., & Triboli, P. (2023, Dec). *Câmara aprova projeto que regulamenta o mercado de carbono no brasil - notícias.* Retrieved from `https://www.camara.leg.br/noticias/1029046-CAMARA-APROVA-PROJETO-QUE-REGULAMENTA-O-MERCADO-DE-CARBONO-NO-BRASIL` (Accessed: 26/05/2025)

Smith, S., Geden, O., Gidden, M., Lamb, W., Nemet, G., Minx, J., … Vaughan, N. (2024). *The state of carbon removal 2024 - 2nd edition* (Tech. Rep.). University of Oxford's Smith School of Enterprise and the Environment. Retrieved from `https://www.stateofcdr.org` doi: 10.17605/OSF.IO/F85QJ

Soares, M. (2024). *Quem compra e busca integridade no mercado voluntário de carbono.* Retrieved from `https://exame.com/esg/quem-compra-e-busca-integridade-no-mercado-voluntario-de-carbono/` (Accessed: 2025-12-26)

S. Oliveira, L., & G.Cruz, A. (2023). Techno-economic analysis and carbon intensity of sugarcane-corn flex plants in brazil. *Bioresource Technology Reports*, *24*, 101694. Retrieved from `https://www.sciencedirect.com/science/article/pii/S2589014X23003651` doi: https://doi.org/10.1016/j.biteb.2023.101694

Speight, J. G. (2019). 3 - unconventional gas. In J. G. Speight (Ed.), *Natural gas (second edition)* (Second Edition ed., p. 59-98). Boston: Gulf Professional Publishing. Retrieved from `https://www.sciencedirect.com/science/article/pii/B9780128095706000035` doi: https://doi.org/10.1016/B978-0-12-809570-6.00003-5

Stellantis. (2023, Mar). *Comparativo de emissões de co2 confirma vantagens do etanol para uma* *mobilidade mais sustentável.* Retrieved from `https://www.media.stellantis.com/br-pt/corporate-communications/press/comparativo-de-emissoes-de-co2-confirma-vantagens-do-etanol-para-uma-mobilidade-mais-sustentavel` (Accessed: 02/06/2025)

Strefler, J., Amann, T., Bauer, N., Kriegler, E., & Hartmann, J. (2018, mar). Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, *13*(3), 034010. Retrieved from `https://dx.doi.org/10.1088/1748-9326/aaa9c4` doi: 10.1088/1748-9326/aaa9c4

Sun, T., Xiao, K.-Q., & Feng, L. (2025). Enhanced rock weathering aids to promote carbon sequestration and yield in china's agricultural fields. *Climate Smart Agriculture*, *2*(4), 100072. Retrieved from `https://www.sciencedirect.com/science/article/pii/S2950409025000334` doi: https://doi.org/10.1016/j.csag.2025.100072

Terradot. (2025). *Terradot Deepens ERW Deployment in Brazil Amid Rising Global Momentum at COP30.* Retrieved from `https://terradot.earth/news/with-cop30-underway-in-brazil-terradot-plans-to-5x-enhanced-rock-weathering-deployments-in-the-country` (Accessed: 2025-12-20)

Torbergsen, L. E., Leinum, B. H., & Røneid, S. (2025). Key considerations for re-qualification of pipelines for carbon dioxide in gas phase transport. In *Proceedings of the 2025 pipeline technology conference.* Berlin, Germany: DNV AS. Retrieved from `https://www.pipeline-conference.com/abstracts/key-considerations-re-qualification-pipelines-carbon-dioxide-gas-phase-transport` (Accessed: 07/10/2025)

Toscano Miranda, N., Lopes Motta, I., Maciel Filho, R., & Wolf Maciel, M. R. (2021). Sugarcane bagasse pyrolysis: A review of operating conditions and products properties. *Renewable and Sustainable Energy Reviews*, *149*, 111394. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1364032121006791` doi: https://doi.org/10.1016/j.rser.2021.111394

TV Câmara. (2014, jul 1). *Lançado há 20 anos, Plano Real acabou com a hiperinflação.* Portal da Câmara dos Deputados. Retrieved from `https://www.camara.leg.br/tv/437249-lancado-ha-20-anos-plano-real-acabou-com-a-hiperinflaca` (Program: Câmara Hoje. Accessed: 2025-12-26)

UNFCCC. (n.d.-a). *Nationally determined contributions (ndcs).* Retrieved from `https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs` (Accessed: 15/01/2025)

UNFCCC. (n.d.-b). *The paris agreement.* Retrieved from `https://unfccc.int/process-and-meetings/the-paris-agreement` (Accessed: 15/01/2025)

Ungureanu, N., Vladut, V., & Biris, S.-S. (2022, 09). Sustainable valorization of waste and by-products from sugarcane processing. *Sustainability*, *14*, 11089. doi: 10.3390/su141711089

Unica. (n.d.). *Fotografia do setor sucroenergético no brasil e os benefícios econômicos, ambientais e sociais gerados.* Retrieved from `https://unicadata.com.br/download_media.php?idM=40519592` (Accessed: 27/05/2025)

Unica. (2024, Apr). *Ethanol.* Retrieved from `https://unica.com.br/en/sugarcane-sector/ethanol/` (Accessed: 02/06/2025)

Unica. (2025, Mar). *Bioeletricidade em números.* Retrieved from `https://unicadata.com.br/download_media.php?idM=14876289` (Accessed: 01/06/2025)

Unica. (2025). *History and mission.* `https://unica.com.br/en/`. (Accessed: 2025-11-05)

USDA. (2024). *Production - sugar.* Retrieved from `https://www.fas.usda.gov/data/production/commodity/0612000` (Accessed: 16/02/2025)

van Bree, B., Verbong, G., & Kramer, G. (2010). A multi-level perspective on the introduction of hydrogen and battery-electric vehicles. *Technological Forecasting and Social Change*, *77*(4), 529-540. Retrieved from `https://www.sciencedirect.com/science/article/pii/S004016250900211X` doi: https://doi.org/10.1016/j.techfore.2009.12.005

Venditte, F. (2025). *Usinas sucroenergéticas vivem fase mais sólida, diz Itaú BBA.* Retrieved from `https://revistacultivar.com.br/noticias/usinas-sucroenergeticas-vivem-fase-mais-solida-diz-itau-bba` (Accessed: 2025-12-26)

Vian, C. (2022, Feb). *Etanol.* Retrieved from `https://www.embrapa.br/agencia-de-informacao-tecnologica/cultivos/cana/pos-producao/alcool/tecnologias-emergentes/etanol` (Accessed: 30/05/2025)

Walton, J. (2024, Aug). *The 5 countries that produce the most sugar.* Investopedia. Retrieved from `https://www.investopedia.com/articles/investing/101615/5-countries-produce-most-sugar.asp` (Accessed: 16/02/2025)

Wang, F., Dreisinger, D. B., Jarvis, M., & Hitchins, T. (2018). The technology of co2 sequestration by mineral carbonation: current status and future prospects. *Canadian Metallurgical Quarterly*, *57*(1), 46–58. Retrieved from `https://doi.org/10.1080/00084433.2017.1375221` doi: 10.1080/00084433.2017.1375221

Wei, B., Wang, B., Li, X., Aishan, M., & Ju, Y. (2023). Co□ storage in depleted oil and gas reservoirs: A review. *Advances in Geo-Energy Research*, *9*(2), 76–93. Retrieved from `https://doi.org/10.46690/ager.2023.08.02` doi: 10.46690/ager.2023.08.02

Worden, R. H. (2024). Carbon dioxide capture and storage in saline aquifers versus depleted gas fields. *Geosciences*, *14*(2), 52. Retrieved from `https://doi.org/10.3390/geosciences14060146` doi: 10.3390/geosciences14060146

WRI Brasil. (n.d.). *Wri brasil-website*. `https://www.wribrasil.org.br/`. (Accessed: 2025-11-09)

Zafeer, M., Menezes, R., Hillemane, V., & K, S. (2023, 12). Sugarcane bagasse-based biochar and its potential applications: a review. *Emergent Materials*, *7*. doi: 10.1007/s42247-023-00603-y

