Wageningen University & Research

Environmental Economics and Natural Resources Group

Exploring the value of temporary credits in voluntary carbon markets

Confronting the insights from theoretical perspectives with the reality of the market

30th August 2024

MSc Climate Studies

Specialization: Climate, Society and Economics

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ENR-80436

Abstract

This thesis explores the valuation of temporary carbon credits within Voluntary Carbon Markets (VCMs). The economic literature interprets the value of temporary storage as a fraction of permanent value, but it is still inconclusive on the precise value of temporary carbon storage. In the practical context of the market instead, temporary storage of 100 years is considered equivalent to permanent storage due to the historical use in international climate agreements of a 100-years time horizon. Therefore, studying the relationship between the value of temporary and permanent storage is only meaningful when considered within this practical context.

The thesis bridges the gap between the economic perspectives found in the literature and the realities of the market. By drawing on established economical frameworks and approaches that assess the value of durability in carbon credits, this analysis aims to deepen understanding of how the market could better reflect the relative value of credits and enhance their environmental integrity.

Methods involved studying literature documents, reports, and grey literature produced by academics, market actors, and watchdogs in addition to a literature review focused on theoretical resource economics perspectives.

The thesis first provides an overview of the market perspective, including the institutional setup, functioning, and structure of VCMs, the quality issues of credits, and current trends. A particular focus is given to the temporal dimension of credits to examine the distinction between 'temporary' and 'permanent' credits in the market. The economic perspective is then explored, analyzing how theory conceptualizes the value of temporary versus permanent carbon credits. Although the literature remains inconclusive on the exact value of temporary storage, ton-year approaches offer valuable insights into current market valuations and potential shifts in response to long-term damage considerations. These approaches are used to develop a novel approach to explore the implicit discount rate corresponding to the 100-year time horizon adopted by the market. Additionally, the Lashof method with extended time horizons assesses how the value of temporary and permanent storage might change if future damages beyond 100 years are given greater importance. The results suggest potential price ratios that reflect different societal values on future damages.

Finally, the thesis merges the economic and market perspectives, revealing that current market prices do not align with theoretical expectations. The current pricing structure incentivizes the purchase of low-durability credits, discouraging investment in medium- and high-durability credits, which are more likely to contribute to the goals of the Paris Agreement.

Acknowledgements

I would like to express my deepest gratitude to my parents, who have supported me every step of the way. Your sacrifices have made this possible. Thank you for always encouraging me to pursue my dreams.

I also want to extend my heartfelt thanks to my thesis supervisor, Hans-Peter Weikard. Without your guidance, this thesis would not have been possible. Thank you for listening to my endless discussions about how voluntary carbon markets function; it has been a pleasure to have someone as interested in this topic as I am to chat with. Your flexibility in allowing me to adapt the thesis timeline to my ambitions, and your invaluable input and perspective, have been crucial in bringing this work to completion.

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List of Abbreviations

Abbreviation	**Meaning**
AFOLU	Agriculture, Forestry, and Other Land Use
BECCS	Bioenergy with Carbon Capture and Storage
CAR	Climate Action Reserve
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CDM	Clean Development Mechanism
COP	Conference of the Parties
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CO_2	Carbon Dioxide
CSR	Corporate Social Responsibility
DACCS	Direct Air Carbon Capture and Storage
ER	Equivalence Ratio
ETS	Emissions Trading System
GHG	Greenhouse Gas
GWP	Global Warming Potential
IAMs	Integrated Assessment Models
IFM	Improved Forest Management
IPCC	Intergovernmental Panel on Climate Change
IRF	Impulse Response Function
MP	Market Perspective
NDC	Nationally Determined Contributions
NGO	Non-Governmental Organization
OTC	Over-the-Counter
REDD+	Reducing Emissions from Deforestation and Forest Degradation
r	Discount Rate
SCC	Social Cost of Carbon
SOMO	Centre for Research on Multinational Corporations
TH	Time Horizon
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar
VC	Verified Carbon Standard
VCMs	Voluntary Carbon Markets
VM	Verified Methodology
VVBs	Validation and Verification Bodies
WRI	World Resource Institute

1 Introduction

To meet the Paris Agreement's objective of 'holding the increase in the global average temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial, there must be a significant reduction in greenhouse gas emissions over the next decade (Emissions Gap Report 2023: Broken Record, 2023) . Rapid and substantial reductions in emissions are necessary across all sectors and systems, including energy, transportation, industry, and agriculture (Errendal, S. Jeudy-Hugo and J. Ellis, 2023). Achieving this target will necessitate a substantial investment in climate mitigation, equivalent to approximately 10% of the world's GDP (Bednar et al., 2021). To induce the required changes, there will be a need for shifts in both the demand for and supply of various goods and services. These shifts can be facilitated through economic mechanisms like carbon markets and carbon taxes, which alter the incentives that firms and private individuals encounter (Shrestha et al., 2022).

Carbon markets are divided into mandatory markets, regulated by governments or international agreements, and voluntary markets, which operate independently of regulatory requirements. The origins of voluntary carbon markets (VCMs) can be traced back to the Kyoto Protocol established in 1997, which introduced binding commitments to reduce emissions (Wessel and de Boer, 2023). The Protocol included mechanisms like the Clean Development Mechanism (CDM), enabling developed countries to invest in emission reduction projects in developing nations to meet their targets. Although primarily designed for compliance, these mechanisms inspired the development of voluntary markets (ibid). Factors such as demand outside the Kyoto framework, the ineligibility of certain activities within the CDM, and high administrative burdens led to the creation of independent carbon trading schemes. These early voluntary markets used measurement and validation techniques from the CDM, adapting and expanding upon them. Over time, VCMs grew significantly, driven by a heightened awareness of corporate social responsibility (CSR). This expansion is primarily driven by the fact that many companies rely on the acquisition of credits within voluntary carbon markets (VCMs) as a pivotal strategy to fulfill their voluntary commitments to achieve net-zero emissions (Day et al., 2022). Voluntary markets allow companies and individuals to purchase carbon offsets[1] at their own discretion, without an obligation to comply with specific mandates, enabling them to create a 'green' image (Lee, Kim and Kim, 2018).

Credits in VCMs are issued according to independent standards and represent carbon removal or emission reduction efforts, with each credit corresponding to the reduction or removal of one metric ton[2] of CO_2 (or CO_2 equivalent) (Procton et al., 2024). VCMs allow the buying and selling of credits corresponding to one ton of CO_2 (or CO_2 equivalent) reduced in emissions or removed from the atmosphere. Reductions and removals are generated by various climate mitigation projects around the world. This market system offers the potential to channel significant private capital into climate action.

[1] The term 'carbon credit' is often used interchangeably with 'carbon offset'.

[2] One metric ton, equivalent to 1,000 kg, is also referred to as a tonne. For simplicity, this thesis will use the term 'ton,' which should be understood as referring to the metric ton.

Carbon removal credits involve projects that remove CO_2 from the air and store it, either temporarily or permanently, such as afforestation, reforestation, and direct air carbon capture and storage (DACCS). Carbon reduction credits represent the avoidance or reduction of greenhouse gas emissions that would have been produced if the project had not been implemented, such as renewable energy projects and energy efficiency improvements.

Further distinctions among credit types include whether the storage is short-lived or long-lived. Emissions reduction with short-lived storage is achieved through avoided damage to ecosystems and changes to agricultural practices that retain already-stored carbon; while emissions reductions with long-lived storage are achieved through CCS technologies on industrial facilities or CCS technologies on fossil-fuel power-plants (Allen et al., 2020). Emissions removal with short-lived storage involves projects like afforestation and reforestation, which store carbon in biomass but may release it over time due to natural processes like decay, forest fires, disease outbreaks or other natural or human disturbances (AFOLU Non-Permanence Risk Tool, 2024). Emissions removal with long-lived storage includes technologies like DACCS, which capture CO_2 directly from the air and store it in geological formations. The duration of storage is critical to the climate mitigation value of the credit, with shorter-duration storage contributing less to climate mitigation than longer-duration storage.

In the economic literature, the relative value of short-term versus long-term carbon storage is often discussed using the terms "temporary" and "permanent" storage. The assumption that storage in geological formations is permanent serves as a simplification to address the risk of carbon reversals. In this context, "permanent" storage is defined as storage that lasts until the future point at which climate damage is considered, rather than implying absolute perpetuity. The relationship between the value of temporary and permanent carbon storage has been a subject of study and debate for decades. The literature that studies this relationship interprets temporary value as a fraction of permanent value. Various methodologies and approaches have been developed to unravel this relationship. Economists who have delved into this topic reach different conclusions based on their methodologies. Some argue that temporary storage holds no value (Herzog, Caldeira and Reilly, 2003; Kim, McCarl and Murray, 2008; van Kooten, 2009), while others contend that its relative value depends on the avoided radiative forcing effect, on trends in the carbon price or on the discount rate (Fearnside, Lashof and Moura-Costa, 2000; Moura Costa and Wilson, 2000; Groom and Venmans, 2022; Parisa et al., 2022). The discussion on the value of temporary carbon storage is further complicated by the lack of consensus on the appropriate carbon price, future carbon prices, and the appropriate discount rate.

Even if a consensus were reached on the 'correct' economic value of carbon credits and how the price for credits representing temporary storage relates to the price for permanent storage, it would not necessarily translate into a positive impact on the market as VCMs are poorly designed to deliver effective climate action.

CLARIFICATION ON THE USE OF THE WORD ‘CARBON’

Carbon credits are linked to projects focused on emission reductions or carbon dioxide removal. When carbon dioxide is removed from the atmosphere, it can be stored in various forms across different environmental reservoirs, such as soil, vegetation, or geological formations. Within these storage mediums, the carbon originally present in CO_2 is converted and stored as organic or inorganic carbon compounds. Terms like ‘carbon in the soil’ or ‘stored carbon’ are used as shorthand to emphasize the critical aspect—the removal of carbon from atmospheric CO_2, regardless of its subsequent chemical form.

These markets are characterized by high levels of opacity, over-the-counter sales, significant variability in both the products sold and the participants involved, and fragmented governance.

Voluntary carbon markets have faced criticism from scholars, NGOs and watchdogs since their inception and are currently experiencing a deep internal credibility crisis driven by demand-side concerns (Delacote et al., 2024). The growth of this market has been accompanied by several scandals that have undermined its credibility in recent years (Delacote et al., 2024). Because of this, several large companies, such as Shell, Nestlé, EasyJet and Fortescue Metals Group have withdrawn their support for carbon offset programmes (Carbon Prices and Voluntary Carbon Markets Faced Major Declines in 2023, What's Next for 2024?, 2024). This withdrawal is undoubtedly due in part to growing scepticism about the effectiveness of these projects and the credibility problem described above, but also to concerns about related greenwashing allegations (ibid).

This thesis aims to explore the VCMs from a market perspective. Through a comprehensive literature review, it provides an in-depth analysis of the VCMs, examining their key characteristics and functioning. The focus is on clarifying what the credits sold in these markets represent and how they differ, particularly in terms of the temporal dimension. The thesis seeks to bridge the gap between the economic perspectives found in the literature and the realities of the market. By drawing on established frameworks and approaches that assess the value of durability in carbon credits, this analysis aims to deepen understanding of how the market can better reflect the relative value of credits and enhance their environmental integrity.

1.1 Research objectives and research questions

In the practical context of the market, temporary storage of 100 years is often considered equivalent to permanent storage. Therefore, studying the relationship between the value of temporary and permanent storage is only meaningful when considered within this current practical context. Understanding this relationship purely in theoretical terms without knowledge of market practices and implementation methods would be insufficient.

By integrating insights from both theoretical perspectives and practical realities, this thesis aims to provide a comprehensive understanding of the valuation of temporary carbon storage in VCMs.

The initial focus will be on examining the practical aspects, including the institutional setup of the markets where these credits are traded, market actors and recent developments in VCMs that have lead to the current credibility crisis. This involves understanding how these credits are defined and what they represent. The following research questions guide this investigation:

1. **What is the institutional setup of Voluntary Carbon Markets (VCMs)?**
    - Who are the main actors involved in VCMs, and what roles do they play?
    - How do VCMs function in practice?
    - How does the institutional setup of VCMs influence transparency and market integrity?
2. **How are carbon credits defined, categorized, and valued in VCMs?**

- How are carbon credits categorized in VCMs?
- What determines the quality and credibility of carbon credits?
- How does the temporal dimension affect the valuation and utility of carbon credits?

Beyond the practical market analysis, the thesis also seeks to understand the theoretical underpinnings of the value of temporary versus permanent storage and to understand whether it is possible to connect these theories with the actual market conditions. Therefore follows an additional research question:

3. **How does economic theory inform the determination of appropriate comparative ratios for permanent and temporary carbon storage?**
    - What do economic frameworks and models suggest about the valuation of temporary storage as a fraction of permanent storage?
    - Considering the market conditions explored in RQ1 and RQ2, and adopting the common literature assumption of valuation of temporary storage as a fraction of permanent storage, what price ratio would economic theory expect to observe between temporary and permanent credits?

Finally, verification will be conducted to determine whether the theoretical relationship between the valuation of temporary and permanent carbon storage credits is observed in actual market conditions. Accordingly, the final research question is:

4. **To what extent do the observed market conditions align with or diverge from theoretical expectations?**
    - What are the observed price ratios between temporary and permanent carbon credits in the market?
    - What are the possible insights from any discrepancies observed between theoretical price ratios and actual market prices?

In order to answer these questions, literature documents, reports, and grey literature produced by academics, market actors, and watchdogs have been studied. The third research question will be addressed through a literature review focused on theoretical resource economics perspectives, while the fourth question will involve comparing observed market price ratios with those predicted by economic theory.

The remainder of this document is structured around the four primary research questions, with each chapter dedicated to a specific inquiry. Chapter 2 focuses on the market perspective, starting with an analysis of the institutional context of VCMs, followed by an exploration of the characteristics and temporal aspects of credits traded in these markets. Chapter 3 shifts to an economic perspective, investigating how economic theories propose these credits should be valued. Chapter 4 juxtaposes theoretical expectations with actual market prices and examines potential insights from any discrepancies between these theoretical ratios and observed market prices. Finally, Chapter 5 presents the conclusions of this study.