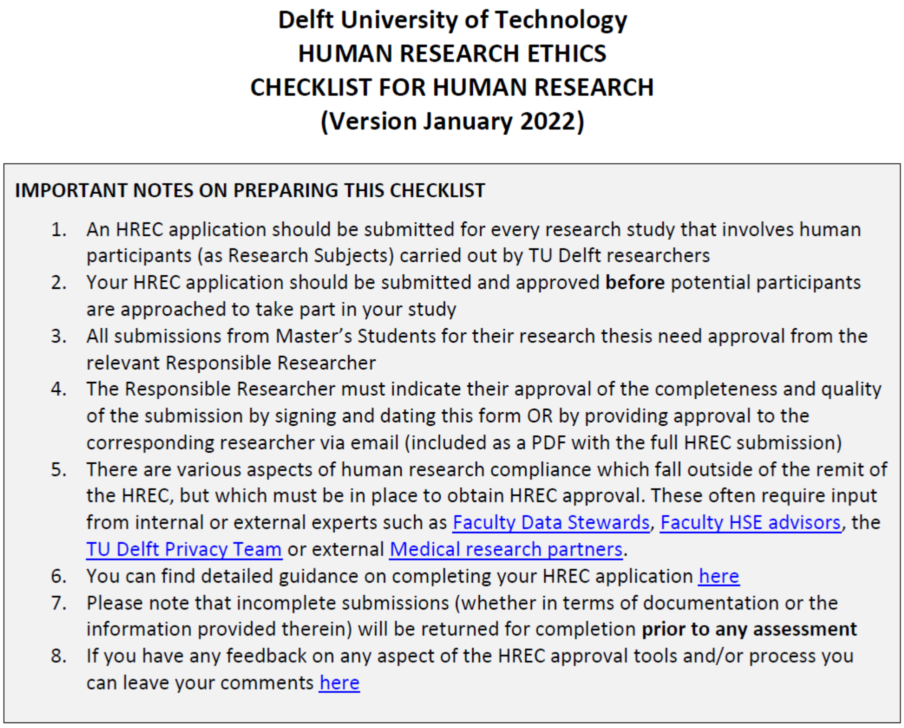
Zhou, S., Yang, X., Tran, T.-K., Shen, J., & An, C. (2025). Paving the way for biochar production, supply chain, and applications toward a sustainable future. *Cleaner Waste Systems*, *10*, 100227. Retrieved from `https://www.sciencedirect.com/science/article/pii/S2772912525000259` doi: https://doi.org/10.1016/j.clwas.2025.100227

Zilberman, D., Laird, D., Rainey, C., Song, J., & Kahn, G. (2022, 10). Biochar supply-chain and challenges to commercialization. *GCB Bioenergy*, *15*. doi: 10.1111/gcbb.12952

Appendix A

Interviews Risk Assessment, and Ethics Approval

A.1 Human Research Ethics Checklist - Risk Assessment



Delft University of Technology
HUMAN RESEARCH ETHICS
CHECKLIST FOR HUMAN RESEARCH
(Version January 2022)

IMPORTANT NOTES ON PREPARING THIS CHECKLIST

1. An HREC application should be submitted for every research study that involves human participants (as Research Subjects) carried out by TU Delft researchers
2. Your HREC application should be submitted and approved **before** potential participants are approached to take part in your study
3. All submissions from Master's Students for their research thesis need approval from the relevant Responsible Researcher
4. The Responsible Researcher must indicate their approval of the completeness and quality of the submission by signing and dating this form OR by providing approval to the corresponding researcher via email (included as a PDF with the full HREC submission)
5. There are various aspects of human research compliance which fall outside of the remit of the HREC, but which must be in place to obtain HREC approval. These often require input from internal or external experts such as Faculty Data Stewards, Faculty HSE advisors, the TU Delft Privacy Team or external Medical research partners.
6. You can find detailed guidance on completing your HREC application here
7. Please note that incomplete submissions (whether in terms of documentation or the information provided therein) will be returned for completion **prior to any assessment**
8. If you have any feedback on any aspect of the HREC approval tools and/or process you can leave your comments here

I. Applicant Information

PROJECT TITLE:	**Regime Actors Role in the Transition of Carbon Dioxide Removal Technologies in Brazil**
Research period: *Over what period of time will this specific part of the research take place*	**November(2025)-January (2025)**
Faculty:	**Technology, Policy and Management**
Department:	**Sustainable Technologies**
Type of the research project: *(Bachelor's, Master's, DreamTeam, PhD, PostDoc, Senior Researcher, Organisational etc.)*	**Master**
Funder of research: *(EU, NWO, TUD, other – in which case please elaborate)*	
Name of Corresponding Researcher: *(If different from the Responsible Researcher)*	**Bruna Vaz Soares da Silva**
Position of Corresponding Researcher: *(Masters, DreamTeam, PhD, PostDoc, Assistant/ Associate/ Full Professor)*	**Master Student**
Name of Responsible Researcher: ***Note:*** *all student work must have a named Responsible Researcher to approve, sign and submit this application*	**Linda Kamp**
E-mail of Responsible Researcher: *Please ensure that an institutional email address (**no Gmail, Yahoo, etc.**) is used for all project documentation/ communications including Informed Consent materials*	
Position of Responsible Researcher : *(PhD, PostDoc, Associate/ Assistant/ Full Professor)*	**Assistant Professor**

II. Research Overview

NOTE: *You can find more guidance on completing this checklist here*

a) Please summarise your research very briefly (100-200 words)

What are you looking into, who is involved, how many participants there will be, how they will be recruited and what are they expected to do?

Add your text here – (please avoid jargon and abbrevations)
The research seeks to investigate the influence of incumbent firms and political dynamics on the development and integration of Carbon Dioxide Removal (CDR) technologies in Brazil's sugarcane and ethanol industry. The actors involved will be people in the industry, policymakers, energy experts, companies working with the studied technologies, and other actors in hard-to-decarbonize industries. It is expected to have around 10-15 participants. They will be recruited via linkedin and email. They are expected to answer some questions about the field and prospects. Participantas will be informed of the risks of being reidentified by people in the field due to the niche nature of the technologies studied and few companies in the field. They will receive the technical summary of the interview that will be published in the appendix of the thesis and they will have say and control of how they can be reidentified.

b) **If your application is an additional project** related to an existing approved HREC submission, please provide a brief explanation including the existing relevant HREC submission number/s.

Add your text here – (please avoid jargon and abbrevations)

c) **If your application is a simple extension of, or amendment to,** an existing approved HREC submission, you can simply submit an HREC Amendment Form as a submission through LabServant.

III. Risk Assessment and Mitigation Plan

NOTE: *You can find more guidance on completing this checklist here*

Please complete the following table in full for all points to which your answer is "yes". Bear in mind that the vast majority of projects involving human participants as Research Subjects also involve the collection of **Personally Identifiable Information (PII)** and/or **Personally Identifiable Research Data (PIRD)** which may pose potential risks to participants as detailed in Section G: Data Processing and Privacy below.

To ensure alighment between your risk assessment, data management and what you agree with your Research Subjects you can use the last two columns in the table below to refer to specific points in your Data Management Plan (DMP) and Informed Consent Form (ICF) – **but this is not compulsory**.

It's worth noting that **you're much more likely to need to resubmit your application if you neglect to identify potential risks**, than if you identify a potential risk and demonstrate how you will mitigate it. If necessary, the HREC will always work with you and colleagues in the Privacy Team and Data Management Services to see how, if at all possible, your research can be conducted.

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	Yes	No	RISK ASSESSMENT – what risks could arise? *Please ensure that you list ALL of the actual risks that could potentially arise – do not simply state whether you consider any such risks are important!*	MITIGATION PLAN – what mitigating steps will you take? *Please ensure that you summarise what actual mitigation measures you will take for each potential risk identified – do not simply state that you will e.g. comply with regulations.*	DMP	ICF
A: Partners and collaboration						
1. Will the research be carried out in collaboration with additional organisational partners such as: • One or more collaborating research and/or commercial organisations • Either a research, or a work experience internship provider[1] *[1] If yes, please include the graduation agreement in this application*		No				
2. Is this research dependent on a Data Transfer or Processing Agreement with a collaborating partner or third party supplier? *If yes please provide a copy of the signed DTA/DPA*		No				
3. Has this research been approved by another (external) research ethics committee (e.g.: HREC and/or MREC/METC)? *If yes, please provide a copy of the approval (if possible) and summarise any key points in your Risk Management section below*		No				
B: Location						
4. Will the research take place in a country or countries, other than the Netherlands, within the EU?		No				
5. Will the research take place in a country or countries outside the EU?	Yes		**Risks: -Language Barries -Privacy Laws**	**-The main researcher is Brazilian, and will be able to run the interviews in the local language and do translation when required -The participants will be informed that the personal data will be handled according to EU regulations (GDPR)**		
6. Will the research take place in a place/region or of higher risk – including known dangerous locations (in any country) or locations with non-democratic regimes?		No				
C: Participants						
7. Will the study involve participants who **may** be vulnerable and possibly (legally) unable to give informed consent? (e.g., children below the legal age for giving consent, people with learning difficulties, people living in care or nursing homes,).		No				
8. Will the study involve participants who **may** be vulnerable under specific circumstances and in specific contexts, such as victims and witnesses of violence, including domestic violence; sex workers; members of minority groups, refugees, irregular migrants or dissidents?		No				
9. Are the participants, outside the context of the research, in a dependent or subordinate position to the investigator (such as own children, own students or employees of either TU Delft and/or a collaborating partner organisation)? *It is essential that you safeguard against possible adverse consequences of this situation (such as allowing a student's failure to participate to your satisfaction to affect your evaluation of their coursework).*		No				
10. Is there a high possibility of re-identification for your participants? (e.g., do they have a very specialist job of which there are only a small number in a given country, are they members of a small community, or employees from a partner company collaborating in the research? Or are they one of only a handful of (expert) participants in the study?	Yes		**Risks: - due to the niche nature of the participants activity in the area, they may still be re-identified by members of the field or community based on the published information**	**The participants will receive the transcripts and anonymized interview summary by email before the thesis finalization and they will have the opportunity to review the summaries and suggest any modification if they think it is necessary.**		
D: Recruiting Participants						