2 Market perspective

This chapter presents the findings for Research Questions 1 and 2. Section 2.1 provides an overview of the institutional setup of VCMs, detailing their structure, key participants, and how VCMs operate. In Section 2.2, the focus shifts to an in-depth analysis of carbon credits, including their categorization by methodology, quality characteristics, and the types of credits available. This section critically examines the factors that determine the credibility and effectiveness of carbon credits, such as additionality, permanence, and the risks of carbon leakage. Section 2.3 delves into the temporal dimension of carbon credits, particularly how the concept of durability affects their valuation and utility as offsets. This section analyzes the market's current approach to equating temporary and permanent storage, highlighting the distortions this creates and its implications for achieving long-term climate mitigation efforts.

2.1 Institutional set up of voluntary carbon markets

Voluntary Carbon Markets (VCMs) emerged in the early 2000s alongside compliance markets allowing companies to take accountability for their emissions. By 2022, the market had grown to a value of $1.8 billion (Donofrio et al., 2023). These markets are marked by a high degree of heterogeneity in both the actors involved and the types of credits issued. This diversity, along with the lack of regulatory oversight, has led to a perception of VCMs as the 'Wild West of carbon markets' (Carbon Market Watch, 2023). The institutional framework of VCMs is characterized by voluntariness, decentralization, and opacity.

1. **Voluntariness**: As the name suggests, participation in VCMs is voluntary. Companies and organizations choose to engage in these markets without any legal or regulatory obligation to produce or purchase carbon credits. Participation is often driven by corporate social responsibility or anticipation of future regulations (Are forest-based carbon offsets worth saving?, 2023).
2. **Decentralization**: Governance in VCMs is decentralized. There is no single regulator overseeing the market. Instead, multiple bodies set standards and maintain registries, delegating parts of their regulatory responsibilities to verifiers (Üblackner, 2023). The lack of a central authority means there is no entity ensuring fair pricing, guaranteeing credit quality, or upholding environmental integrity across the entire market. This decentralization leads to a fragmented regulatory landscape, complicating the oversight and standardization of VCM activities. Decentralization also affects transactions , as these typically occur over-the-counter (OTC): transactions are conducted directly between sellers and buyers, with no legal requirements to disclose sensitive information.
3. **Opacity**: Lack of transparency is a critical issue in VCMs. While carbon offset programs are increasingly providing public information on projects, such as documentation, sourcing, transfer, and retirement, information on prices and volumes of each type of credit remains scarce and incomplete. Geographic data on reference areas for base emission levels is also limited (Delacote et al., 2024), making it difficult for researchers to verify claims and validate project outcomes. Additionally, data on prices and the identities of buyers and sellers are often unavailable. The lack of transparency is further amplified by the nature of carbon credits as 'credence goods,' whose qualities cannot be observed by consumers post-purchase (Battocletti, Enriques and Romano, 2023). This makes assessing the quality of credits challenging. The variety and complexity of carbon credits make it difficult to distinguish between

high and low-quality credits (Calyx Global, 2023). Consequently, buyers often cannot ascertain whether the price they are offered is fair or if the credit is reliable.

The following subsections provide a detailed analysis of the primary participants in the voluntary carbon markets (VCMs), elucidating their roles and how these roles interconnect to facilitate the creation, verification, and sale of carbon credits. This section also explores how the relationships among key players generates perverse incentives to inflate the number of credits issued by projects.

2.1.1 Structure of voluntary carbon markets

As stated above VCMs are characterized by decentralization, there is no unified global market for carbon credits, the structure of VCMs has been previously described as an 'ecosystem' (Delacote et al., 2024) of different standards, platforms and organisations that share some common characteristics (*Are forest-based carbon offsets worth saving?*, 2023).

The following distinct roles can be identified:

- **Project Developers**: These companies or organizations develop and manage projects aimed at reducing greenhouse gas emissions or removing carbon from the atmosphere. They estimate the number of credits their projects will generate according to specific accreditation standards and guidelines. Project developers are the supply-side of VCMs.
- **Carbon Standards**: These bodies define the specific standards and protocols that projects must adhere to in order to issue credits. They provide independent methodologies for certifying projects and issuing credits, and they also administer registries where carbon credits are hosted or displayed. The most widely used standard is the Verified Carbon Standard (VCS) defined by Verra, with other notable standards including the Gold Standard and the Climate Action Reserve (CAR).
- **Validation and Verification Bodies (VVBs)**: Also known as auditors, these third parties verify that projects meet the required criteria. They examine documentation, visit project sites, and approve or modify estimates of the number of credits generated.
- **Buyers**: Representing the demand side of the market, buyers are primarily private companies, though there are also investors looking to profit from the continuous price increase in carbon credits.
- **Brokers and Traders**: Similar to other commodity markets, brokers and retail traders play a crucial role in linking supply and demand for carbon credits. Acting as intermediaries, brokers and traders connect buyers with project developers. Retail traders purchase large quantities of credits directly from suppliers, bundle them into portfolios, and sell these bundles to end buyers, typically earning a commission (Favasuli and Sebastian, 2021). While many transactions occur through private conversations and over-the-counter deals, some exchange platforms are emerging, aiming to simplify and expedite carbon credit trading by creating standard products with set characteristics (ibid).
- **Carbon Credit Rating Agencies**: Given the wide variety of credits and the 'credence good' nature of these products, distinguishing between high and low-quality credits is challenging (Calyx Global, 2023). These agencies offer credit quality assessment services to meet this need. Prominent agencies include BeZero, Sylvera, and Calyx Global.
- **Integrative Initiatives:** Over the years, integrative initiatives have emerged to address the perceived lack of regulation and uniformity in the market. These

initiatives play a crucial role in market governance, setting high standards for quality on both the supply and demand sides (Procton *et al.*, 2024). For example, the Integrity Council for the Voluntary Carbon Market (ICVCM) developed the Core Carbon Principles (CCPs) to establish a global standard and benchmark for high-quality carbon projects, providing a reference for the supply side. On the demand side, the Voluntary Carbon Markets Integrity Initiative (VCMI) created the Claims Code of Practice, which provides guidelines to help companies credibly use voluntary carbon market credits in their net-zero decarbonization goals. Another significant initiative is the Science Based Targets Initiative (SBTi), which has gained considerable attention recently. The SBTi supports companies in setting ambitious emission reduction targets with clearly defined deadlines (ibid).

As stated above, the carbon credit market is characterized by a diversity of roles and fragmented governance, leading to a decentralized structure. Despite this decentralization, certain players dominate within their respective roles. For instance, at the standards level, the Verified Carbon Standard covered about two-thirds of the transacted volumes in 2019-2020, with further growth in 2021 (Crehalet *et al.*, 2021). The Gold Standard followed in second place with a market share of about 10 percent (ibid). Among project developers, the market is dominated by a few large developers with extensive portfolios of projects, while a long tail of small and medium-sized developers manage smaller portfolios. The top 20 developers account for over a third (39%) of the total volume of credits issued, with the top five managing 19% (Filmanovic, 2021).

2.1.2 Functioning of voluntary carbon markets

The process of developing a carbon offset project typically takes between 18 months and six years and involves six phases:

1. **Project Design**: The project developer selects a standard setter for project registration and chooses a Validation and Verification Body (VVB) accredited to that standard; They document the project's methodology, baseline, and monitoring plan in a Project Design Document (PDD) and submit it to the VVB;
2. **Project Validation**: The VVB assesses whether the project meets the eligibility criteria set by the carbon standard; If it does, the project moves to the next phase;
3. **Project Registration**: The carbon standard reviews the VVB's validation report; If the standard is satisfied, the project is officially registered;
4. **Project Implementation**: The developer implements the monitoring plan outlined in the PDD, measuring and quantifying reductions; Although actual implementation may start earlier, this phase focuses on monitoring and accounting for emission reductions or carbon removal;
5. **Project Verification**: A VVB, often different from the one that validated the project, reviews the monitoring report to ensure the project proceeds as planned; They provide an ex-post assessment to confirm whether the claimed reductions were achieved;
6. **Project Certification and Credit Issuance**: The carbon standard and the respective registry review the verification report; Once approved, offsets are issued, listed on the registry, and ready for purchase; Upon purchase, the credits are considered ‘retired’ (Battocletti, Enriques and Romano, 2023; Üblackner, 2023).

The relationships between project managers, standards, and auditors are inherently susceptible to conflicts of interest, which can significantly compromise their credibility. Notably, the same organizations that develop and manage projects also choose the auditors (Hengeveld, 2024). This means they select who will judge whether their projects meet the

standards required to issue credits, while their profit depends on the sale of these credits. Validators and verifiers, ostensibly acting as independent third parties, must be accredited by the standard that governs the credits from the projects they validate or verify. Although formally independent, their profit depends on being hired by project developers.

Standard-setting bodies receive fees from project developers for each credit issued, from buyers for each credit withdrawn, and from verifiers for their accreditation (*Verra Publishes Updated Fee Schedules*, 2023). Therefore, it is also in their interest to issue as many credits as possible. Figure 1 delineates these financial and preferential relationships, highlighting the systemic incentive to inflate the volume of credits produced.

The current market structure encourages project developers to manipulate baseline assumptions to maximize credit issuance, leading to the proliferation of 'hot air' credits—credits that fail to represent genuine emission reductions or removals.

While the introduction of Carbon Credit Rating Agencies could enhance the independence and reliability of market oversight, their involvement introduces additional costs for buyers. Moreover, not all buyers opt to utilize these agencies, allowing 'hot air' credits to persist in the market.

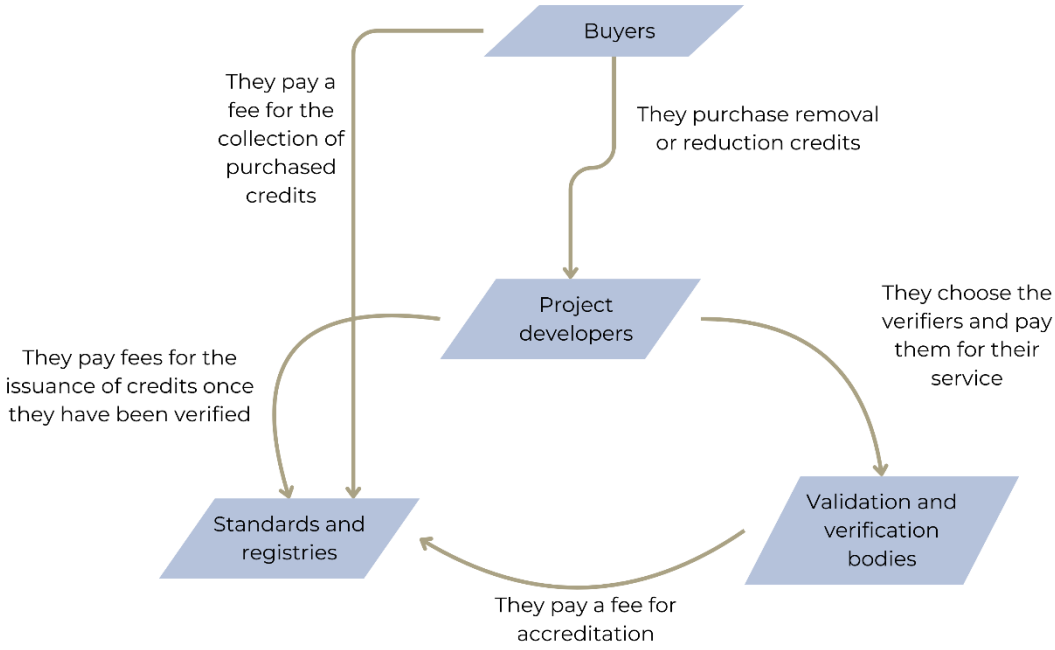

Figure 1 Financial and preference relationships among VCMs participants

2.2 Carbon credits

According to South Pole, one of the largest project developers in the VCMs, 'Carbon credits are measurable, verifiable emission reductions from certified climate action projects that reduce, avoid, or remove greenhouse gas (GHG) emissions'(*Carbon Credits Explained*, no date). The term 'carbon credit' is often used interchangeably with 'carbon offset'. However, to be precise, 'carbon credit' is a more general term that can refer to credits exchanged in both voluntary and compliance markets, whereas 'carbon offset' specifically denotes credits sold in VCMs (ibid).

Despite the common terminology, carbon credits represent different things depending on whether they pertain to compliance or voluntary carbon markets. For instance, in compliance carbon markets that adopt a cap-and-trade approach where credits are auctioned, a credit grants the right to emit one ton of CO_2. Cap-and-trade systems are designed with a decreasing number of allowable emissions each year to reach specific targets, embodying the 'polluter pays' principle. The economic incentives created by such systems ensure that emission reductions are additional to what would have occurred without such a system. Conversely, in voluntary carbon markets, a credit signifies the reduction, avoidance, or removal of one ton of CO_2 from the atmosphere. Therefore, a carbon offset in VCMs is equivalent to one ton of CO_2 less in the atmosphere, which the buyer uses to claim the offset of an equal amount of carbon emissions.

2.2.1 Taxonomy of Carbon Credits

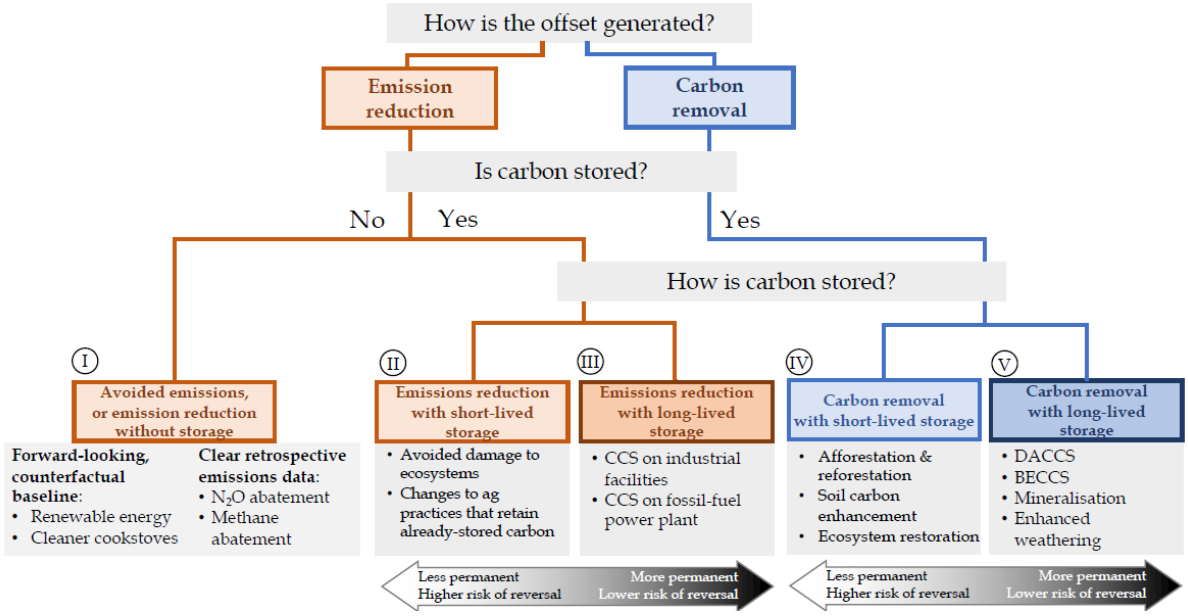

Figure 2 Taxonomy of Carbon Credits (Allen *et al.*, 2020)

Figure 2 presents the credit taxonomy according to experts from the University of Oxford who authored the Oxford Principles for Net Zero Aligned Carbon (Allen *et al.*, 2020; Axelsson *et al.*, 2024). This taxonomy initially differentiates credits into emission reduction and carbon removal categories.