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?** *Please ensure that you list ALL of the actual risks that could potentially arise – do not simply state whether you consider any such risks are important!*	**MITIGATION PLAN – what mitigating steps will you take?** *Please ensure that you summarise what actual mitigation measures you will take for each potential risk identified – do not simply state that you will e.g. comply with regulations.*	**DMP**	**ICF**
11. Will your participants be recruited through your own, professional, channels such as conference attendance lists, or through specific network/s such as self-help groups	**Yes**		**Risks:** **Losing the list of participants**	**The list of participants is stored at TUD, accessible only to the TUD team.**		
12. Will the participants be recruited or accessed in the longer term by a (legal or customary) gatekeeper? (e.g., an adult professional working with children; a community leader or family member who has this customary role – within or outside the EU; the data producer of a long-term cohort study)		**No**				
13. Will you be recruiting your participants through a crowd-sourcing service and/or involve a third party data-gathering service, such as a survey platform?		**No**				
14. Will you be offering any financial, or other, remuneration to participants, and might this induce or bias participation?		**No**				
E: Subject Matter *Research related to medical questions/health may require special attention. See also the website of the CCMO before contacting the HREC.*						
15. Will your research involve any of the following: • Medical research and/or clinical trials • Invasive sampling and/or medical imaging • Medical and *In Vitro Diagnostic Medical* Devices Research		**No**				
16. Will drugs, placebos, or other substances (e.g., drinks, foods, food or drink constituents, dietary supplements) be administered to the study participants? *If yes see here to determine whether medical ethical approval is required*		**No**				
17. Will blood or tissue samples be obtained from participants? *If yes see here to determine whether medical ethical approval is required*		**No**				
18. Does the study risk causing psychological stress or anxiety beyond that normally encountered by the participants in their life outside research?		**No**				
19. Will the study involve discussion of personal sensitive data which could put participants at increased legal, financial, reputational, security or other risk? (e.g., financial data, location data, data relating to children or other vulnerable groups) *Definitions of sensitive personal data, and special cases are provided on the TUD Privacy Team website.*		**No**				
20. Will the study involve disclosing commercially or professionally sensitive, or confidential information? (e.g., relating to decision-making processes or business strategies which might, for example, be of interest to competitors)	**Yes**		**Risks:** **-The participants may reveal confidential information during the interview**	**The participants will have the opportunity to review the summaries before analysis and suggest any modification they deem necessary**		

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?** *Please ensure that you list ALL of the actual risks that could potentially arise – do not simply state whether you consider any such risks are important!*	**MITIGATION PLAN – what mitigating steps will you take?** *Please ensure that you summarise what actual mitigation measures you will take for each potential risk identified – do not simply state that you will e.g. comply with regulations.*	**DMP**	**ICF**
21. Has your study been identified by the TU Delft Privacy Team as requiring a Data Processing Impact Assessment (DPIA)? *If yes please attach the advice/ approval from the Privacy Team to this application*		**No**				
22. Does your research investigate causes or areas of conflict? *If yes please confirm that your fieldwork has been discussed with the appropriate safety/security advisors and approved by your Department/Faculty.*		**No**				
23. Does your research involve observing illegal activities or data processed or provided by authorities responsible for preventing, investigating, detecting or prosecuting criminal offences *If so please confirm that your work has been discussed with the appropriate legal advisors and approved by your Department/Faculty.*		**No**				
F: Research Methods						
24. Will it be necessary for participants to take part in the study without their knowledge and consent at the time? (e.g., covert observation of people in non-public places).		**No**				
25. Will the study involve actively deceiving the participants? (For example, will participants be deliberately falsely informed, will information be withheld from them or will they be misled in such a way that they are likely to object or show unease when debriefed about the study).		**No**				
26. Is pain or more than mild discomfort likely to result from the study? And/or could your research activity cause an accident involving (non-) participants?		**No**				
27. Will the experiment involve the use of devices that are not 'CE' certified? *Only, if 'yes': continue with the following questions:*		**No**				
• Was the device built in-house?						
• Was it inspected by a safety expert at TU Delft? *If yes, please provide a signed device report*						
• If it was not built in-house and not CE-certified, was it inspected by some other, qualified authority in safety and approved? *If yes, please provide records of the inspection*						
28. Will your research involve face-to-face encounters with your participants and if so how will you assess and address Covid considerations?		**No**				
29. Will your research involve **either:**		**No**				

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	Yes	No	RISK ASSESSMENT – what risks could arise? *Please ensure that you list ALL of the actual risks that could potentially arise – do not simply state whether you consider any such risks are important!*	MITIGATION PLAN – what mitigating steps will you take? *Please ensure that you summarise what actual mitigation measures you will take for each potential risk identified – do not simply state that you will e.g. comply with regulations.*	DMP	ICF
a) "big data", combined datasets, new data-gathering or new data-merging techniques which might lead to re-identification of your participants **and/or** b) artificial intelligence or algorithm training where, for example biased datasets could lead to biased outcomes?						
G: Data Processing and Privacy						
30. Will the research involve collecting, processing and/or storing any directly identifiable PII (Personally Identifiable Information) including name or email address that will be used for administrative purposes only? (eg: obtaining Informed Consent or disbursing remuneration)	**Yes**		**Risks:** **Losing personal data, unwanted access to personal data**	**All personal data will be stored at TUD, accessible only to the TUD team**		
31. Will the research involve collecting, processing and/or storing any directly or indirectly identifiable PIRD (Personally Identifiable Research Data) including videos, pictures, IP address, gender, age etc and **what other Personal Research Data** (including personal or professional views) will you be collecting?	**Yes**		**Risks:** **Losing personal data, unwanted access to personal data**	**All personal data will be stored at TUD, accessible only to the TUD team**		
32. Will this research involve collecting data from the internet, social media and/or publicly available datasets which have been originally contributed by human participants		**No**				
33. Will your research findings be published in one or more forms in the public domain, as e.g., Masters thesis, journal publication, conference presentation or wider public dissemination?	**Yes**		**Risks:** **Possible identification of the participants, due to job, company, field of work**	**the indentifiable information will be taken off of the transcripsts and results and written in a way that the interviewee will not be identifiable.**		
34. Will your research data be archived for re-use and/or teaching in an open, private or semi-open archive?	**Yes**		**Risks:** **Possible identification of the participants, due to job, company, field of work**	**Anonymosu summaries reviewed by participants**		

H: More on Informed Consent and Data Management

***NOTE:** You can find guidance and templates for preparing your Informed Consent materials) here*

Your research involves human participants as Research Subjects if you are recruiting them or actively involving or influencing, manipulating or directing them in any way in your research activities. This means you must seek informed consent and agree/ implement appropriate safeguards regardless of whether you are collecting any PIRD.

Where you are also collecting PIRD, and using Informed Consent as the legal basis for your research, you need to also make sure that your IC materials are clear on any related risks and the mitigating measures you will take – including through responsible data management.

Got a comment on this checklist or the HREC process? You can leave your comments here

IV. Signature/s

Please note that by signing this checklist list as the sole, or Responsible, researcher you are providing approval of the completeness and quality of the submission, as well as confirming alignment between GDPR, Data Management and Informed Consent requirements.

Name of Corresponding Researcher (if different from the Responsible Researcher) (print)
Bruna Vaz Soares da Silva

Signature of Corresponding Researcher:

Date:07-10-2025

Name of Responsible Researcher (print)
Linda Kamp

Signature (or upload consent by mail) Responsible Researcher:
LMKamp

Date: 07-10-2025

V. Completing your HREC application

Please use the following list to check that you have provided all relevant documentation

Required:

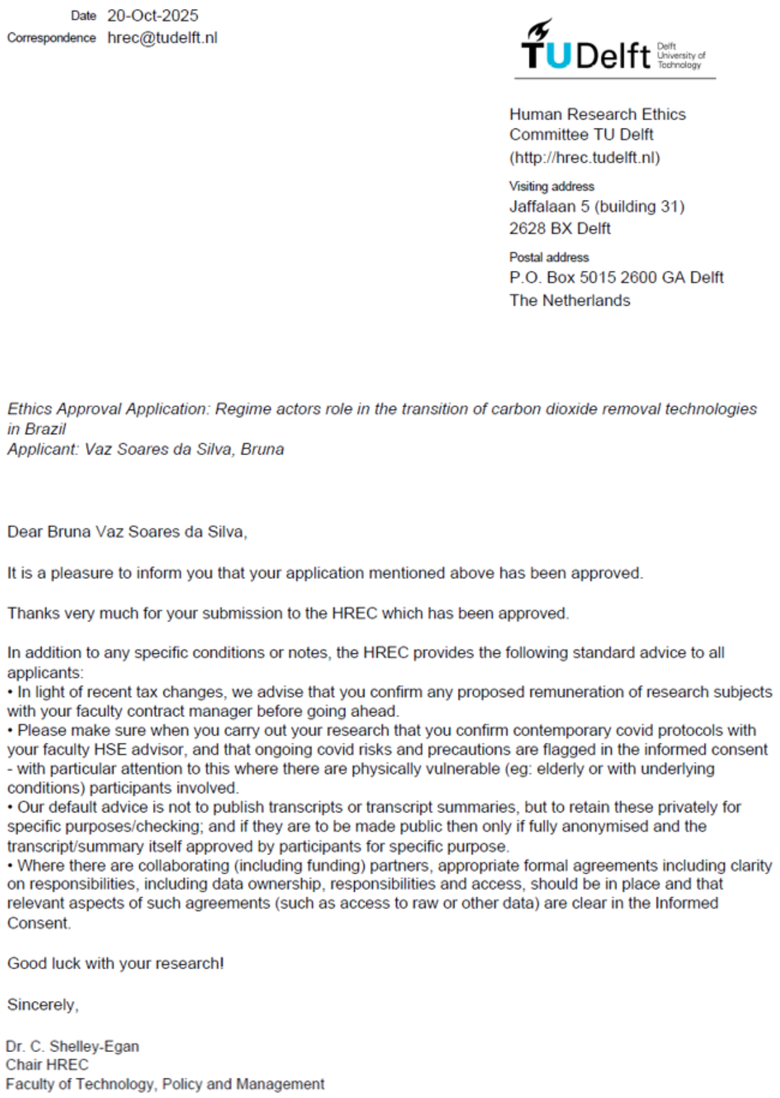
○ **Always:** This completed HREC checklist
○ **Always:** A data management plan (reviewed, where necessary, by a data-steward)