Within each category, various project types from which the credits are derived are further distinguished:

- **CO_2 Removal**: The IPCC defines CO_2 removal as 'anthropogenic activities that remove CO_2 from the atmosphere and durably store it in geological, terrestrial, oceanic reservoirs, or products' (Babiker *et al.*, 2022). Numerous removal methods exist, varying by process type (nature-based or technologically mediated), storage duration (ranging from decades to millennia), technological maturity, mitigation potential, costs, and governance requirements (ibid). Generally, these methods are categorized into short-term and long-term CO_2 storage (Allen *et al.*, 2020). Short-term storage projects include reforestation, ecosystem restoration, and enhanced soil carbon sequestration, characterized by higher carbon release risk and lower permanence. Long-term storage projects encompass bioenergy with carbon capture and storage (BECCS), direct air capture with geological

storage (DACCS), atmospheric carbon conversion into rock through enhanced weathering, and ocean-based methods like increasing ocean alkalinity. These methods are noted for lower carbon release risk and greater permanence.

- **Emission Reduction**: This involves the reduction of greenhouse gas emissions relative to a baseline, which can be calculated differently depending on the mechanisms and standards employed. Emission reduction projects can include or exclude carbon (ibid). Projects with storage are divided into short-term and long-term categories (Allen *et al.*, 2020; Axelsson *et al.*, 2024). Short-term storage is achieved through ecosystem protection and changes in agricultural practices that conserve already stored carbon. Long-term storage is implemented through carbon capture and storage (CCS) technologies applied to industrial facilities or fossil fuel power plants. Emission reductions without storage are typically referred to as 'avoided emissions' and include projects such as the deployment of renewable energy to replace fossil fuel power plants and programs to upgrade inefficient boilers.

2.2.2 Quality of Carbon Credits

This section delves into the characteristics that define the quality of a carbon credit. The primary function of a carbon credit is to ensure and represent the reduction of one ton of CO_2 from the atmosphere. Thus, the quality of a credit is intrinsically linked to its environmental integrity. Carbon credits are used by purchasers to offset their emissions; therefore, the quality of a credit directly impacts the credibility of the offset claims made by the buyer.

To assess the effectiveness and climate benefits of a project, both emission reductions and removals necessitate a reference scenario. This concept, known as additionality, ensures that credits represent a genuine decrease in global emissions. Emission reductions must exceed the baseline scenario, and atmospheric CO_2 removal must be contingent on the project's existence. Without additionality, purchasing a carbon credit fails to ensure actual emission compensation. Therefore, additionality is a crucial indicator of a credit's quality. The reliability and certainty of additionality are paramount in determining the credit's value.

Additionality encompasses three dimensions:

- **Regulatory Additionality**: The project must reduce emissions beyond what is mandated by existing regulations or industrial standards.
- **Technological Additionality**: The project must employ emission reduction technologies that would not otherwise be used in the absence of the project and are not already common practice in the sector.
- **Financial Additionality**: The project must be financially viable only due to the anticipated revenue from selling emission credits. This implies that the project relies on the income from credit sales to be economically sustainable

For instance, if a project uses already common technologies, is financially attractive without credits, or is mandated by existing regulations, it is not considered additional. To make the concept more stringent, it is crucial to define a period within which the project's activities are deemed additional. As financial and technological contexts change over time, a project might cease to produce additional emission reductions if one of these conditions is no longer met.

Evaluating a project's additionality is complex and involves several critical factors. For example, it is important to establish the project's intentionality: the reductions must be actively induced by human intervention and not result from natural processes, such as the normal growth of forests

Ensuring the permanence of carbon reductions is crucial; projects must clearly demonstrate that the reductions are long-lasting and that the carbon removed is stored safely and not released. The concept of additionality is intrinsically linked to permanence, which pertains to the enduring nature of carbon reductions. For instance, if a project lasting several decades avoids emissions but ultimately allows conditions to revert to their original state, the emissions were merely temporarily delayed. Thus, both emission reductions and carbon removals must account for storage duration.

The Oxford Principles initially categorized storage into short-term and long-term. However, as market standards have evolved and novel methodologies, such as biochar, have gained prominence in discussions, the differentiation between these types has become increasingly nuanced. This recognition highlights a spectrum of durability and associated risks, acknowledging that the classification is not binary but rather a continuum influenced by various factors. In the revised 2024 Oxford Principles, 'durability' replaces 'permanence,' reflecting the continuum of durability and the varying risks across different storage types (Axelsson *et al.*, 2024). 'Durability' better captures the temporal variability inherent to most forms of carbon storage, recognizing that each storage method carries potential risks of project failure or non-permanence due to factors such as natural disasters, changes in management, or policy shifts (Criteria for High-Quality Carbon Dioxide Removal 2024).

Durability is currently categorized as low (fewer than 100 years), medium (100 to 1,000 years), and high (thousands of years or longer) (ibid). Each storage type is classified based on the characteristic timescale of the carbon pool utilized (Geden *et al.,* 2024). The storage methodologies falling in each category are as follows :

Low Durability:
Nature-based activities, such as forestry projects, fall into this category. These projects are highly susceptible to reversals and have low durability. Ensuring permanence is challenging for these credits due to the high risks involved. While contractual commitment periods are typically set at 100 years, the actual project durations are much shorter (29 years for Verra's projects[3]). This period is artificially extended to

CLARIFICATIONS OF CARBON STORAGE TERMINOLOGY

All forms of carbon storage inherently carry risk, with varying levels of risk associated with different types of storage. High durability storage, defined as storage lasting over 1,000 years and typically involving technologically mediated, geo-based methods, presents a minimal risk of reversal and is increasingly referenced as the benchmark for 'permanent' storage. 'Permanent' in this context means long enough to be considered effective within the relevant time horizon to claim an offset and ensure high integrity.

In this report, both the terms 'durability' and 'permanence' are used to describe the characteristic indicating the length of storage, with a preference for 'durability' to avoid misleading implications of perpetual storage. To specify the length of storage in years, the terms 'permanence period' or 'storage period' are employed. Instead of categorizing storage as short-term or long-term, a more nuanced classification using 'low,' 'medium,' and 'high durability' is adopted. However, a binary distinction is maintained when discussing temporary versus permanent credits: temporary credits are associated with storage periods below 1,000 years, while permanent credits pertain to high durability storage. This approach acknowledges the significant differential risk levels and the fact that high durability storage has a minimal risk of reversal.

[3] Verra is the leading carbon standard , responsible for the approval of approximately three-quarters of all voluntary offsets. The deduction of an average of 29 years is based on data retrieved from the Verra registry (https://registry.verra.org/app/search/VCS/All%20Projects) and applies to all AFOLU projects, regardless of their current status or category.

100 years by a ‘buffer’ of additional credits that cannot be sold, serving as a safeguard against carbon leakage for the subsequent 100 years (*AFOLU Non-Permanence Risk Tool*, 2024). Low-durability options (Christie-Miller and Harvey, 2023).

Medium Durability:
Examples of medium durability storage methods include biochar, biomass burial, and deep ocean storage. These methods store carbon for 100 to 1,000 years, providing a longer-term solution compared to nature-based activities . However, they are still subject to degradation over time, leading to a gradual release of carbon back into the atmosphere (Cullenward, 2023).

High Durability:
Technology-based solutions are categorized as high durability. These methods ensure that carbon remains stored for over 1,000 years with minimal risk of re-emission, offering the most reliable and long-lasting carbon storage options. High-durability opportunities need the greatest scaling. The current availability of high-durability carbon credits is markedly insufficient to satisfy present demand. This shortfall has prompted companies to proactively purchase permanent carbon removal credits for future use, essentially locking in supply years ahead (Rigodanzo, 2024). By the end of 2023, 3.9 million credits for engineered carbon removal had been secured, but only 1.9% of these removals had been delivered (Christie-Miller and Harvey, 2023).

Another important factor defining the quality of a carbon credit is the phenomenon of ‘carbon leakage,’ which refers to the unintentional displacement of avoided emissions to other areas. When leakage occurs, this by definition reduces the additionality of a project (Filewod and Mccarney, 2023). A reduction in deforestation rates within the project area could lead to an increase in deforestation rates elsewhere, or an event such as a fire or natural disaster could cause leakage, releasing previously removed and stored carbon.

The fact that the climate benefits of carbon credits can only be estimated against an abstract and supposed scenario (the baseline) represents one of the main challenges to the integrity and credibility of these markets. The quality of a credit depends on additionality, permanence, and the risk of leakage, which are difficult to assess upon purchase. This underscores the centrality of credibility in the discourse surrounding VCMs.

2.2.3 Carbon credits as a mix of lemon good and credence good

VCMs are characterized by information asymmetry. The suppliers, or project developers, possess more information about the projects than the buyers. This lack of transparency is a defining feature of these markets and is the primary cause of information asymmetry. Buyers do not have adequate information about the appropriate prices for credits, they cannot verify the quality and must trust that the suppliers or intermediaries are truthful about the quality of the credits.

Carbon credits sold in VCMs are considered ‘credence goods.’ The term ‘credence good’ originated in the literature on professional services, starting from the work of Arrow (1963), and refers to goods that cannot be evaluated by consumers even after they have been consumed. These markets are prone to inefficiencies due to asymmetric information, where informed expert sellers interact with uninformed consumers.

Inefficiencies arise from underprovision or overcharging (Balafoutas and Kerschbamer, 2020). Underprovision occurs when the goods or services provided fail to meet the customers' needs, resulting in resource costs that yield minimal to no benefit. Conversely, overcharging involves billing for goods or services that were not actually provided, prompting consumers to seek multiple opinions, delay necessary purchases, or avoid the market entirely due to fear of being overcharged.

A parallel stream of literature, developed alongside the credence goods literature, is the market for lemons, initiated by Akerlof (1970), which also deals with information asymmetries in the provision of goods and services. In a 'lemon market,' asymmetric information means that product quality is unobservable by consumers before purchase. Lemon goods are products with hidden defects. The introduction of a low-quality product that cannot be differentiated from higher quality counterparts will drive the latter out of the market. Buyers assume the worst about product quality, leading to lower prices and potentially driving good-quality products out of the market.

Both markets for credence goods and markets for lemons share information asymmetries where the buyer cannot verify the quality of the good purchased. However, in lemon goods, the defect becomes apparent later, while for credence goods, the buyer cannot verify the quality even post-consumption.

Carbon credits sold on VCMs exhibit characteristics of both credence goods and lemons: buyers cannot verify the environmental integrity of the credits, even post-purchase, making them credence goods, as highlighted in a paper by Battocletti et al.(2023). However, VCMs can also be seen as markets for lemons (Bell and Baxi, 2021). Without rigorous mechanisms to verify the claims of carbon credit vendors, even minimally credible schemes find buyers. This leads to a 'low quality, low price' equilibrium, where buyers are sold 'lemons' – poor-quality products. Sellers profit because their actions cost less than the price paid, but these actions often do not reduce emissions.

Recent events have made these lemon market characteristics more evident. In January 2023, an article in The Guardian (Patrick Greenfield, 2023), based on three recent scientific studies (West *et al.*, 2020, 2023; Guizar-Coutiño *et al.*, 2022), revealed that about 94% of reforestation credits from Verra, the world's largest carbon credit provider, had no real climate impact. Subsequent scandals followed: in July, a systematic review (Probst *et al.*, 2023) of over 2000 offset projects found that 88% of credits did not represent genuine emission reductions. In August 2023, an article by Carbon Brief highlighted social impacts of projects, revealing that over 70% of reports indicated harm to indigenous populations and local communities (Hengeveld, 2024). By September 2023, VCMs experienced a contraction for the first time in at least seven years, and the market is facing a credibility crisis, with major companies reducing their purchases. The loss of buyer trust validates the dynamics predicted by lemon market literature. VCMs still retain characteristics of credence goods because the credibility crisis is driven by external experts studies. Buyers cannot independently verify the quality of the credits and must rely on the standards and methodologies that issued them.

2.2.4 Current trends

Following the various scandals of 2023, the market has shown signs of crisis, with its value plummeting dramatically. The total reported transaction value was USD 723 million, representing a 61% decrease compared to 2022 (Procton *et al.*, 2024) . This downturn indicates that buyer confidence in the integrity of credits has been compromised. However,

not all credits have been affected equally. There is a growing interest in credits that represent emission removals and clearly demonstrate project additionality, as opposed to emission reduction credits, which suffer more from additionality issues (Donofrio et al., 2022, 2023). For example, within the Nature-based credits category, REDD+ credits (the most common project type) experienced a 62% reduction in value from the previous year, with transaction volume dropping by 51% and prices falling by 23%. This trend is further highlighted by the fact that removal credits commanded an average price nearly three and a half times higher than that of reduction credits in 2023 (Procton et al., 2024). This shift marks a reversal of previous trends, which favored reduction credits, and indicates a movement towards credits with greater additionality. Despite this development, reduction credits still dominate the market (Delacote et al., 2024).

2.3 Relationship between the value of temporary and permanent storage from the market perspective

In the taxonomy of carbon credits, they are categorized as removal or reduction. Within these categories, distinctions are made based on how long the CO_2 will be kept out of the atmosphere, a characteristic known as durability. Durability is linked to the method of carbon storage (nature-based or technology-based), but legal or financial mechanisms, such as insurance or legal liability, can guarantee the permanence of carbon that is otherwise stored temporarily. Significant differences exist between low-durability credits (nature-based, high risk of reversal, theoretically 100 years of storage) and high-durability credits (geological, minimal risk of reversal, more than 1000 years of storage).