- **Usually:** A complete Informed Consent form (including Participant Information) and/or Opening Statement (for online consent)

Please also attach any of the following, if relevant to your research:

Document or approval	Contact/s
Full Research Ethics Application	After the assessment of your initial application **HREC will let you know if and when you need to submit additional information**
Signed, valid Device Report	Your Faculty HSE advisor
Ethics approval from an external Medical Committee	TU Delft Policy Advisor, Medical (Devices) Research
Ethics approval from an external Research Ethics Committee	Please append, if possible, with your submission
Approved Data Transfer or Data Processing Agreement	Your Faculty Data Steward and/or TU Delft Privacy Team
Approved Graduation Agreement	Your Master's thesis supervisor
Data Processing Impact Assessment (DPIA)	TU Delft Privacy Team
Other specific requirement	Please reference/explain in your checklist and append with your submission

A.2 Letter of Approval from Educational Institution



Date 20-Oct-2025
Correspondence hrec@tudelft.nl

TU Delft Delft University of Technology

Human Research Ethics
Committee TU Delft
(http://hrec.tudelft.nl)

Visiting address
Jaffalaan 5 (building 31)
2628 BX Delft

Postal address
P.O. Box 5015 2600 GA Delft
The Netherlands

Ethics Approval Application: Regime actors role in the transition of carbon dioxide removal technologies in Brazil
Applicant: Vaz Soares da Silva, Bruna

Dear Bruna Vaz Soares da Silva,

It is a pleasure to inform you that your application mentioned above has been approved.

Thanks very much for your submission to the HREC which has been approved.

In addition to any specific conditions or notes, the HREC provides the following standard advice to all applicants:
- In light of recent tax changes, we advise that you confirm any proposed remuneration of research subjects with your faculty contract manager before going ahead.
- Please make sure when you carry out your research that you confirm contemporary covid protocols with your faculty HSE advisor, and that ongoing covid risks and precautions are flagged in the informed consent - with particular attention to this where there are physically vulnerable (eg: elderly or with underlying conditions) participants involved.
- Our default advice is not to publish transcripts or transcript summaries, but to retain these privately for specific purposes/checking; and if they are to be made public then only if fully anonymised and the transcript/summary itself approved by participants for specific purpose.
- Where there are collaborating (including funding) partners, appropriate formal agreements including clarity on responsibilities, including data ownership, responsibilities and access, should be in place and that relevant aspects of such agreements (such as access to raw or other data) are clear in the Informed Consent.

Good luck with your research!

Sincerely,

Dr. C. Shelley-Egan
Chair HREC
Faculty of Technology, Policy and Management

Appendix B

Informed Consent Interviews

Informed Consent Form

Para versão em português veja próxima página

You are invited to participate in a research study titled Regime Actors' Role in the Transition of Carbon Dioxide Removal Technologies in Brazil. This study is being done by Bruna Vaz Soares da Silva from TU Delft as part of her Master's Thesis. The research seeks to investigate the influence of incumbent firms and political dynamics on the development and integration of Carbon Dioxide Removal (CDR) technologies in Brazil's sugarcane and ethanol industry.

What Participation Involves

If you agree to participate, you will take part in an interview lasting approximately 60 minutes. During the interview, you will be asked for your views and expectations regarding BECCS, biochar, and enhanced rock weathering (ERW) technologies, as well as the prospects for integrating CDR technologies into Brazil's sugarcane and ethanol industry. We will also discuss potential policies, drivers, and barriers relevant to the deployment of these technologies within sustainability agendas.

Confidentiality and Data Protection

Your participation is voluntary and your responses will be treated with strict confidentiality. To minimize risks:

- Personal details shared during the interview will be omitted or anonymized in the research results to avoid any possibility of identification.
- The interview will be recorded for study purposes and later transcribed. Only relevant information regarding the research study will be included in the thesis appendix, with all identifying information redacted.
- If at any point you share information that you prefer not to be included, you may request its removal.
- All data will be securely stored on TU Delft's OneDrive and handled in compliance with the European Union's General Data Protection Regulation (GDPR).
- All personal data will be permanently deleted after the completion of the project, expected in February 2026.

Voluntary Participation and Right to Withdraw

Your participation in this study is entirely voluntary. You are free to decline to answer specific questions, and you may withdraw from the study at any time.

Participant Review and Possible Re-identification Risks

You will receive both the transcript of your interview and a technical summary by email. This will allow you to request corrections, clarifications, or removal of any information. Only the anonymized summary will be included in the MSc thesis and made publicly available.

Despite best efforts to protect your identity, due to the specialized nature of your role and community, there remains the possibility that you may be re-identified by peers or other members of your field based on the published information. To minimize this risk, only anonymized summaries will be included in the thesis, this summary of your interview will be sent to you by email. You will also have the opportunity to request modifications or the removal of any information you do not wish to be made public, provided such requests are submitted no later than one week before the final submission deadline of the thesis. The exact deadline will be clearly stated in the email accompanying your interview summary.

Contact Information

If you have any questions about this study, please feel free to contact the responsible researcher

Termo de Consentimento Livre e Esclarecido

Você está convidado(a) a participar de uma pesquisa intitulada “Actors’ Role in the Transition of Carbon Dioxide Removal Technologies in Brazil”. Este estudo está sendo conduzido por Bruna Vaz Soares da Silva, estudante da TU Delft, como parte de sua dissertação de mestrado. A pesquisa tem como objetivo investigar a influência de empresas estabelecidas e de dinâmicas políticas no desenvolvimento e na integração de tecnologias de Remoção de Dióxido de Carbono (CDR) na indústria brasileira de cana-de-açúcar e etanol.

O Que é Esperado da Sua Participação

Se você concordar em participar, será convidado(a) para uma entrevista com duração aproximada de 60 minutos. Durante a entrevista serão solicitadas suas opiniões e expectativas a respeito das tecnologias de BECCS, biochar e intemperismo acelerado de rochas (ERW), bem como sobre as perspectivas de integração dessas tecnologias ao setor de cana-de-açúcar e etanol no Brasil. Também discutiremos possíveis políticas, fatores impulsionadores e barreiras relevantes para a implementação dessas tecnologias dentro de agendas de sustentabilidade..

Confidencialidade e Proteção de Dados

Sua participação é voluntária e suas respostas serão tratadas com estrita confidencialidade. Para minimizar quaisquer riscos:

- Detalhes pessoais compartilhados durante a entrevista serão omitidos ou anonimizados nos resultados da pesquisa, a fim de evitar qualquer possibilidade de identificação.
- A entrevista será gravada exclusivamente para fins acadêmicos e posteriormente transcrita. Apenas informações relevantes para o estudo serão incluídas no apêndice da dissertação, e todos os dados identificáveis serão removidos.
- Caso, você compartilhe informações que prefira não incluir, poderá solicitar sua remoção.
- Todos os dados serão armazenados com segurança no OneDrive da TU Delft e tratados em conformidade com o Regulamento Geral de Proteção de Dados (GDPR) da União Europeia.
- Todos os dados pessoais serão permanentemente excluídos após a conclusão do projeto, prevista para fevereiro de 2026.

Participação Voluntária e Direito de Encerramento

Sua participação neste estudo é inteiramente voluntária. Você tem o direito de não responder a perguntas específicas e pode retirar seu consentimento e encerrar a participação a qualquer momento, sem qualquer prejuízo.

Revisão do Participante e Possíveis Riscos de Reidentificação

Você receberá por e-mail tanto a transcrição da entrevista quanto um resumo técnico. Isso permitirá que solicite correções, esclarecimentos ou remoção de informações que considerar necessárias. Somente o resumo anonimizado será incluído na dissertação de mestrado e disponibilizado publicamente.

Apesar dos esforços para proteger sua identidade, devido à natureza especializada da sua função e da sua comunidade profissional, existe a possibilidade de que você seja reidentificado(a) por colegas ou outros membros da área com base nas informações publicadas. Para minimizar esse risco, apenas resumos anonimizados serão incluídos na dissertação, e esse resumo será enviado a você por e-mail. Você também terá a oportunidade de solicitar modificações ou a remoção de qualquer informação que não deseje tornar pública, desde que o pedido seja feito até uma semana antes da data final de submissão da dissertação. O prazo exato será informado no e-mail que acompanhará o resumo da sua entrevista.

Informações de Contato

Se você tiver qualquer dúvida sobre este estudo, entre em contato com a pesquisadora responsável

Signature

Assinatura

____________________________	___________________________	_________
Name of participant [printed]	Signature	Date
Nome do participante	Assinatura	Data

Appendix C

Interviews Summary

C.1 ERW Practitioner (INT-01)

Interview Profile:

The interviewee is a professional working in a company specialized in enhanced rock weathering (ERW) projects in Brazil, with direct involvement in project implementation, MRV, certification of carbon credits, and interaction with sugarcane producers, mining companies, and policymakers. The participant has prior experience in agronomy and agro-industrial supply chains.

Interview Context:

- **Date:** 26th November 2025
- **Format:** Online
- **Duration:** 57 minutes
- **Focus:** Understand ERW prospects in Brazil and possible integration in the sugar-energy sector

Main Themes and Key Insights:

1. **How the agriculture sector is shaped in Brazil**
   The participant argued that Brazilian agriculture is primarily demand-driven rather than technically driven, which can hinder the long-term diffusion of emerging technologies. He gave an example to this dynamic with the early commercialization of "rock dust," a precursor to ERW, which was sold without proper regulation or adequate processing. At the time, mining companies marketed "rock dust" as a soil amendment capable of improving soil health and crop performance. However, this product was sold without adequate regulation, primarily as a means for mining companies to dispose of residues. Due to insufficient milling and inappropriate granulometry, the product did not deliver the expected agronomic benefits. This early failure generated lasting scepticism within the agricultural sector, although subsequent regulation by the Ministry of Agriculture established technical standards. The participant noted that negative perceptions persist within the sector, continuing to act as a barrier for ERW development.

2. **Readiness of the Sugarcane Sector and Role of Incumbents**
   The participant emphasized that the Brazilian sugarcane sector is more technologically advanced and environmentally proactive than often portrayed, with many mills already adopting organic or low-input soil management practices. According to the interviewee, the sector has undergone a technological shift following

economic crises, which increased openness to innovations such as ERW, biochar, and BECCS. Large mills and producer associations were described as politically influential incumbents, capable of accelerating regulatory changes and market adoption.

3. **ERW is an Operationally Attractive CDR Technology**
   ERW was described as particularly attractive due to its operational compatibility with existing agricultural practices. Sugarcane producers already apply large quantities of lime and gypsum, meaning ERW does not require new machinery or major behavioural change. This low operational barrier was contrasted with BECCS and biochar, which were described as more capital-intensive and logistically complex.

4. **Importance of MRV, Certification, and Market Legitimacy**
   A central theme was the critical role of measurement, reporting, and verification (MRV). The participant argued that ERW only gained momentum after robust methodologies allowed for certified carbon credit issuance, including the first globally certified ERW credits generated on a sugarcane farm in Brazil. This certification was described as a "turning point" that transformed ERW from a conceptual solution into a bankable and scalable technology.

5. **Policy Integration and Regulatory Momentum**
   The interview highlighted recent policy developments as decisive, particularly:

   - Inclusion of remineralizers under RenovaBio, enabling the generation of CBIOs
   - Approval of legislation to establish a regulated carbon market in Brazil, expected to become mandatory by 2030.

   These policies were framed as strong incentives for incumbent industries (energy, cement, steel, oil gas) to engage with CDR technologies, including ERW, both for compliance and cost reasons.

6. **Economic Co-benefits**
   Beyond carbon removal, ERW was described as generating agronomic co-benefits, including improved soil fertility, increased resistance to pests and diseases (linked to silicon content), and significant productivity gains in sugarcane yields. The participant stressed that these co-benefits are essential for adoption, as producers prioritize yield stability and profitability over abstract climate benefits.

7. **Interaction with Other CDR Technologies**
   The interviewee viewed ERW, BECCS, and biochar as complementary rather than competing technologies, but noted that ERW currently benefits from lower costs per hectare, easier operationalization, and faster integration into existing regulatory frameworks. Biochar was described as facing challenges related to carbon permanence and certification, while BECCS was characterized as technologically mature but require high capital investments and infrastructure modifications.

8. **Social Acceptance and Knowledge Barriers**
   Public awareness of ERW remains limited, but the participant argued that non-agricultural audiences often understand and accept the technology more easily than producers, who may be constrained by entrenched agronomic paradigms. Pilot projects with smallholder farmers were presented as effective tools for building legitimacy and trust through visible, empirical results.

Relevance to the Thesis:

This interview provides strong empirical and practical support for the argument that incumbent actors, regulatory frameworks, and MRV capacity are very relevant to the diffusion of CDR technologies in Brazil. It highlights how ERW aligns with existing regime structures in the sugarcane sector, how it is growing in Brazil and how it has room to evolve and develop in this sector. The findings also illustrate how policy alignment (RenovaBio, regulated carbon markets) and co-benefits can accelerate niche-to-regime transitions within the MLP framework.

C.2 BECCS Practitioner (INT-02)

Interview Profile:

The interviewee is a professional working at a BECCS project in Brazil, with direct involvement in project development, regulatory engagement, and strategic planning. The participant has experience interfacing with regulators (ANP, MME), industry associations, and international policy frameworks.

Interview Context:

- **Date:** 27th November 2025
- **Format:** Online
- **Duration:** 57 minutes
- **Focus:** Understand BECCS prospects in Brazil with emphasis on regulation, incumbents, and market formation.

Main Themes and Key Insights:

1. **Strategic Role of BECCS in the Sugar-energy Sector**
   The participant framed BECCS as a strategic opportunity to transform ethanol into a carbon-negative fuel, with significant implications for Brazil's overall fuel carbon intensity. Rather than viewing BECCS solely as a carbon credit strategy, the interviewee emphasized its potential to redefine industry standards, positioning carbon-negative ethanol as the default product in the long term. The objective is to scale BECCS across all its plants, embedding carbon capture and storage as a structural component of production rather than a marginal add-on.

2. **First-Mover Risks and Incumbent Dynamics**
   The BECCS project was consistently described as a high-risk pioneer initiative. As a pioneer, the project bears high costs and uncertainties, including technological, regulatory, and commercial risks. However, the participant argued that because it is a pilot project it will probably generate a transfer of knowledge and experience, enabling more conservative incumbents to adopt the technology later with lower risk. In this sense, it is believed that the project has potential to act as a path-opening, potentially accelerating diffusion once a standardized workflow is established

3. **Technological and Operational Barriers**
   A central challenge highlighted was that BECCS requires expertise from the oil and gas sector, particularly in subsurface engineering and well drilling, a knowledge that is largely absent from the traditional sugarcane and ethanol industry. This creates steep learning curves, high upfront capital expenditures, and new operational risks unfamiliar to the sector. The participant identified well drilling and subsurface storage as the largest cost components and the most significant initial barriers.

4. **Regulatory Uncertainty and Institutional Gaps**
   interview underscored that Brazil's regulatory framework for BECCS and CCS remains immature and incomplete. While recent legislation acknowledges carbon capture and storage and assigns regulatory authority to the ANP, detailed rules regarding liability, monitoring, long-term responsibility, and credit recognition are still lacking. They are actively engaged with regulators to help shape these

frameworks, but the absence of clear rules was identified as a major deterrent for wider adoption.

5. **Regulatory Engagement and Political Enablement**
   The interviewee highlighted that active engagement with policymakers is essential for the BECCS project. The company maintains a dedicated institutional relations team working with Congress, the ANP, and relevant ministries to ensure that BECCS is discussed and incorporated into emerging regulations. According to the participant, without this sustained political presence, the project would not have advanced beyond the planning stage, given the current regulatory uncertainty surrounding CCS and BECCS in Brazil.

6. **Insufficiency of Current Incentives**
   Existing policy instruments, particularly RenovaBio, were described as insufficient to make BECCS economically viable. Although carbon-negative fuels receive a CBIOs, the participant stressed that this incentive does not come close to covering BECCS costs, especially given high capital investments. Without additional incentives, BECCS remains financially unattractive for most firms.

7. **Carbon Markets and Commercial Viability**
   The participant expressed scepticism regarding the ability of voluntary carbon markets to absorb large volumes of high-quality, high-cost BECCS credits. While BECCS credits are considered premium, their high price limits demand, as most buyers diversify portfolios with cheaper credits. Consequently, the interviewee emphasized the importance of regulated carbon markets and the need for flexibility to sell credits internationally, avoiding confinement to domestic markets with limited liquidity.

8. **Comparison with Other CDR Technologies**
   Among the CDR options discussed, biochar was viewed as more likely to scale in the short term due to lower costs; BECCS was identified as having the greatest medium-term impact potential, due to its scalability and integration with existing ethanol infrastructure; ERW was perceived as promising but still relatively immature and dependent on stronger incentives and validation. This comparison prioritized scale and immediate emissions impact.

9. **Role of the State and Political Economy**
   The participant argued that large-scale diffusion of BECCS is unlikely without strong state involvement, either through mandatory standards or indirect incentives such as tax exemptions. Unlike countries such as Norway, Brazil is unlikely to co-finance CCS projects directly, making regulatory obligation and fiscal incentives the most realistic tools. The interview highlighted the political power of the oil and gas sector and suggested that stronger engagement from these actors could significantly accelerate CCS-related regulation.