Despite the significant differences in storage periods, current market practice treats temporary and permanent credits as equal when it comes to their offsetting ability, as long as the stored or avoided carbon remains out of the atmosphere for at least 100 years. Chapter 3 will demonstrate how this approach corresponds to adopting a time horizon of 100 years.

From a temporal perspective, carbon credits traded on the market are categorized as follows:

- Reduction credits represent the amount of emissions that are stored away from the atmosphere for at least 100 years instead of being emitted. For example, Verra's methodology VM0003 for Improved Forest Management through Extension of Rotation Age classifies emission reduction from the biosphere. By extending the period before trees are harvested, the projects effectively increase the average carbon stock on the land. This means that carbon, which would have been released if the trees were cut earlier, remains stored in the forest biomass. Over the span of 100 years, the credits are calculated based on the difference in average carbon stock between the scenario without the project and the scenario with the project, thereby reflecting the net reduction in emissions.(Parisa *et al.*, 2022).
- Avoidance credits refer to carbon not released from burning fossil fuels thanks to a project, though those fuels could potentially be burned by future generations. As Herzog et al. explain, 'avoiding fossil fuel use now is a permanent reduction in concentrations only to the extent that we trust that all intervening future generations do not shirk.' Thus, permanence issues also exist here. An example of an avoidance methodology is VM0008 for Weatherization of Single Family and Multi-Family Buildings, which quantifies GHG emissions reduced through energy efficiency measures.
- Removal credits represent a ton of CO_2 that has been removed from the atmosphere and stored for at least 100 years. For instance, in a reforestation project, the project manager is

legally obligated to ensure the carbon stored remains in the trees for the project's duration. However, after the project ends, this carbon could be released.

The assumption that 100 years of carbon storage equates to permanence distorts the market. It fails to recognize the differences between temporary and permanent storage, leading to a market that favors low-durability credits. Such an equivalence is often used to justify offsetting claims.

2.3.1 Carbon Offsets

The current market perspective on the relationship between the value of temporary and permanent storage has significant implications for the use of credits as offsets. The purchase of carbon credits allows companies to make environmental claims at a firm level or to declare products as 'carbon neutral'. Buyers utilize low durability credits to offset their own emissions. Given that the market adopts a 100-year time horizon, low durability credits associated with 100 years of storage (hereafter referred to as temporary credits) are considered equivalent to high durability credits (hereafter referred to as permanent credits). Current compensation claims are based on an economic-equivalence paradigm, wherein benefits are calculated as the climate impacts avoided or deferred through carbon storage, and costs are based on the climate impacts caused by emissions at the end of the storage period (Chay *et al.*, 2022). Within this framework, storage is deemed permanent if it endures for the entirety of the time horizon. Other economic claims are based on arbitrary discount rates and use an economic equivalence that compares the time-discounted costs and benefits of temporary carbon storage against the costs and benefits of permanently avoiding CO_2 emissions (Mitchell-Larson, Allen and Koponen, 2021). In contrast, physical-equivalence claims equate carbon durability requirements to the physical properties of the climate system, necessitating that carbon be stored in permanent (geological timescale) storage to be considered for compensation. In fact, true physical equivalence happens only when the radiative forcing is fully counteracted, which is only possible with permanent carbon storage (Cullenward, 2023).

Current compensation claims are criticized for three main reasons:

- **Physical Inconsistency:** The market ignores the physical reality of CO_2 residence time in the atmosphere, adopting economic equivalence claims to justify compensation claims. The concept of permanence in the market differs from the scientific definition, which requires carbon storage on timescales greater than the time it takes to remove carbon from the short carbon cycle and return it to the geosphere, exceeding 100,000 years (Scott *et al.*, 2015). Temporary storage cannot offset permanent CO_2 emissions. Global temperatures depend on cumulative CO_2 emissions rather than emission rates, meaning temporary reductions do not significantly contribute to long-term climate stabilization (Mitchell-Larson, Allen and Koponen, 2021).

- **False Sense of Progress**: Low quality compensation claims create moral hazard by giving a false sense of progress, reducing the pressure for stricter regulatory systems and real carbon pricing (Üblackner, 2023). Currently, there is not only a risk of creating a false impression of progress but also a certainty that emission reductions represented by credits are not adjusted correctly. This means that emission reductions may be claimed by both the host country and the purchasing company, thus complicating the integrity of carbon credits, which are already plagued by issues of additionality. This dual counting further undermines the credibility and effectiveness of VCMs.

- **International and Intergenerational Ethical Concerns**: The logic of offsetting suggests that an entity can continue emitting CO_2 if it purchases credits representing an equivalent reduction or removal elsewhere. Availability of cheap low-durability credits disincentivizes significant corporate investments in emission reductions across value chains, allowing wealthy countries and companies to continue polluting. Carbon offsets convey a deceptive message regarding the true extent of effort necessary for effective climate action by suggesting that abatement can be achieved at a very low cost. This system puts the burden of recapturing the CO_2 released by temporary credits onto future generations.

In summary, the current system of carbon credits has significant issues limiting their effectiveness as a climate mitigation tool. To overcome these offsetting logics, Carbon Market Watch (2020), Day et al. (2022), Mitchell-Larson et al. (2022), and Brander and Broekhoff (2023) propose viewing the value of credits in their ability to 'buy time' for humanity to decarbonize society rather than as effective offsets. In other words, credits would be seen as a way for humanity to gain time to decarbonize, acknowledging that the buyer has contributed to reducing their overall impact without claiming to have completely counterbalanced the effects of a ton of CO_2 equivalent.

Given that conservation, restoration, and improved land management practices are expected to provide over one-third of the climate mitigation needed by 2030 to stabilize warming below 2°C (Roe et al., 2019), it might be assumed that an offset system is essential. However, AFOLU emissions are already accounted for in GHG inventories. Under the Paris Agreement, parties are required to reduce their own AFOLU emissions regardless.

Voluntary carbon markets are often perceived as a means to mobilize the necessary capital for nature-based solutions. Despite this potential, the reality is starkly different. In 2021, the vast majority of global funding for nature-based solutions—$133 billion—came from public sources, with less than 0.5% from VCMs credits' sales (Mitchell-Larson et al., 2022). Although these projects typically do not aim primarily at mitigation, many do yield such benefits. Companies can contribute to natural conservation projects by purchasing temporary (low durability) credits, without declaring these contributions as offsets. Such financing can serve as a means for companies to acknowledge their historical responsibility for climate change. However, these contributions must be supplementary to the essential investments required to reduce emissions from their operations. They should not exempt companies from the responsibility of directly reducing the emissions they produce.

From a strictly physical standpoint, temporary storage should not be equated with permanent storage. However, temporary storage can provide a 'peak shaving effect', reducing the maximum level of peak warming that occurs in the future (Cullenward, 2023). If the duration of temporary storage extends beyond the time of peak warming, it can have a recognized value within this physical framework. The exact timing of temperature stabilization varies depending on specific scenarios but is linked to when each scenario achieves net-zero CO_2 emissions and net-zero greenhouse gas emissions (ibid). Some scenarios aiming to limit warming to 2 degrees Celsius do not reach net-zero greenhouse gas emissions until after 2100 (ibid). Consequently, low-durability credits are unlikely to contribute to peak shaving and, therefore, will not aid long-term emission reduction. Medium durability, at a minimum, is necessary for temporary storage to be valuable within the physical framework.

In contrast, an economic framework that is not constrained by specific targets (favoring welfare maximization over cost efficiency) would always find value in the delay of climate

damage that temporary storage provides, even if it does not contribute to the Paris Agreement targets. Therefore, the valuation of temporary storage varies based on the adopted framework and objective. Section 3 delves into economic frameworks that use different approaches to assess the value of temporary storage.

3 Economic theory perspective

This chapter presents the findings for Research Question 3, exploring the economic frameworks that utilize different approaches to assess the value of temporary carbon storage. It provides an in-depth analysis of how economic theory conceptualizes the relative value of temporary and permanent carbon credits, with "permanent" defined as storage lasting for the entire time horizon. The conclusions highlight that the economic literature is still inconclusive on the precise value of temporary carbon storage. However, ton-year approaches offer valuable tools for understanding how the market currently values temporary storage and how this valuation could shift if future long-term damages are accounted for.

3.1 Overview of previous approaches

Over the past two decades, academics have engaged in a debate centering on the question of the value of temporary carbon storage through various methodologies. Within this realm of research, three distinct approaches emerge.

The first approach, known as the ‘ton-year approach,’ creates an equivalence between permanent and temporary emission reductions by leveraging the Global Warming Potential (GWP). The GWP is calculated via the cumulative radiative forcing over a specified time horizon, which typically is 100 years. Cumulative radiative forcing is used as a proxy for the damage caused by CO_2 emissions. This method employs vertical stacking principles, equating a greater amount of temporary carbon storage with a single unit of permanent storage. It does so by balancing the benefits of avoiding a certain amount of future damage against the cost of the damages caused by one unit of CO_2 in the atmosphere.

Advocates of the ton-year approach highlight its ability to calculate equivalence time without reliance on a specific price trajectory or discount rate. These variables are deemed ‘particularly uncertain and speculative’ by Herzog et al. (2003). However, critics of this approach, argue that the value of temporary storage obtained is heavily influenced by the chosen time horizon. They also contend that the use of GWP lacks economic justification, as it lacks a ‘connection to underlying economic conditions that would determine the carbon price’ (Herzog, Caldeira and Reilly, 2003). Furthermore, this method does not adequately address the challenge of selecting an appropriate discount rate, implicitly assuming a 0% discount rate for the first 100 years and infinite discount rate thereafter. In economic terms, this implies that future damage from emissions is valued equally with immediate damage for the first 100 years, while the damage caused by emissions beyond that point is considered as having no worth.

The other two approaches apply economic principles to quantify the benefits of temporary carbon storage (Groom and Venmans, 2022). One applies cost-effectiveness principles, the second approach employs cost-benefit optimization (or welfare maximization). These approaches differ from the ton-year method in how they conceptualize the substitution between permanent and temporary storage. While the ton-year approach applies vertical

stacking principles, the other approaches apply horizontal stacking principles: instead of assuming that a decision-maker seeking permanent climate benefits buys a number of temporary credits equivalent to permanent credits, these approaches envision the decision-maker purchasing temporary storage and repurchasing it when the carbon is rereleased. This cycle continues until the prices for permanent removal become more favorable.

The cost-effectiveness approach is grounded in the principle that when CO_2 is sequestered and stored at a specific time t, the sequesterer receives the prevailing carbon price at that moment. If the same ton of CO_2 is subsequently released at a later time $t + x$, the responsible party must pay the carbon price applicable at that future time, reflecting the assumption of permanent liability for the stored carbon. Consequently, the value of the stored carbon is determined by the difference in carbon prices over time, adjusted for appropriate discounting to reflect the time value of money and the risk associated with future carbon prices. In this perspective, the societal economic worth of damages from emissions or benefits from avoided emissions is reflected in the cost of abatement, which is signaled by the carbon price (ibid). When the carbon price is projected to rise at the same rate of discounting, the timing of damages becomes irrelevant. Consequently, under these assumptions, this approach assigns zero value to temporary storage, failing to assign value to the delay in emissions. This is not a surprise as, under a cost-effectiveness framework, any carbon storage that ends before achieving the climate goal does not contribute to staying below the target temperature increase (ibid). The lack of consensus on appropriate carbon pricing, future carbon price trajectories, and discount rates contributes to the inconclusiveness of this approach. Nevertheless, it offers a relevant perspective, particularly as it aligns the economic viewpoint with the physical reality discussed in Section 2.3.1, which explains that temporary storage does not contribute to reducing global temperatures at peak warming unless the storage duration extends beyond that peak. Temporary storage holds no value under a cost-effectiveness framework unless it contributes to the Paris Agreement's target of keeping global temperature rise well below 2 degrees Celsius above pre-industrial levels.

The third approach is welfare maximization, which relies on the use of the social cost of carbon (SCC) calculated using integrated assessment models (IAMs) to ensure intertemporal optimization. The SCC quantifies the marginal damage cost of climate change, meaning it calculates the additional damage from one extra ton of CO_2 emissions (Tol, 2008). Unlike using the carbon price, employing the SCC ensures that prices are optimized over time to maximize welfare. A relevant example of this approach is the World Resource Institute's working paper titled ‘The Time Value of Carbon and Carbon Storage: Clarifying the Terms and the Policy Implications of the Debate’ (Marshall and Kelly, 2010). The welfare maximization approach is valuable for understanding the economic value of temporary storage, however the primary focus of this thesis is to investigate its value in comparison to the value of permanent storage.

This section has provided a brief overview of the approaches used in the literature to value temporary carbon storage. While these approaches have been developed to establish appropriate values for storage and facilitate the issuance of credits, this thesis primarily employs them as tools to integrate economic reasoning with a market perspective rather than as definitive methods for determining value. Given the thesis's focus on the relationship between the value of temporary and permanent credits, and the significance of time horizons in determining when a credit is considered permanent by a given society, further exploration of time horizon-based approaches is essential. The ton-year approach, which directly uses time horizons, is therefore extensively employed to model how the relative value of

temporary and permanent storage changes over varying time periods. This approach will be applied in two key ways:

1. The ton-year approach will be used to develop a novel method, referred to as the 'novel approach.' This method will explore the implicit discount rate corresponding to the 100-year time horizon adopted by the market perspective. Section 3.2.4 will elaborate on this novel approach.
2. The Lashof approach will be used to examine how the relative value of temporary and permanent storage evolves when the time horizon is extended, incorporating updated knowledge on the long-term impacts of CO_2. Section 3.2.6 will explore the outcomes of the Lashof method under these extended time horizons.

The cost-effectiveness approach, including the vertical stacking perspective, will not be explored further in this thesis beyond what has been discussed here, but it will be revisited in Chapter 4. The welfare maximization approach will also not be further examined, as IAMs introduce a range of complexities related to climate modeling, damage assessment, and future emission pathway predictions, which extend beyond the scope of this research.

3.2 Traditional ton-year approaches (vertical stacking approaches)

Vertical stacking involves equating a larger amount of temporary carbon storage with one unit of permanent storage. Approaches utilizing vertical stacking principles, known as ton-year approaches, determine the equivalence between temporarily stored CO_2 and the permanent removal or avoidance of CO_2 emissions. The number of tons of CO_2 that need to be stored temporarily to be equivalent to one ton stored permanently is called equivalence ratio (ER). The ER is a measure of how valuable temporary CO_2 storage is in comparison to permanent storage. This interpretation aligns with the established economic literature, which interprets the value of temporary storage as a fraction of the value of permanent storage

The Moura-Costa and Lashof methods are frequently referenced approaches in this context (Fearnside, Lashof and Moura-Costa, 2000; Moura Costa and Wilson, 2000), are hereby referred to as traditional ton-year approaches due to their frequent citation in the literature. Both methods assess the area under the 100-year decay curve of CO_2 in the atmosphere to establish equivalence. The function describing this decay is known as the Impulse Response Function (IRF), also referred to as the radiative forcing curve, as it reflects the concentration of CO_2 and, consequently, radiative forcing. The IRF reflects the additional carbon present in the atmosphere due to emissions. Given the near-linear relationship between cumulative CO_2 emissions and average global temperature increase (Canadell et al., 2021), the fraction of CO_2 that persists in the atmosphere is used as a proxy for CO_2 damage. The specification of this function will be discussed later.

The selected time horizon, also referred to as the evaluation period, represents the duration over which the damages from emissions and the benefits from emission reductions are assessed. Future damage within this period is valued equally with immediate damage, while damage beyond this point is considered to have no worth. The equivalence ratio of a temporary project is calculated by dividing the cost of the damages caused by CO_2 emissions and the persistence of that CO_2 in the atmosphere over a specific time horizon by the benefits of storing CO_2 outside the atmosphere, which is equivalent to delaying the emission of CO_2.

The selection of a 100-year time horizon is likely influenced by its historical use in international climate agreements (Murray et al., 2012). The adoption of a 100-year timeframe in traditional carbon credit accounting originated three decades ago when the concept of

Global Warming Potential (GWP) was utilized to assess and compare greenhouse gas (GHG) emissions in the Kyoto Protocol. Over time, it gained official recognition and was officially adopted by the IPCC (Shine, 2009). It is also used in VCMs where standards require a guaranteed permanence period of 100 years.

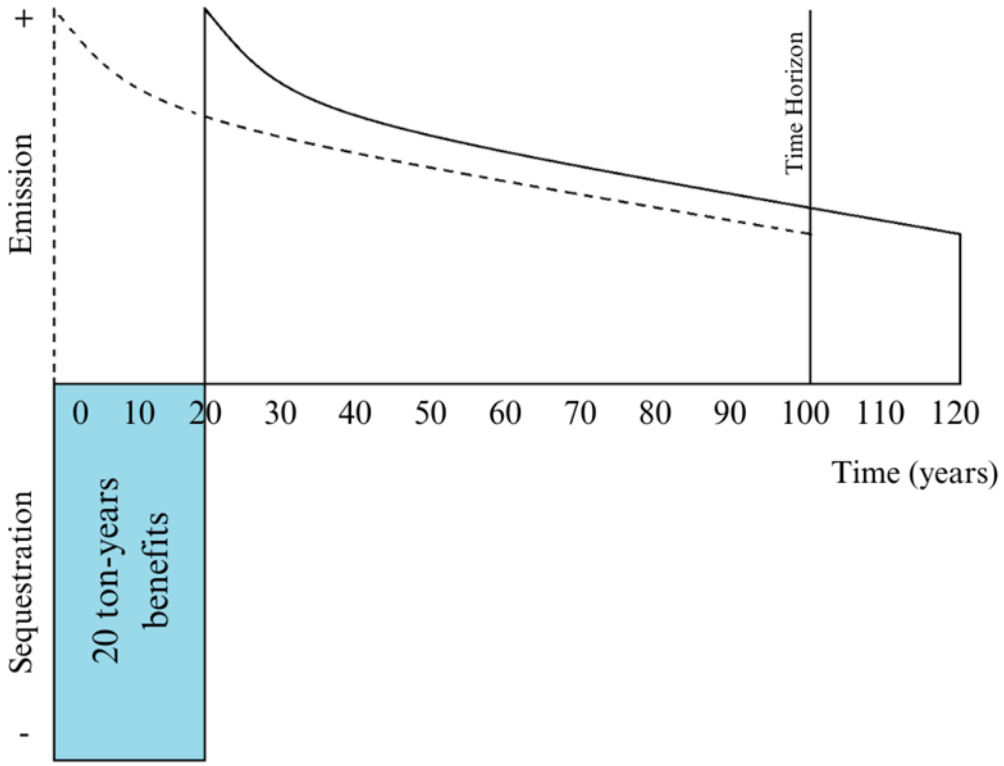

Figure 3 Moura-Costa method. The area under the dashed curve corresponds to the costs of the emission and comprises 55 ton-years. The impulse response function (IRF) depicting the release of carbon occurring at year 20 (after the end of the project) is represented by a solid line. The light blue area corresponds to the benefits. According to the Moura Costa method, a project that temporarily stores 1 tCO_2 for 20 years before releasing it back into the atmosphere yields benefits equivalent to 20 ton-years. The equivalence ratio, calculated as the ratio between the costs and benefits, is 2.75 for the specifcase depicted in the image. This implies that 2.75 tons of CO_2 must be stored for 20 years to offset the cumulative radiative forcing over 100 years resulting from the emission of 1 t of CO_2.

Both the Moura-Costa and the Lashof methods quantify the 'costs' of the damage related to an emission as the area under the decay curve from the time of emission to year 100, while they interpret the area under the avoided emissions as the benefits obtained from temporary storage. When plotting the IRF function, the x-axis represents time in years, and the y-axis represents the stock of CO_2 in the atmosphere, measured in tons. Consequently, the associated costs and benefits are quantified in ton-years.

For traditional ton-year approaches, the equivalence between permanent and temporary storage is defined when the area representing the undiscounted costs of emissions (occurring within the first 100 years) is equal to the area representing the benefits from temporary storage. Moura Costa employs a straightforward method to calculate the benefits of carbon storage, simply quantifying the total number of tons stored and multiplying it by the duration of storage. A clearer explanation of the calculations involved can be found in Figure 3. Instead, the Lashof method is more conservative when determining the benefits. It takes into account the re-emission of CO_2 at the conclusion of the storage period, which the Moura-Costa method does not. Specifically, the Lashof approach views temporary carbon storage as

a means of delaying the release of emissions. Hence, the benefits of temporary storage can be seen as the cumulative radiative forcing effectively being pushed beyond the specified time horizon. A more in depth explanation of the calculations involved in the Lashof method can be found in Figure 4.

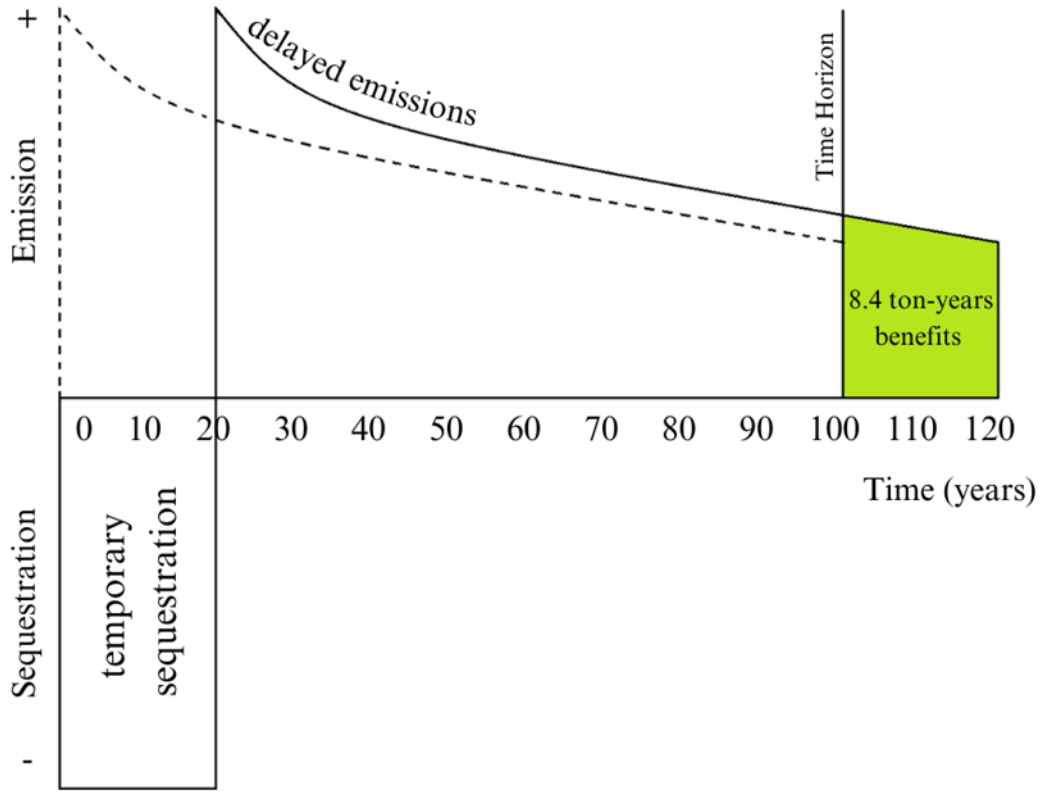

Figure 4 Lashof method. The area under the dashed curve corresponds to the costs of the emission and comprises 55 ton-years. The impulse response function (IRF) depicting the release of carbon occurring at year 20 (after the end of the project) is represented by a solid line. The green area corresponds to the benefits. For this method, the benefits of temporary storage can be seen as the cumulative radiative forcing effectively being pushed beyond the specified time horizon. According to the Lashof method, a project that temporarily stores 1 tCO_2 for 20 years before releasing it back into the atmosphere yields benefits equivalent to 8.4 ton-years. The equivalence ratio, calculated as the ratio between the costs and benefits, is 6.54 for the specific case depicted in the image. This implies that 6.54 tons of CO_2 must be stored for 20 years to offset the cumulative radiative forcing over 100 years resulting from the emission of 1 t of CO_2.

3.2.1 Updating impulse response functions: implications for ton-year approaches

Although ton-year approaches are grounded in the physical measure of GWP, they are fundamentally economic in nature, using cumulative radiative forcing as a proxy for the damage caused by CO_2 in the atmosphere. In fact, these approaches adopt a time horizon of 100 years that corresponds to applying a 0% discount rate to costs and benefits from the time of emission up to the time horizon, followed by an infinite discount rate beyond that point.

The ton-year approach will be employed to develop a new method, referred to as the 'novel approach.' This method aims to explore the implicit discount rate corresponding to the 100-year time horizon typically used in market assessments. Additionally, a ton-year approach will be used to investigate how the relative value of temporary versus permanent carbon storage changes when the time horizon is extended. However, the Impulse Response Function

(IRF) employed by traditional ton-year approaches, like the Moura Costa and Lashof methodologies, in the early 2000s was based on the 1990 formulation by the IPCC, which is now outdated. The upcoming calculations exploring the implicit discount rate and the consequences of adopting longer time horizons will utilize the updated IRF formulation.

This section explains the rationale for updating the Impulse Response Function (IRF) to reflect the latest advancements in climate science and addresses the limitations of traditional methods that rely on the outdated 100-year time horizon. The updated IRF more accurately accounts for the long-term impacts of CO_2 emissions, which were underestimated in earlier models.

The 1990 Impulse Response Function (IRF), given by Equation (1), is as follows:

$$A(t) = 0.301e^{-\frac{t}{6.6993}} + 0.343e^{-\frac{t}{71.109}} + 0.357e^{-\frac{t}{815.727}} \qquad (1)$$

In this equation, $A(t)$ represents the IRF for CO_2 concentration over time t. It describes how the concentration of CO_2 in the atmosphere evolves in response to an instantaneous release of CO_2.

The 1990 IRF lacked a time-independent term—a constant that does not diminish over time—resulting in the assumption that all CO_2 would eventually be reabsorbed by the ocean and biosphere. It is now understood that this assumption is incorrect.

As explained in Section 1, in ton-year approaches, the area under the IRF represents the cumulative radiative forcing caused by the impulse emission of CO_2 in the atmosphere. This radiative forcing leads to an increase in global temperature, thereby representing damage. Ton-year approaches equate permanent and temporary storage by requiring that the area representing emission costs equals the area representing the benefits of temporary storage. For ton-year approaches to yield a finite equivalence ratio, the area under the IRF needs to be finite.

At the time when Moura Costa and Lashof developed their methods, there was no necessity to adopt a specific time horizon, since the models assumed complete absorption of CO_2 (mathematically approaching zero). The area under the IRF, as expressed back then, allowed for the calculation of the integral from 0 to infinity, resulting in a finite number of 317.62 ton-years. Moura Costa and Lashof used a 100-year time horizon even though there was no need to artificially cut the integral, as the integral of the IRF function was a finite number. This further proves that these methods are economic in nature and don't represent a physical equivalence—the time horizon reflects society's concern, the point up to which society cares about the damages caused by emissions, and how forward-looking the calculation of equivalence between temporary and permanent storage value is. These older models overlook significant long-term damage.

Advancements in climate science and changes in atmospheric conditions have led to revisions in the specification of the IRF. The most up to date version of IRF is the 2013 IRF from Joos et al.(Equation 2), includes a constant term that represents a portion of CO_2 remaining in the atmosphere indefinitely. This update shows that 21.7% of CO_2 emissions persists in the atmosphere indefinitely as it is not reabsorbed by the ocean and biosphere.

$$A(t) = 0.217 + 0.186e^{-\frac{t}{1.186}} + 0.338e^{-\frac{t}{18.51}} + 0.259e^{-\frac{t}{172.9}} \qquad (2)$$

However, the 2013 IRF from Joos et al. is accurate only up to 1,000 years, showing the reduction of CO_2 concentration as it is absorbed by the biosphere and ocean. If one is interested in the behavior of CO_2 over more than 1,000 years, it is necessary to use an extended version of the IRF. Joos's IRF does not account for exchanges between the atmosphere, geosphere, and ocean, which significantly influence long-term projections over 1,000 years. Key processes such as the dissolution of seafloor carbonates, weathering of terrestrial carbonate rocks, and silicate weathering are not considered. Including the effect of geological processes involves adding a decay factor to the time-independent term (0.217), utilizing the time constants of geological carbon removal processes as described by Archer et al.