10. **Knowledge, Legitimacy, and Human Capital**
    Public understanding of BECCS and carbon markets remains limited. The participant emphasized that universities and engineering education should play a central role in building long-term legitimacy and technical capacity. Integrating decarbonization technologies into engineering curricula was identified as a key driver for future innovation and societal acceptance.

Relevance to the Thesis:

This interview provides strong empirical evidence of how incumbent firms, regulatory uncertainty, and market design shape the feasibility of BECCS in Brazil. It illustrates how BECCS currently functions as a niche innovation constrained by high costs and weak incentives, yet with significant potential to reshape the regime if supported by regulation and incumbent leadership. The findings reinforce the importance of state coordination, first-mover firms, and international policy alignment in enabling large-scale CDR deployment in the Brazilian sugar-energy sector.

C.3 Sugar-energy sector Practitioner (INT-03)

Interview Profile:

The interviewee is a professional with extensive experience in the Brazilian sugar and ethanol sector, working within a large, long-established incumbent organization operating nearly 40 production plants. The participant has experience in strategic decision-making, market positioning, decarbonization discussions, and interaction with actors in bioenergy and carbon markets. The interviewee is familiar with carbon removal technologies, though not directly responsible for their implementation.

Interview Context:

- **Date:** 5th December 2025
- **Format:** Online
- **Duration:** 33 minutes
- **Focus:** Perceptions of carbon removal technologies (BECCS, biochar, ERW) in the sugar-energy sector, with emphasis on scalability, investment profiles, market formation, and policy constraints.

Main Themes and Key Insights:

1. **Investment Profiles, Scale, and Incumbent Constraints**
   The interview highlighted a clear distinction between large incumbents and smaller producers in their ability to engage with emerging decarbonization technologies. Large firms operating dozens of plants prioritize scale, standardization, and cost competitiveness, as sugar and ethanol are highly commoditized products with limited tolerance for differentiated operating costs. As a result, tailor-made or niche solutions are structurally misaligned with incumbent business models. Smaller producers, by contrast, are better positioned to target specific buyers or experiment with differentiated low-carbon products.

2. **Absence of a Price Premium and Immature Markets for CDR**
   The interviewee emphasized that carbon removal technologies have not yet translated into a consistent premium price for sugar or ethanol. Although demand for lower-carbon-intensity products is increasing, buyers often lack clarity or the willingness to pay. This results in an underdeveloped market for CDR-based differentiation. Niche opportunities may emerge, particularly for smaller producers, but for large incumbents, the absence of a scalable premium market remains a central barrier.

3. **Role of CDR Technologies in Decarbonization: Necessary but Insufficient**
   Carbon removal technologies were described as important but insufficient on their own to address climate change in the sector, playing a complementary role to emissions reduction. Biochar was seen as socially and economically relevant for small producers and rural communities but constrained by a lack of infrastructure, processing capacity, and market maturity, making it currently irrelevant at the climate scale. BECCS was acknowledged as technologically more advanced, with projects emerging, yet still lacking sufficient scale to significantly alter sectoral emissions. ERW was viewed as even more limited due to strong geographic and logistical dependencies.

4. **Maturity, Scalability, and Operational Integration of CDR Technologies**
   In terms of current scalability, the interviewee ranked the technologies as BECCS first, followed by biochar, and then ERW, reflecting observed deployment

rather than technological sophistication alone. However, within the Brazilian sugar-energy context, biochar and ERW were considered easier to integrate operationally, as they rely on existing agricultural practices and equipment already used for soil correction. BECCS, by contrast, was described as capital-intensive and operationally complex, lying outside the sector's traditional competencies and requiring specialized infrastructure and knowledge of oil and gas actors. As a result, biochar was identified as the most viable near-term option for Brazil, despite its current limitations.

5. **Government Inaction, Taxation, and Structural Barriers to Innovation**
   The interviewee strongly criticized the slow response of government and policymakers, emphasizing that innovation in Brazil is structurally penalized by the tax system. A key barrier highlighted was that entrepreneurs must pay high import taxes on specialized machinery required to deploy new technologies, as this equipment is often not manufactured domestically. This significantly raises costs at early stages of innovation, precisely when technologies face the highest uncertainty and financing constraints. Rather than isolated incentives or subsidized credit lines, the interviewee argued for structural tax reform oriented toward innovation, including differentiated treatment for new technologies. Without such systemic changes, even technically viable solutions remain financially inaccessible, discouraging entrepreneurial risk-taking and large-scale deployment.

6. **Framing Biochar as Carbon Removal Rather Than a Soil Amendment**
   The interviewee argued that biochar should be primarily framed and monetized as a carbon removal solution, rather than as a soil amendment. Selling biochar mainly on agronomic benefits risks undervaluing its climate function and weakening its business case. Any productivity gains should be treated as secondary co-benefits rather than the main revenue driver.

7. **Emissions Reduction and Cost Optimization as the Primary Sectoral Priority**
   The interviewee emphasized that the primary priority of the sugar-energy sector is reducing emissions through cost optimization within the production chain, rather than pursuing carbon removal as a first step. A large share of emissions originates from agricultural activities, particularly fertilizer use and soil correction, meaning that reducing these inputs directly lowers both emissions and production costs. As a result, emissions mitigation is largely driven by economic rationality, with climate benefits emerging as a direct consequence of efficiency gains. Carbon removal was therefore framed as a secondary and longer-term strategy, to be considered after this "homework" of internal emissions reduction is sufficiently advanced. Nevertheless, the interviewee stressed that they study and monitor in parallel new technologies, including carbon removal technologies.

8. **Interaction with Oil and Gas Actors**
   The interviewee highlighted increasing interaction between the sugar-energy sector and oil and gas companies, particularly around fuel substitution, illustrated as replacing bunker fuels with cleaner alternative, and discussions related to CCS and BECCS.

9. **International Market Barriers and the European Context**
   Finally, the interview addressed difficulties in accessing European markets for ethanol. While biofuel adoption is expanding in regions such as California, Japan, India, and Indonesia, Europe was described as lagging due to land-use and food competition concerns. The interviewee argued that concerns around land use

and food competition are highly context-dependent and often misapplied to developing countries. Drawing on existing empirical studies published by the Agencia Maritima Internacional (AMI), he noted that while competition between bioenergy and food production may be observable in already industrialized regions with limited land availability, such as Europe, this dynamic does not translate directly to countries like Brazil. In developing and emerging economies, the expansion of bioenergy crops has frequently been associated with positive development outcomes, including improvements in income, rural employment, and broader human development indicators. According to the interviewee, these gains can indirectly strengthen food security by increasing purchasing power and local economic resilience, rather than displacing food production.

Relevance to the Thesis:

This interview provides strong empirical evidence of how incumbent business models, commodity market structures, taxation regimes, and policy inertia constrain the diffusion of carbon removal technologies in the Brazilian sugar-energy sector. The findings support the argument that without structural policy reform, clearer market signals, and differentiated demand, CDR technologies will remain niche solutions, more accessible to smaller producers, while large incumbents prioritize emissions reduction through efficiency-driven pathways.

C.4 Energy and Climate Policy Expert (INT-04)

Interview Profile:

The interviewee works as a consultant in the fields of energy transition, climate policy, and decarbonization strategies, with experience advising industrial and agricultural actors in Brazil. The participant has a broad, cross-sectoral perspective and is not directly involved in the implementation of CDR projects.

Interview Context:

- **Date:** 10th November 2025
- **Format:** Online
- **Duration:** 48 minutes
- **Focus:** Perspectives on carbon dioxide removal (CDR) technologies in Brazil, with emphasis on their economic viability, relative maturity, and potential relevance for the sugar-energy sector, as well as broader policy and market constraints.

Main Themes and Key Insights:

1. **Knowledge of CDR Technologies**

   The interviewee demonstrated familiarity with carbon dioxide removal (CDR) technologies, including biochar, BECCS, and enhanced rock weathering (ERW). CDR was described as encompassing both technological and nature-based solutions, ranging from engineered capture and storage to land-based approaches such as forestry and soil-based carbon sequestration.

2. **Role of CDR in Decarbonization**

   participant argued that CDR technologies should not be prioritized over direct emissions reduction, particularly when lower-cost mitigation options are available. Engineered CDR solutions, such as DAC and BECCS were characterized as high-cost and context-dependent, making them relevant mainly where cheaper alternatives are unavailable. In contrast, nature-based solutions, especially biochar, were seen as more attractive due to their lower costs and potential co-benefits, such as productivity gains in agriculture.

3. **Relative Maturity of Technologies**

   The interviewee perceived biochar as the most mature and immediately promising CDR-related option in the Brazilian context. Its relative maturity was attributed to the simplicity of the technology, the large availability of agricultural residues, and its compatibility with existing agricultural practices. Importantly, biochar was described as potentially economically viable even in the absence of carbon credit revenues, particularly because Brazil imports a substantial share of its fertilizers. If the application of biochar contributes to reducing fertilizer demand while improving soil productivity, its adoption could already be justified on economic grounds alone. However, the interviewee emphasized that wider diffusion would require a clear demonstration of agronomic benefits, in order to convince farmers that switching practices is worthwhile.