The long-term IRF version[4] is given by Equation 3:

$$A(t) = 0.217 * (0.54e^{-\frac{t}{5500}} + 0.14e^{-\frac{t}{8200}} + 0.32e^{-\frac{t}{200000}}) + 0.186e^{-\frac{t}{1.186}} + 0.338e^{-\frac{t}{18.51}} + 0.259e^{-\frac{t}{172.9}} \quad (3)$$

This thesis investigates the dynamics between temporary and permanent CO_2 storage beyond the conventional 100-year timeframe, examining how the equivalence ratio changes when the 100-year assumption is extended. The analysis extends the time horizon to 100,000 years, necessitating a reformulation of the IRF to ensure long-term accuracy. For this purpose, the most complete IRF version, Equation 3, is employed. Similar modeling has been previously used by Lyngfelt et al. (2019) to model mixtures of leakage rates on long timescales.

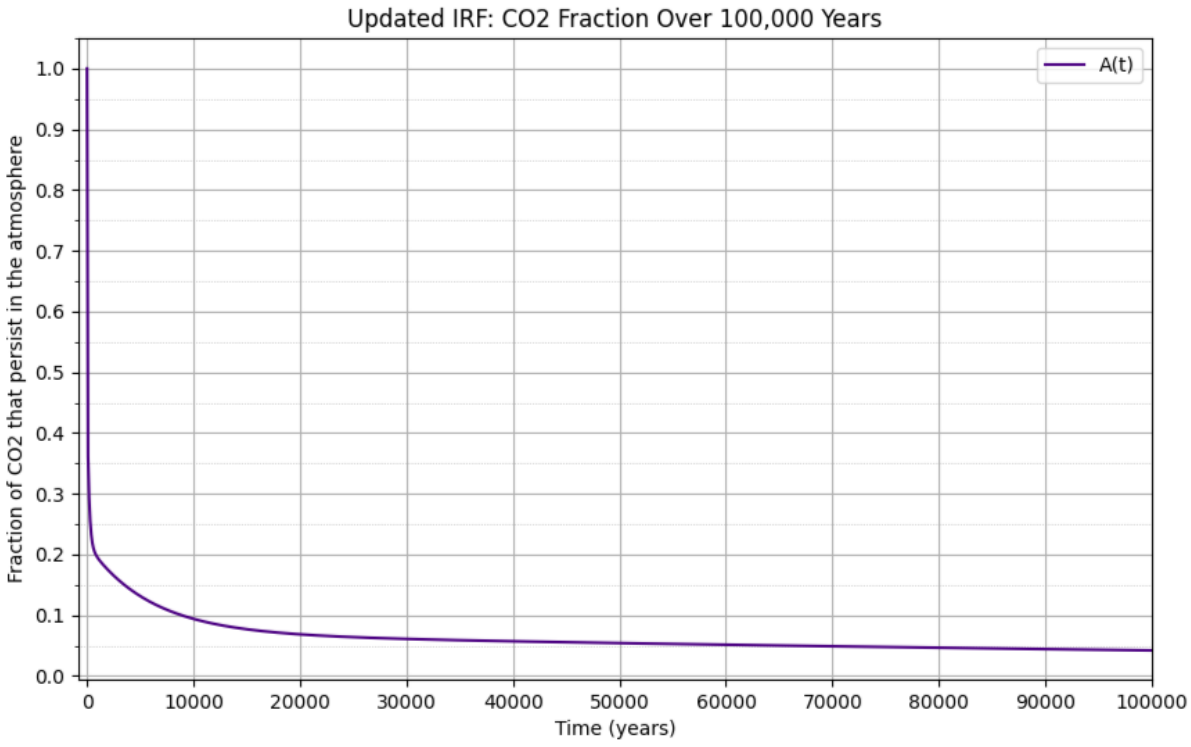

Figure 5 Long-term Impulse Response Functions (IRF). This figure illustrates the long-term IRF based on Equation 3, which models the fraction of CO_2 that persists in the atmosphere over a period of 100,000 years.

[4] Over very long periods, this function approaches asymptotically to zero, with the fraction of CO_2 falling below 0.01 at approximately t ≈ 387,576 years and below a threshold of 10^{-10} at approximately t ≈ 4,071,712 years.

Figure 5 illustrates the long-term IRF and that the area under the IRF within the first 100 years is significantly smaller compared to the area considered over a longer term. By adopting a 100-year time horizon, one ignores long-term damage.

3.2.2 A novel approach

This section introduces a 'novel approach'; an alternative to traditional ton-year methods. In ton-year approaches, the fraction of CO_2 remaining in the atmosphere is used as a proxy for the damage caused by CO_2. Traditional ton-year approaches use a fixed time horizon, the novel approach substitutes the time horizon with the adoption of discount rate.

The discount rate (r) and time horizon (TH) both represent societal preferences for delaying CO_2 emissions, but they operate through different mechanisms. The time horizon approach models society's concern as being limited to a specific future period, beyond which no additional concern is given to the damages caused by emissions. When a certain TH is adopted, it implies that society values future damages equally (0% discount rate) up to a certain point in time, and then completely disregards them afterward (effectively an infinite discount rate). Since this thesis focuses on the relationship between the value of temporary and permanent credits, it's important to reiterate that the time horizon corresponds precisely to the duration of storage required for a credit to be classified as permanent by a given society. For instance, a society that only values the next 500 years would consider a storage period of 500 years as permanent.

On the other hand, adopting a specific discount rate applies a continuous compounding discount rate over the entire time period, reflecting society's decreasing concern for future damages as they occur further into the future. This approach suggests that as time progresses, society places less and less value on the consequences of emissions, gradually diminishing the weight given to future damages.

The novel approach is used to identify the discount rates that correspond to different time horizons. Specifically, this analysis aims to determine which discount rate aligns with the commonly adopted 100-year cutoff used in credit standards.

In the novel approach, the IRF function is discounted, meaning it gradually decreases asymptotically to zero. The total costs over time are represented by the area under the radiative forcing curve, therefore discounting allows for integration over an infinite period of time. In other words, the discounting allows to account for the full scope of damages caused by CO_2 in the atmosphere, which extend infinitely into the future, while at the same time accounting for time preference.

Mathematically, the discounting is applied to radiative forcing because cumulative radiative forcing serves as a proxy for total damage, consequently instant radiative forcing represents immediate damages. It's important to note that the physical measure of radiative forcing itself isn't being discounted—rather, it's the associated damages that are adjusted to reflect the diminishing importance of future impacts.

In the novel approach, the benefits of delaying an emission are calculated by comparing the costs of an immediate emission with those of a delayed one. The core idea is to account for

society's time preference, recognizing that future damages are of less concern than immediate ones. The benefits of delaying an emission are determined by comparing the total discounted damages of an immediate emission with those of a delayed emission. The way benefits are defined in the novel approach mirrors the calculation of benefits in the Lashof method. In fact, in Lashof too, the benefits are identified by the difference between the area under the avoided emission curve (representing the immediate emission scenario) and the area under the delayed emission curve.

The equivalence ratio (ER) is calculated by dividing the costs (damages to be compensated) by the benefits of temporarily storing CO_2 out of the atmosphere or delaying an emission.. A higher ER would indicate that temporary storage is less valuable compared to permanent storage because it suggests that the costs (or damages) associated with temporary storage are high relative to the benefits. Conversely, a lower ER suggests that temporary storage is closer in value to permanent storage because the costs are lower relative to the benefits.

Illustration and Mathematical Formulation of the Novel Approach

For better understanding, Figure 6 Figure 6 illustrates the novel approach. The blue line represents the baseline scenario, this baseline shows the situation without any carbon removal or emission reduction efforts. The area under this line corresponds to the total discounted costs, calculated by integrating the curve from the time of emission (time zero) until it converges to zero. The orange line represents the emission released at a later time $t_{release}$. In Figure 6, this happens at $t = 40$, representing a project where permanence is guaranteed for 40 years. Thanks to the project, the emission that would have occurred at time zero is delayed by 40 years. Although this delayed emission still causes damage, it happens later, making this scenario preferable to an immediate emission. To clarify, the term ‘delayed emission’ can be used for removal, reduction, and avoidance projects. The effect of these projects, which guarantee permanence and additionality for a temporary period, is the same: they delay an emission that would have occurred at time zero if the project did not exist. This emission release will occur at the end of the project or when permanence and additionality are no longer guaranteed.

The equation for the blue line is the Discounted damage (DD). Discounted damage (DD) refers to the damage caused by the fraction of CO_2 that remains in the atmosphere at time t, calculated by applying exponential discounting. This approach models the diminishing present value of future damages. The formula for exponential discounting is:

$$DD(t) = D(t)\mathrm{e}^{-\mathrm{rt}}$$

where *D(t)* is the value at time t and r is the discount rate.

The integral of $DD(t)$ to infinity represents the discounted total cost (or Net Present Value) of the damage caused by a unit of CO_2 emission and is expressed by the equation:

$$Total\ discounted\ damage = \int_{t\ emission}^{\infty} DD(t)$$

The benefits are obtained by subtracting the damages caused by the delayed emission from the damages caused by an immediate emission. As shown in the figure, the area under the curve representing the damage caused by the delayed release of carbon is smaller than the area under the curve representing the damage that would have been caused in the absence of

the project by the emission that has been avoided. This is because the equation for the orange line is:

$$DD\ delayed(t, t_{\text{release}}) = \mathrm{e}^{-\mathrm{rt}}\,[\,0.217 * (0.54e^{-\frac{t-t_{\text{release}}}{5500}} + 0.14e^{-\frac{t-t_{\text{release}}}{8200}} + 0.32e^{-\frac{t-t_{\text{release}}}{200000}}) + 0.186e^{-\frac{t-t_{\text{release}}}{1.186}} + 0.338e^{-\frac{t-t_{\text{release}}}{18.51}} + 0.259e^{-\frac{t-t_{\text{release}}}{172.9}}\,]$$

where t_{release} is the time at which the emission is released (in the example above, $t_{\text{release}} = 40$), and t is the time on the x-axis, representing the time passed since the emission would have originally occurred. Therefore, $t - t_{\text{release}}$ represents the time that has passed since the re-release of the emission. The decay of the curve happens as if the emission were released at time zero, but the value is discounted considering the delay, so the time term multiplying the discount rate is the time on the x-axis.

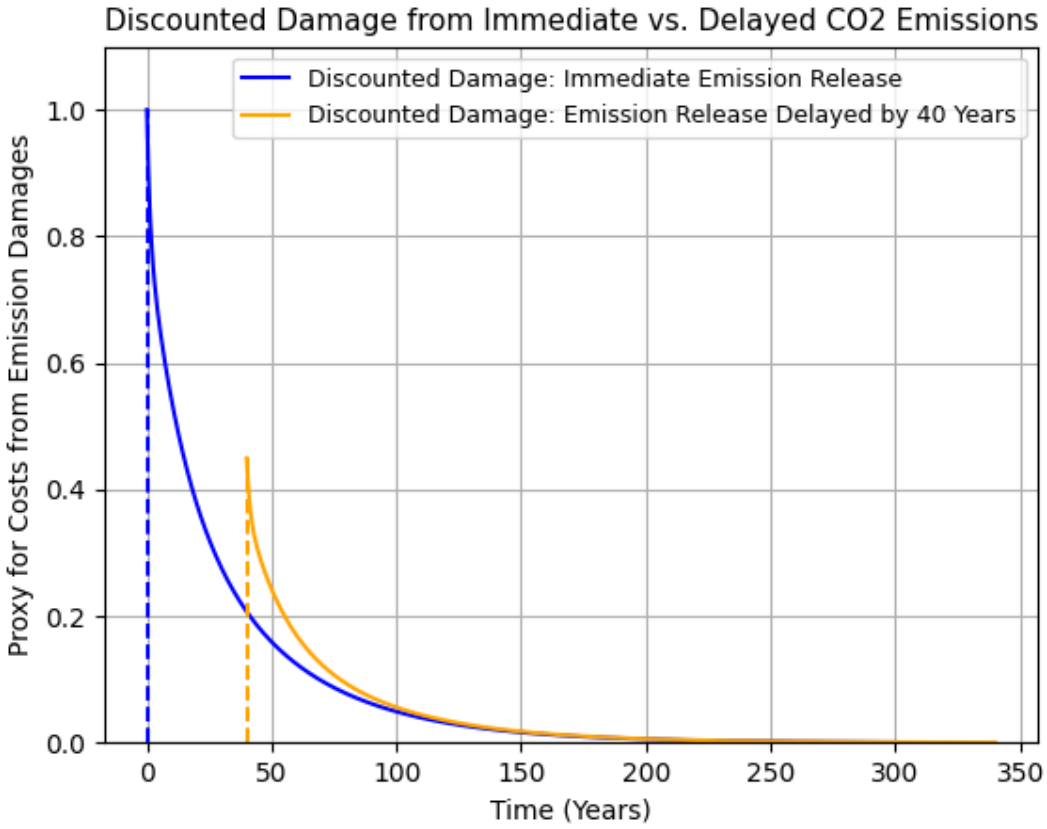

Figure 6 Illustration of the novel approach developed in this thesis to study which discount rate corresponds to a given time horizon. The blue line represents the baseline scenario without intervention, while the orange line shows the effect of delaying emissions by 40 years, reducing immediate damage and shifting costs into the future.

As a result, the area under the orange curve is smaller than the area under the blue curve. The benefits of this delayed emission or temporary carbon storage are given by the difference between the area under the blue curve (the avoided damage) and the area under the orange curve (the delayed but still occurring damage). The formula for the equivalence ratio (ER) is:

$$ER_{New\ Approach} = \frac{\int_0^{\infty} DD(t)}{\int_0^{\infty} DD(t) - \int_{t_{\text{release}}}^{\infty} DD\ delayed(t)}$$

Here, the numerator represents the costs: the total discounted damage of one unit of CO_2 without delay, indicating the damage caused by one unit of CO_2 in the atmosphere. The denominator represents the benefits: the difference between the total discounted damage without delay and the discounted damage considering the delay, which is the damage avoided by delaying the emission for a certain period. Equivalence is achieved when the amount of damage equals the amount of benefits. For example, an equivalence ratio of five calculated for an emission delayed by 50 years implies that delaying five units of CO_2 by 50 years results in benefits equivalent to the costs of immediate release.