   BECCS was considered to be at an earlier stage of diffusion, with viability highly dependent on site-specific conditions, such as access to suitable geological storage, and on external incentives, including carbon markets.

   Enhanced rock weathering (ERW) was viewed as the least mature option from a market perspective, due to limited awareness, logistical challenges, and the need for further validation of agronomic benefits.

4. **Relevance for the Sugar-Energy Sector**

   Biochar was highlighted as particularly attractive in the current context of the sector, as many sugar-energy plants face declining revenues from bioelectricity generation due to increased competition from wind and solar, which has driven electricity prices down. In this context, redirecting agricultural residues toward biochar production could offer alternative revenue streams and productivity gains. The interviewee identified BECCS and biochar as the most relevant CDR-related options for the sugar-energy sector. BECCS was viewed as a way to further reduce the carbon intensity of ethanol and potentially access additional revenues through carbon markets. Another alternative being explored is the capture and use of CO_2 for synthetic fuels was described as a longer-term and currently uncertain option. While ongoing discussions within the International Maritime Organization (IMO) on carbon pricing for maritime transport could, in the future, increase demand for low-carbon fuels, the interviewee emphasized that this pathway is not yet economically viable and remains dependent on external regulatory developments. This way the geological constraint of BECCS could be minimized.

5. **Key Challenges for CDR Technologies**

   The interviewee identified distinct challenges across CDR technologies, reflecting differences in cost structures, maturity, and institutional requirements. For BECCS, the main barrier is economic feasibility, as current incentives, particularly low CBIO prices and a volatile voluntary carbon market, are insufficient to offset high capture and storage costs. Additional challenges include limited knowledge of suitable geological storage sites and the need for oil and gas expertise, which increases project complexity and costs. For biochar, the key challenge is demonstrating consistent productivity gains to farmers. Although the technology may be economically attractive, wider adoption depends on credible validation of agronomic benefits. In this context, public research institutions, such as Embrapa, were seen as important actors for reducing uncertainty. For enhanced rock weathering (ERW), challenges are primarily related to logistics and market maturity, including the transport and processing of large material volumes and limited awareness among potential users.

6. **Economic Constraints**

   Across the technologies discussed, economic feasibility emerged as a central limiting factor. The interviewee expressed skepticism regarding the ability of carbon markets in Brazil to generate price signals strong enough to support high-cost CDR options, particularly in an industrial context already facing intense competitive, cost, and regulatory pressures. Especially because agriculture was not included in the Brazilian regulated carbon market. The interviewee further noted that the regulated carbon market is expected to absorb credits from the voluntary market, where prices are typically low, often ranging between USD 2 and USD 20 per tonne of CO_2. As a result, carbon prices are expected to remain low, as the government is unlikely to impose higher costs on industry. In this context, carbon revenues were seen as insufficient on their own to drive investment in capital-intensive CDR technologies, reinforcing the importance of complementary value propositions such as productivity gains or cost reductions.

7. **Policy and Institutional Constraints**

   Beyond economic barriers, the interviewee identified policy and institutional constraints that limit the diffusion of CDR technologies in Brazil, particularly the lack of coordinated public support for knowledge generation and validation. This was seen as especially relevant for agricultural-based solutions, where uncertainty about productivity impacts remains high. The interviewee emphasized that government action should prioritize research and demonstration through public institutions such as Embrapa, to provide credible evidence of agronomic benefits and reduce risks for farmers. In addition, mandatory RD programs in the energy sector, coordinated through ANP, were identified as potential channels to include CDR technologies as priority research themes. Complementary instruments, such as the ABC agricultural Plan and innovation-oriented financing through Finep, were also highlighted as relevant.

8. **Political Influence of the Sugar-Energy Sector**

   The interviewee noted that the sugar-energy sector has significant political influence in Brazil, particularly in policy debates related to fuels and energy transition. However, this influence is currently concentrated on technologies that clearly align with existing business models, especially BECCS. Other CDR-related options, such as biochar and enhanced rock weathering, are not yet priorities, as their benefits for producers are not sufficiently demonstrated. Currently, the interviewee feels there is limited interest in actively mobilizing political influence to support CDR technologies.

9. **Future Perspectives for CDR Technologies**

   interviewee anticipated that carbon dioxide removal technologies are likely to grow in relevance over time, but emphasized that they are unlikely to become a central or dominant feature of the sector in the near to medium term. At present, the participant does not see CDR technologies becoming common agricultural or industrial practices, but rather remaining complementary solutions.
   The future role of these technologies was described as closely linked to the future of ethanol, particularly within the sugar-energy sector. According to the interviewee, if ethanol gains new strategic importance, such as through expanded use in shipping or other hard-to-abate sectors, CDR technologies may become more attractive. However, given the currently uncertain and relatively weak expectations for ethanol, the interviewee expressed caution regarding the scale and speed at which carbon removal solutions are likely to diffuse.

Relevance to the Thesis:

This interview provides a cross-sectoral and comparatively neutral perspective on the role of CDR technologies in Brazil, highlighting the importance of economic feasibility, co-benefits, and sector-specific conditions. It reinforces the argument that, within the sugar-energy sector, nature-based solutions such as biochar may diffuse more rapidly than capital-intensive CDR options, while policy uncertainty and low carbon prices remain key barriers to large-scale deployment.

C.5 Hard-to-decarbonize Industry Practitioner (INT-05)

Interview Profile:

The interviewee is a professional with a background in chemical engineering and experience in sustainability and circular economy initiatives within a large, energy-intensive industrial company operating globally. The participant has worked on emissions reduction strategies, sustainability reporting, and innovation projects, but is not directly involved in carbon dioxide removal (CDR) technologies.

Interview Context:

- **Date:** 28th November 2025
- **Format:** Online
- **Duration:** 40 minutes
- **Focus:** Interview on decarbonization practices in a non-sugar, energy-intensive industrial sector, examining awareness of CDR technologies and possible connections with the sugar-energy sector

Main Themes and Key Insights:

1. **Limited Familiarity with CDR Technologies**
   The interviewee indicated limited familiarity with the CDR technologies discussed in this thesis, namely BECCS and enhanced rock weathering. The interviewee reported a vague knowledge of biochar, mainly through academic training rather than professional practice. CDR technologies were described as outside the current strategic focus of the sector, which prioritizes emissions reduction within existing production processes rather than atmospheric carbon removal.

2. **Priority on Circular Economy and Internal Emissions Reduction**
   The main strategy for CO_2 reduction in the company is internal mitigation through circular economy practices. The interviewee emphasized that the largest sources of emissions are associated with raw material production and energy-intensive thermal processes, making material recycling and reuse the most immediate and cost-effective mitigation pathway. Reducing the demand for virgin raw materials was described as the first step toward lowering emissions across the production chain, before considering more complex mitigation or removal options.
   In parallel, the sector is also pursuing process-level technological changes, particularly related to furnace and equipment transitions. The interviewee highlighted an industry trend, especially in the steel sector, from traditional converters based on primary raw materials toward electric furnaces using recycled inputs, which require less energy and result in lower CO_2 emissions. These transitions were framed as complementary to circular economy strategies and central to medium- and long-term decarbonization efforts.

3. **CCU Pilot Project and Industrial Innovation**
   The interview highlighted the development of a carbon capture and utilization (CCU) pilot plant, carried out in partnership with an international technology provider based in Australia. This project focuses on capturing CO_2 from industrial processes and reusing it as an input material, rather than storing it underground. The CCU initiative was described as one of the company's most significant long-term decarbonization investments, reflecting a strategy of integrating carbon management directly into industrial value chains.

4. **Energy Transition Focused on Fuel Switching**

   Energy transition efforts in the company currently prioritize fuel switching, particularly the transition from oil-based fuels to natural gas in high-temperature industrial processes. These initiatives were presented as concrete and ongoing, though strongly conditioned by infrastructure availability, such as access to gas pipelines, and by regional constraints.

5. **Perceptions of the Steel Sector's Engagement with CO_2 Reduction**

   The interviewee perceived the steel sector as increasingly concerned with CO_2 emissions, driven both by environmental considerations and by financial and regulatory pressures, such as carbon pricing and compliance costs. These economic drivers were described as important catalysts for change. At the same time, the participant noted that some companies demonstrate a proactive commitment to sustainability, investing in decarbonization initiatives even when short-term financial returns are uncertain. This reflects differing levels of maturity within the sector, where long-term strategic positioning and reputational considerations may outweigh immediate profitability.

6. **Carbon Markets as an Uncertain Policy Environment**

   The Brazilian carbon market was described as an emerging and uncertain policy space, with limited clarity regarding rules, obligations, and implementation timelines. While the sector is actively monitoring regulatory developments and participating in discussions, the lack of defined parameters makes it difficult to assess how industrial actors will ultimately be integrated into the regulated market. As a result, companies remain attentive but cautious, particularly regarding how carbon pricing and credit mechanisms may influence future investment decisions.

Relevance to the Thesis:

This interview illustrates that, outside the sugar-energy sector, decarbonization strategies are currently dominated by internal efficiency gains, circular economy practices, process optimization, and CCU solutions, rather than dedicated CDR technologies. It highlights a pragmatic approach in which companies prioritize reducing emissions within their own production chains as a first step, while remaining attentive to evolving carbon market regulations. The findings reinforce the importance of sector-specific pathways, economic drivers, and regulatory clarity in shaping how and when CDR technologies may be diffused across different industrial regimes.