3.2.3 Exploring the relationship between discount rates, delay times and equivalence ratios using the novel approach

The novel approach, substituting the time horizon with a constant discount rate, has been modeled using Python (full script available on the project's GitHub repository[5]). This methodology has been applied to various delay times, ranging from 10 years to 200 years, and to various discount rates, from 0.1% to 3%, to understand how the ER varies with changes in the discount rate and delay time. The results are displayed in Figure 7, which illustrates the relationship between the ER and the discount rate as determined by the novel approach.

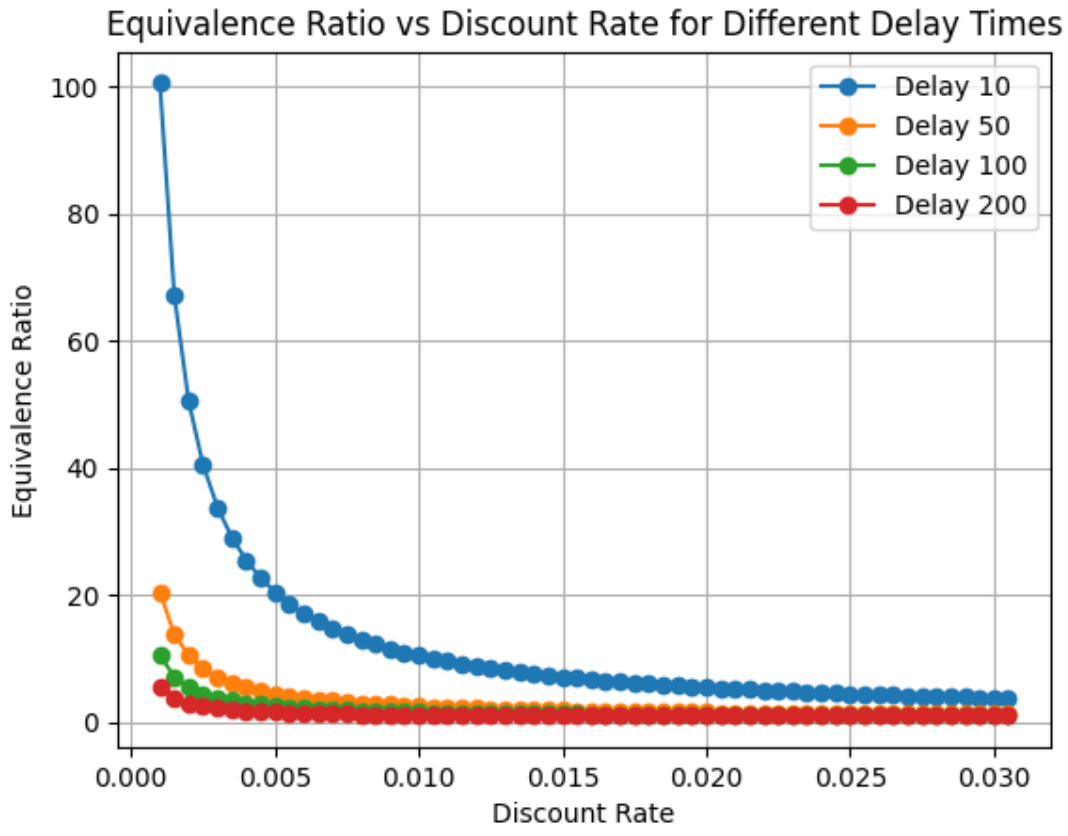

Figure 7 Relationship between Equivalence Ratio (ER) and Discount Rate using the novel approach. The ER is analyzed across a range of delay times and discount rates to illustrate how variations in discount rates and delay times affect the ER.

[5] https://github.com/federicadossi/TemporaryStorage

These results confirm previous expectations: as the discount rate increases, the ER decreases. This means higher discount rates require less temporary storage to offset the damage from an emission because future damages are valued less.

ER changes more significantly with varying delays at lower discount rates. High discount rates reduce the cost of emissions to such an extent that even short delays result in a low ER. The changes in ER are not strictly proportional but follow a pattern of diminishing returns. Higher discount rates or longer delays lead to smaller changes in ER, indicating a nonlinear relationship where initial changes have more significant impacts than subsequent changes.

3.2.4 Evaluation of Discount Rates and Extended Time Horizons

As discussed in Section 3.1, the focus is on determining the implicit discount rate corresponding to the 100-year time horizon commonly adopted in market perspectives and investigating how the relative value of temporary versus permanent carbon storage changes as the time horizon is extended.

To achieve this, it is necessary to identify the discount rate that aligns the results of a novel approach with those of traditional methods, thereby analyzing the interplay between discount rates and time horizons. To explore this relationship, outcomes were calculated by adopting extended time horizons using the Lashof method, which was applied to compute equivalence ratios for varying delay times. Equivalence ratios serve as a means of comparing the results.

Notably, the discount rate (r) and the time horizon (TH) have opposite effects on the ER. As the discount rate increases, the ER decreases, while an increase in the time horizon increases the ER. This occurs because the damage caused by emissions released at the end of the delay period is smaller when the discount rate is higher.

The analysis centered on identifying, for each discount rate derived from the novel approach, the time horizon that minimized the absolute difference in the equivalence ratio.

Table 1 presents a subset of the results obtained using the Lashof method. Utilizing the Lashof method with the complete version of the IRF function and a 100,000-year time horizon, the equivalence ratio for a 100-year delay (representing low durability credits) is found to be 1521. A duration of 100,000 years reflects the period required for atmospheric carbon to be removed from the surface carbon cycle and return to the geosphere. This indicates that 1004 low durability credits, which guarantee additional storage for 100 years, are required to equate to the value of one permanent credit when considering a time horizon of 100,000 years. In this scenario, it assumes a society that is deeply concerned about the damages caused by emissions over an extremely long period—up to 100,000 years—placing equal importance on damage occurring far in the future as on damage happening in the near term. Even though an extremely extended period of time is considered, the equivalence is based on vertical stacking principles, therefore it is an economic equivalence, not a physical one. In reality the contribution of such short-term storage merely delays climate damage without lowering long-term temperatures (Cullenward, 2023), as all the carbon would likely be released before temperature stabilization.

When using the Lashof method with an extended 10,000-year time horizon, the calculated equivalence ratio for a 100-year delay (corresponding to low-durability credits) is 153. If a 1,000-year time horizon is considered, which is currently seen as the minimum length for buyers interested in high-quality removals to define the credit as ‘permanent’ (Joppa et al., 2021), the equivalence ratio for the 100-year delay represented by AFOLU credits is 13 when any damage happening after 1,000 years is ignored. This implies that 13 AFOLU credits, representing additional storage guaranteed for 100 years, are needed to match the climate

value of one permanent credit when permanence is defined as any storage lasting at least 1,000 years.

Table 1 Subset of Results from the Lashof Method with Extended Time Horizons up to 100,000 Years. The complete tables of results are available at the project repository on GitHub. The 'Costs' column indicates the total damages caused by an immediate emission within the given time horizon, while the 'Benefits' column reflects the damages effectively postponed beyond the time horizon, thereby avoided. The Equivalence Ratio (ER) represents the ratio of costs to benefits.

Time Horizon (years)	Delay (years)	Costs (ton-years)	Benefits (ton-years)	Equivalence Ratio
200	40	80.1	12.2	6.6
200	100	80.1	32.4	2.5
200	200	80.1	80.1	1.0
500	40	154.2	8.9	17.4
500	100	154.2	22.5	6.8
500	200	154.2	46.9	3.3
1000	40	256.1	7.8	32.8
1000	100	256.1	19.6	13.1
1000	200	256.1	39.5	6.5
10000	40	1444.0	3.8	383.4
10000	100	1444.0	9.4	153.1
10000	200	1444.0	18.9	76.4
100000	40	6409.4	1.7	3804.1
100000	100	6409.4	4.2	1521.4
100000	200	6409.4	8.4	760.5

Table 2 Subset of results from the novel approach with various discount rates. The complete tables of results are available at the project repository on GitHub. The column labeled 'Costs of Emission' reports the total discounted damages caused by an immediate emission over time. The 'Costs of Release' column reports the discounted damages that occur when the storage period ends and the emission is eventually released, with the resulting damage being less severe compared to an immediate release. The 'Benefits of Delayed Emission' column shows the net advantages of delaying emissions, calculated by subtracting the costs associated with the delayed release from the immediate emission costs. Finally, the Equivalence Ratio (ER) is provided, representing the ratio of 'Costs of Emission' to 'Benefits of Delayed Emission'.

Discount Rate (%)	Delay period (years)	Costs of Emission (ton-years)	Costs of Release (ton-years)	Benefits of Delayed Emission (ton-years)	Equivalence ratio
0.1	40	239.9	230.5	9.4	25.5
0.1	100	239.9	217.0	22.8	10.5
0.1	200	239.9	196.4	43.5	5.5
0.5	40	72.4	59.3	13.1	5.5
0.5	100	72.4	43.9	28.5	2.5
0.5	200	72.4	26.6	45.8	1.6
1	40	43.4	29.1	14.3	3.0
1	100	43.4	16.0	27.4	1.6
1	200	43.4	5.9	37.5	1.2
2	40	25.6	11.5	14.1	1.8
2	100	25.6	3.5	22.1	1.2
2	200	25.6	0.5	25.1	1.0

3	40	18.7	5.6	13.1	1.4
3	100	18.7	0.9	17.7	1.1
3	200	18.7	0.0	18.6	1.0

Table 2 presents a subset of the results from the novel approach. These results are also discussed in section 3.2.3 to show how variations in discount rates affect the ER. In this section, however, the results from the novel approach are compared to those from the Lashof method using extended time horizons. The primary objective is to evaluate how the relative value of temporary versus permanent storage changes when the time horizon is extended, and to explore the implicit discount rate associated with varying time horizons, particularly the 100-year horizon commonly adopted in market contexts. Figures 8 and 9 illustrate the outcomes of the comparative analysis of discount rates and their corresponding time horizons.

Figure 8 highlights how the outputs of the two methods align. The findings confirm that higher discount rates correlate with shorter time horizons. For discount rates between 0.01% and 3%, the corresponding time horizons do not exceed 850 years. While the analysis includes time horizons up to 100,000 years, such long horizons correspond to very high equivalence ratios (temporary storage has less value when future damages are considered), which would require discount rates below 0.1%. Conversely, higher discount rates correspond to shorter time horizons, as they place less emphasis on future damages. In this analysis, the shortest time horizon considered is 50 years.

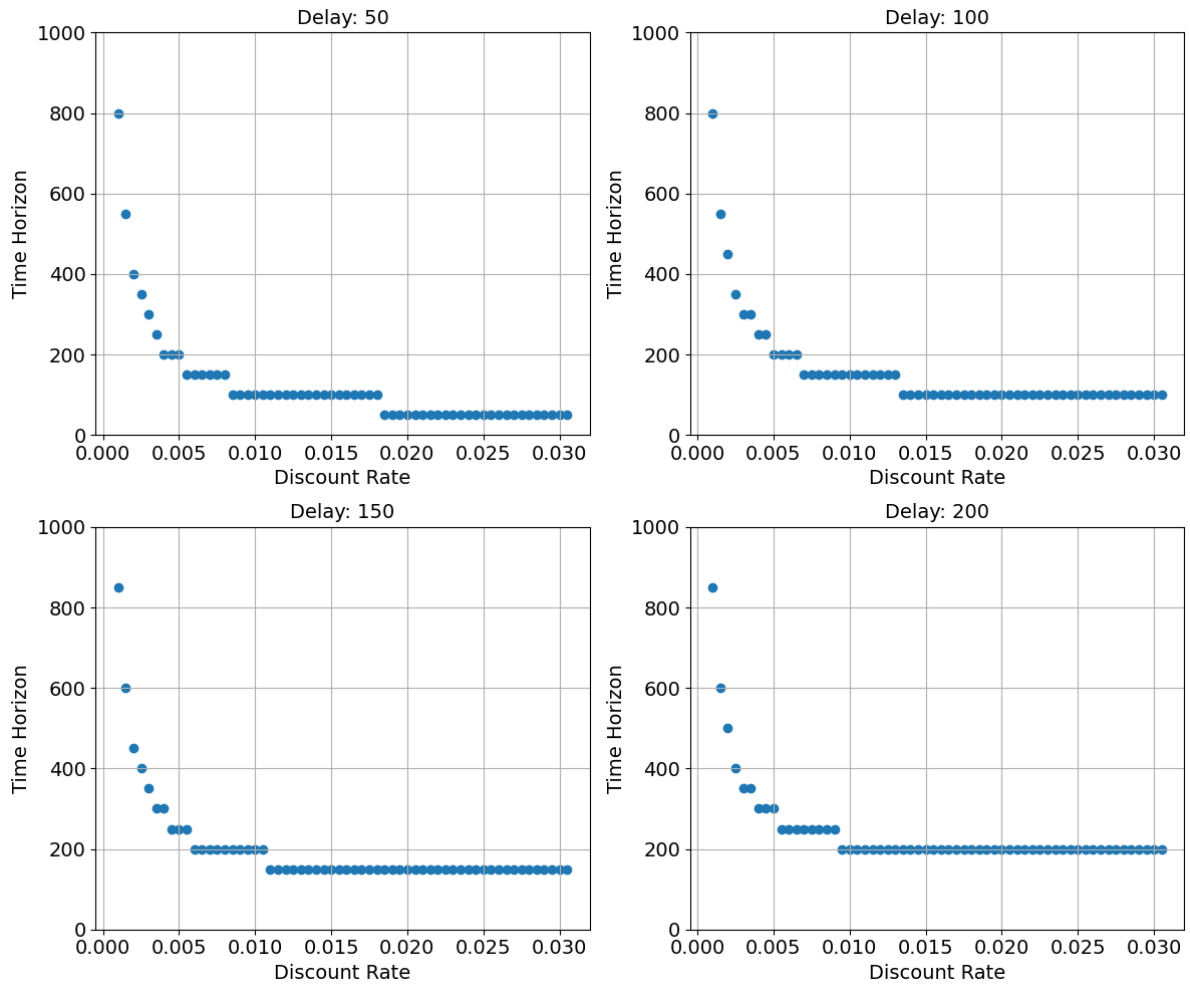

Figure 8 Comparison of discount rates and corresponding time horizons. The plots indicate the time horizon that minimizes the absolute difference in the equivalence ratio for each discount rate. The figure illustrates the relationship between discount rates and time horizons.