C.6 Hard-to-decarbonize Industry Practitioner (INT-06)

This interview was not authorized to be made public and it was made available exclusively to the assessment committee for the purpose of confirming the information.

C.7 Sugar-energy and Hard-to-decarbonize Industry Practitioner (INT-07)

Interview Profile:

The interviewee is an experienced professional working across industrial technology and energy-intensive sectors with long-standing engagement with Brazilian industry. The participant does not work directly with CDR technologies but brings a broad systemic perspective on energy use, industrial processes, and environmental challenges.

Interview Context:

- **Date:** 9th November 2025
- **Format:** Online
- **Duration:** 57 minutes
- **Focus:** Perceptions of carbon dioxide removal technologies, their relevance for Brazil and the sugar-energy sector, and the roles of industry, government, and cultural change in decarbonization pathways.

Main Themes and Key Insights:

1. **Understanding of CDR and Energy Use**
   interviewee framed carbon dioxide removal primarily as a response to the structural dependence of modern industry on fossil fuels, particularly for high-temperature processes in sectors such as steel, cement, and petrochemicals. While familiar with the general concept of carbon mitigation, the participant had no prior detailed knowledge of biochar, BECCS, or enhanced rock weathering (ERW) before the interview.

2. **Perceptions of CDR Technologies**
   After the technologies were explained, the interviewee perceived Enhanced Rock Weathering (ERW) as the most promising option for Brazil in the medium to long term. This assessment was based on Brazil's strong mining sector, the large volumes of mineral residues generated, and the potential to reuse certified mining tailings in agriculture, creating a circular flow between mining and farming. Biochar was viewed as potentially beneficial but more dependent on cultural change and farmer awareness.

3. **Relevance for the Sugar-Energy Sector**
   The interviewee considered CDR technologies to be relevant for the sugar-energy sector, particularly due to the importance of soil quality for sugarcane productivity and Brazil's long-standing investment in biofuels. Technologies that improve soil conditions while reducing environmental impacts were seen as compatible with the sector's trajectory. The participant highlighted the historical role of ethanol development and second-generation technologies as evidence that the sector can adopt innovations when aligned with productivity and efficiency gains.

4. **Role of Government and the Private Sector**

   The interviewee expressed a critical view of direct government involvement in industrial activities, arguing that the state's primary role should be limited to regulation and financing, rather than direct participation in technology development. In this context, the participant highlighted the role of public development banks, particularly BNDES, which offers relatively low interest rates compared to commercial financing. However, the interviewee emphasized that access to these favourable rates is not guaranteed. In practice, many companies face bureaucratic barriers, limiting their ability to benefit from public financing instruments. As a result, while concessional credit exists in principle, its impact on accelerating industrial decarbonization and CDR-related investments remains uneven and constrained.

5. **Corporate Behaviour and Environmental Commitment**

   The interviewee expressed a sceptical view of corporate environmental commitment, arguing that many companies adopt environmental measures only to meet minimum regulatory requirements and avoid sanctions. Investments beyond compliance were described as uncommon when they do not offer clear short-term financial returns, with profitability generally taking precedence over voluntary environmental action.

6. **Economic Constraints**

   Across the technologies discussed, economic feasibility emerged as a central limiting factor. The interviewee expressed skepticism regarding the ability of carbon markets in Brazil to generate price signals strong enough to support high-cost CDR options, particularly in an industrial context already facing intense competitive, cost, and regulatory pressures. Especially because agriculture was not included in the Brazilian regulated carbon market. The interviewee further noted that the regulated carbon market is expected to absorb credits from the voluntary market, where prices are typically low, often ranging between USD 2 and USD 20 per tonne of CO_2. As a result, carbon prices are expected to remain low, as the government is unlikely to impose higher costs on industry. In this context, carbon revenues were seen as insufficient on their own to drive investment in capital-intensive CDR technologies, reinforcing the importance of complementary value propositions such as productivity gains or cost reductions.

7. **Political Versus Technical Challenges**

   The interviewee argued that, in Brazil, business challenges are primarily political and institutional rather than technical. Although many decarbonization technologies already exist, regulatory uncertainty and unstable policy signals increase investment risk, leading companies to delay adoption until clearer rules and enforcement mechanisms are in place.

8. **Political Influence and Sectoral Dynamics**

   The interviewee acknowledged that parts of the sugar-energy sector demonstrate greater openness to innovation and environmental concerns, particularly larger and more technologically advanced companies. These actors were seen as more capable of influencing political debates and shaping innovation pathways, although the sector as a whole was described as heterogeneous, with many family-owned and conservative producers remaining risk-averse.

9. **Carbon Markets and Economic Signals**

   The interviewee expressed scepticism regarding the short-term role of carbon markets in driving CDR deployment in Brazil. Both voluntary and regulated markets were viewed as unlikely to provide sufficiently strong incentives in the near future, with meaningful impacts expected only in the longer term, potentially driven by international pressure rather than domestic initiative.

10. **Future Outlook**

    Looking ahead, the interviewee emphasized that the diffusion of CDR technologies depends less on technical feasibility and more on cultural and generational change within industry and society. While acknowledging that investments in carbon removal are likely to increase over time, the participant argued that significant progress will only occur as new generations assume decision-making roles, bringing different values and priorities regarding environmental responsibility.

Relevance to the Thesis:

This interview contributes a broad, cross-sectoral perspective on CDR technologies, highlighting the importance of industrial structure, cultural factors, and political economy in shaping innovation pathways. It reinforces the argument that, in Brazil, the future of CDR in the sugar-energy sector will be influenced not only by technology and policy design, but also by sectoral traditions, generational shifts, and the strategic use of existing industrial residues, especially from mining.

Appendix D

Interview Questionnaire

D.1 Questionnaire for Niche Actors

1. How is this technology relevant to the Brazilian sugar-energy sector?
2. What are the main benefits of adopting this technology?
3. Is there any risk or main challenge that comes to mind regarding this technology?
4. Is there any political discussion regarding this technology?
5. Is there any policy/program that support this technology? Are they enough to foster it?
6. How do you see the role of government X private sector in advancing these technologies?
7. Do you see oil and gas and hard-to-decarbonize companies (e.g., Petrobras) advocating this technology? Do you see them advocating against it?
8. Do you think the sugar-energy sector has political influence and will to shape innovation?
9. Have you heard about ... (the other two technologies)?
10. Do you see collaboration or competition among the organizations working on CDR or other low-carbon innovations?
11. How do you think they can contribute with each other?
12. Do you have interaction with established actors (big companies) or policymakers in the sugar-energy sector?
13. Do you know about researchs happening in Brazil with this technology?
14. Do you see carbon markets or credits playing a role in making these technologies more attractive?
15. Do you know the society perception regarding this technology? Is there anything that can be done to increase public legitimacy?
16. Can you say a main driver that could accelerate this technology diffusion in Brazil? Do you see anything as a mains barrier?
17. How do you see the future of carbon removal in the sugar-energy sector in the next medium- to long-term future?
18. Do you see all this three technologies in the same level of development?

D.2 Questionnaire for Sugar-Energy Incumbent Actors

1. Have you heard of Carbon Dioxide Removal (CDR) technologies? What doe it mean to you?
2. Specifically, are you familiar with Biochar, BECCS and ERW?
3. How would you this describe these technologies role in decarbonization?
4. Do you see these technologies relevant in the sugar-energy sector?
5. Do you see all this three technologies in the same level of development?
6. Which of these technologies do you see as more feasible or promising for Brazil?
7. What do you think would be the main benefits of adopting them? And risks and challenges?
8. Is there any policy/program that support these technologies? Do you think they are enough to foster them?
9. How do you see the role of government X private sector in advancing these technologies?
10. o you see oil and gas and hard-to-decarbonize companies (e.g., Petrobras) advocating this technology? Do you see them advocating against it?
11. Do you think the sugar-energy sector has political influence and will to shape innovation?
12. Do you see your company interacting with actors working with these technologies? If yes, is this relationship collaborative?
13. Do you see carbon markets or credits playing a role in making these technologies more attractive?
14. Do you know if your company/institution would be interested in developing or investing in negative emissions projects? (if no) And if there was a carbon market in Brazil?
15. How do you see the future of carbon removal in the sugar-energy sector in the next medium- to long-term future?

D.3 Questionnaire for actors in Hard-to-Decarbonize Sector

1. Have you heard of Carbon Dioxide Removal (CDR) technologies? What doe it mean to you?
2. Specifically, are you familiar with Biochar, BECCS and ERW?
3. How would you this describe these technologies role in decarbonization?
4. Do you see these technologies relevant in the (steel/cement/oil&gas) sector?
5. Is there any relationship with your company and actors of CDR technologies? And with sugar-energy actors?
6. How does your company positions itself in relation to decarbonization measures? Is there an awareness?
7. Is this level of awareness with less emissions and energy transition common in your sector?
8. How do you see the role of government X private sector in advancing these technologies?
9. Do you know if your company/institution would be interested in developing or investing in negative emissions projects? (if no) And if there was a carbon market in Brazil?