Regarding the effect of delay, as the delay increases, the minimum time horizon also increases, even for high discount rates. Additionally, longer delays result in higher equivalence ratios, indicating that fewer units of temporary storage are needed to achieve the same climate benefits as one unit of permanent storage. All these results confirm the relationship between discount rates and equivalence ratios: as the discount rate increases, the equivalence ratio decreases, and vice versa. However, what this comparative analysis adds is an understanding of which specific discount rates correspond to certain time horizons. This allows us to say that in a scenario where society is only concerned with the next 200 years (TH=200), it is equivalent to society adopting a particular discount rate for the future damages caused by CO_2 emissions in the atmosphere.

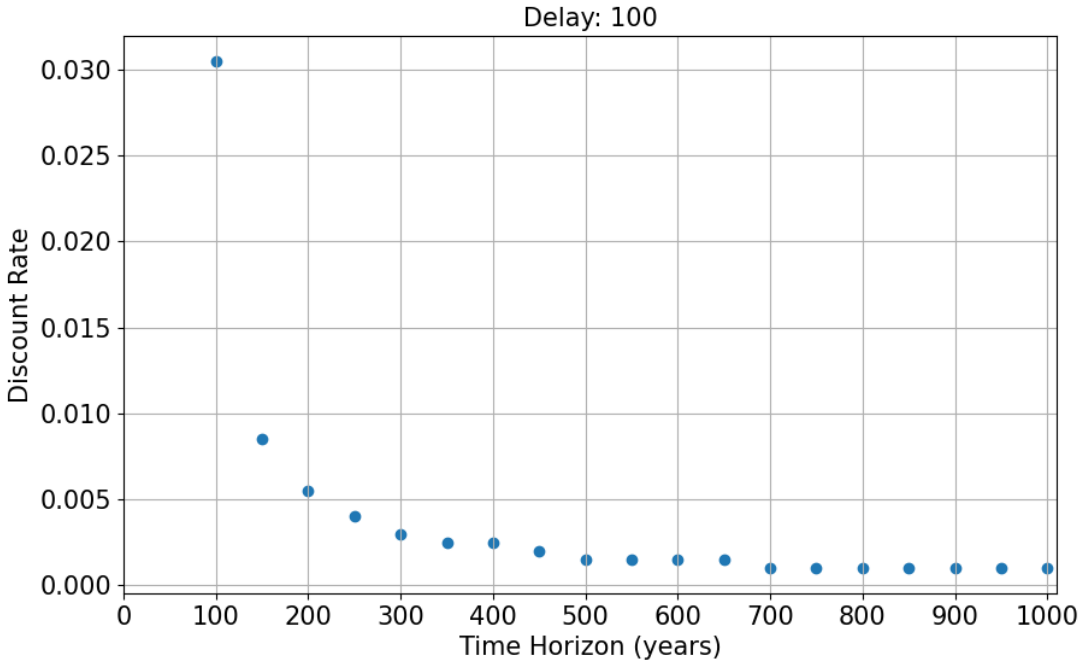

Figure 9 Discount rates associated with a delay of 100 years across different time horizons.

Figure 9 presents an analysis of the discount rate that yields a similar equivalence ratio when a 100-year delay is considered across different time horizons. This 100-year period is central to the investigation because, as discussed in Section 2.3, most credits in the VCMs currently represent 1 ton of CO_2 equivalent reduced or removed from the atmosphere, guaranteed for 100 years. This corresponds to a 100-year delay in emissions. Given that the conventionally adopted time horizon is also 100 years, the market equates this temporary storage with permanent storage, assigning it an equivalence ratio of 1. In other words, storing 1 ton of CO_2 equivalent for 100 years is treated as equal in value to permanently avoiding or removing 1 ton of CO_2 equivalent. Figure 9 illustrates that the discount rate yielding the same equivalence ratio as the one obtained with a 100-year time horizon and a 100-year delay is 3%. This indicates that, from an economic perspective, the market's current approach to valuing the relationship between temporary and permanent credits is equivalent to applying a 3% discount rate to emission damages and benefits.

3.2.5 Conclusions from the Economic Perspective

In conclusion, Chapter 3 outlines how the economic perspective conceptualizes the relative value of temporary and permanent carbon credits, specifically between temporary storage and permanent storage, where "permanent" refers to storage that lasts for the entire time horizon. This chapter examines the role of economic theory in determining appropriate comparative ratios for these two forms of carbon storage.

The analysis reveals that the economic literature is not yet conclusive on the value of temporary carbon storage. However, ton-year approaches, which allow for a vertical stacking perspective, provide tools to better explain how the market currently values temporary storage. These approaches provide valuable insight into how the valuation of temporary credits could shift if long-term future damages are accounted for.

Section 3.1 provides an overview of the approaches used in the literature to value temporary carbon storage. Under a cost-effectiveness framework, any carbon storage that ends before achieving the climate goal does not contribute to staying below the target temperature increase. This perspective is particularly relevant as it aligns with the physical reality discussed in Section 2.3.1, which explains that temporary storage does not contribute to reducing global temperatures at peak warming unless it extends beyond that peak. Thus, temporary storage holds no value under a cost-effectiveness framework unless it contributes to the Paris Agreement's target of keeping global temperature rise well below 2°C above pre-industrial levels. From this perspective, temporary credits should have zero value. However, other perspectives recognize the value of delaying emissions, as society has a preference for postponing climate damages.

Section 3.2 examines ton-year approaches, which directly utilize time horizons and are discussed in more detail. These approaches are employed to model how the relative value of temporary and permanent storage changes over varying periods. It also introduces the novel approach that shows how the market’s current valuation of the relationship between temporary and permanent credits corresponds to applying a 3% discount rate to emission damages and benefits. This demonstrates that while the ton-year approach is grounded in physical measures, it ultimately incorporates economic reasoning through the application of a discount rate. Lastly, the Lashof method with extended time horizons assesses how the relative value of temporary and permanent storage would change if the market perspective placed greater importance on damages occurring more than 100 years into the future. The results provide insights into what price ratios an economic perspective would expect in different scenarios where society values future damages differently. Under current market conditions, economic reasoning would predict an equivalence ratio of 1, indicating the same price for both temporary and permanent credits given that currently credits of all durability levels can be used for offsetting.

As discussed in detail in the section "Clarifications of Carbon Storage Terminology" on page 17, the term "durability" has emerged as a more nuanced way to distinguish between different levels of permanence in carbon credits. Increasing attention is being paid to the differences in storage duration among credits (Rigodanzo, 2024). Notably, credits with higher durability, particularly those obtained through technology-based solutions that ensure carbon storage for over 1,000 years, are being recognized as more robust. This recognition is driving a shift toward longer time horizons for evaluating carbon credits.

In a context where the time horizons adopted by the market are becoming longer (e.g., 1,000 years), the analysis reported in section 3.2 finds that at least 13.1 low durability credits would be required to match the climate benefits provided by a single high durability credit. Given

these findings, the next chapter explores the market signals regarding storage duration. Specifically, it investigates whether current market prices reflect differences in storage length, potential explanations for any discrepancies between theoretical price ratios and actual market prices, and the consequences of these discrepancies.

4 Market signals explained

This chapter presents the findings for Research Question 4, which explores the extent to which observed market conditions align with or diverge from theoretical expectations.

Section 4.1 provides a general perspective on stability and price dynamics in VCMs. Section 4.2 offers an overview of the prices at which various types of credits are sold, aiming to determine the equivalence ratio ranges reflected in the current price ratios between low durability and high durability credits in the market. It will be demonstrated that the durability of a credit is not reflected in the relative pricing between credits with varying durability, as would be expected based on economic theory rooted in ton-year approaches. Section 4.3 and Section 4.4.discuss possible explanations for and consequences of the current price ratios.

4.1 Premise: market instability and non-transparency

Transaction data is particularly limited as VCMs operate over-the-counter (OTC). Therefore, price information is drawn from gray literature and the annual report ‘State of the Voluntary Carbon Markets’ published by Ecosystem Marketplace, which is one of the main efforts to improve transparency by collecting annual declarations from market participants via questionnaires. It is important to note that the prices reported in these reports are for retired (i.e., sold) credits, not for unsold credits.

Recent years have demonstrated the market's instability, with significant fluctuations in both prices and credit volumes:

- **2020 and 2021**: Years of strong market growth, with volumes increasing by 130% compared to 2019 and an average price of $2.82.
- **2022**: A year where prices increased substantially and volumes decreased, resulting in the total market volume remaining quite stable thanks to an average price of $7.37.
- **2023**: A further decrease in volume was followed by a decrease in price, with the average price for 2023 being $6.53. The total reported transaction value was $723 million, a 61% decrease from 2022.

The price increase from 2021 to 2022 was justified by buyers focusing on purchasing high-integrity credits driven by reputational risk, hence more expensive. The drop in 2023 is attributed to various scandals questioning the integrity of credits, leading to a credibility crisis.

The price of credits in ETS systems (compliance markets) constitutes the cost of reducing one ton of emissions with high-integrity additionality since it comes from a regulated system. Prices of emission reductions in VCMs are far below the compliance market. While the average price for emission reduction credits in VCMs for 2023 was 8.36 USD, the price for allowances in the EU ETS averaged 90 USD (EU Emissions Trading System (EU ETS), no date). This disparity raises questions about the quality of the reduction credits exchanged in

VCMs and suggests that pricing dynamics are not based on the real-world costs to reduce carbon emissions and the actual demand for carbon emission reductions. The distortion created by the low cost of reduction credits discourages companies from reducing their own emissions when these emissions are not subject to compliance obligations (Wessel and de Boer, 2023).

For the purpose of this discussion, reduction and avoidance credits will be excluded, as the primary issue with these credits is additionality. Instead, the focus will be on the temporal aspect of carbon removal credits, selecting those considered low-risk in terms of additionality. As noted in Section 2.2.4, there is growing interest in removal credits. The price differential between reduction and removal credits is influenced more by the type of credit than by the durability of carbon reduction or removal. This factor complicates the objective of determining whether the durability of a credit is reflected in its price and in the relative pricing between credits with varying durability.

4.2 Observed price ratios

Price ratios for removal credits were examined, particularly to highlight the respective price ratios between low durability credits (up to 100 years), medium durability credits (from 100 up to 1000 years), and high durability credits (more than 1000 years). Given the market's high variability, when sufficient information is available, price averages are adopted to determine the current markets' price ratio.

For low-durability credits, Afforestation, Reforestation, and Revegetation (ARR) credits are used, with an average price of $11.8 over the last three years. The decision to limit the price consideration to ARR credits was made because these credits represent pure removal. In contrast, other nature-based credits are a mix of removal and reduction. Additionally, some methodologies for soil carbon do not adhere to the 100-year storage requirement, necessitating a detailed evaluation on a case-by-case basis (Zelikova et al., 2021). For medium-durability credits, the price of biochar is used as a proxy, as it is the most popular option and the only one with available price information. The average price for biochar between 2022 and 2023 was $171.5. For high-durability carbon removal credits, information is limited. The '2023 Year in Review' report from CDR.fyi reports average prices related to different methodologies (2023 Year in Review, 2024). Table 3 shows the average prices for 2022 and 2023 for main high durability carbon removal methods, with the average price for high durability removal being $ 843.7.

Table 3 Average prices for long-term carbon removal methods in 2022 and 2023 (2023 Year in Review 2024)**.**

Method	**Average price 2022-2023 ($/ton of CO_2)**
Direct Ocean Capture (DOC)	1193
Enhanced Weathering (EW)	402
Direct air capture (DAC)	988
Bioenergy with carbon capture and storage (BECCS)	300
Ocean Alkalinity Enhancement (OAE)	1608

This discussion employs a simplified interpretation of durability for economic analysis, a common approximation in the literature (Cullenward, 2023). It assumes that storage remains intact until the end of the designated durability period. In practice, however, the risk of carbon loss is more nuanced, with storage systems either exhibiting a steady decay, as seen with biochar, or facing stochastic risks of reversal and re-emission, such as the risk of fire in a forest (ibid).

Based on the prices reported above, the current prices in the VCMs suggest an equivalence ratio of 74 when comparing the price of low durability credits to high durability credits, and an equivalence ratio of 5 when comparing medium durability credits to high durability credits. These ratios are calculated by dividing the average price of high durability credits by the average price of low durability and by the average price of medium durability credits, respectively. Notably, the price ratios between low and high durability credits observed in the market do not correspond to the ratios expected under the economic ton-year approach with a time horizon (TH) of 1,000 years, reported in Table 4. However, the price ratios between medium and high durability credits in the market do align with the expected ratios under the same economic approach and time horizon.

4.3 Meaning of observed misalignment

Evaluating whether market prices align with expected equivalence ratios allows for the determination of whether the durability of a credit is accurately reflected in the relative pricing of credits with varying durability. The prices reported in Section 4.2 clearly indicate that low-durability credits are significantly cheaper, creating a strong incentive for buyers to select them. This section demonstrates that these low prices for low-durability credits result in a distortion, as they do not accurately represent the climate benefits associated with these credits. Even if the market adopted a vertical stacking approach—where buyers are responsible for purchasing enough credits to achieve the same climate benefits as those provided by high-durability credits—low-durability credits would remain cheaper. This highlights the pricing distortion.

To demonstrate this point, the principle of vertical stacking is applied to compare costs. By purchasing the number of credits specified by the equivalence ratio, it is possible to match the climate benefits of long-term storage over different time horizons. Table 4 presents the equivalence ratios for three levels of durability across various time horizons, while Table 5 shows the total cost of purchasing enough low and medium durability credits to achieve climate benefits equivalent to those of higher durability credits for the same time period. It illustrates that equating 100 years of storage to permanent storage leads to significantly lower prices for low durability credits compared to longer durability credits.

Table 4 Equivalence ratios, from an economic perspective, for different durability levels and time horizons.

	Equivalence ratios		
Durability	**TH=1000**	**TH=5000**	**TH=10000**
AFF durability (100 years)	13.1	54.6	153.1
Biochar durability (306 years)	4.2	21.9	49.7

High durability (assumed to be permanent)	1	1	1

Table 5 Total Costs for Achieving Equivalent Storage Durations Using Low and Medium Durability Credits. This table shows the total cost of securing carbon storage for time horizons (TH) of 1000, 5000, and 10000 years, using credits with varying durability. The total cost is calculated by multiplying the equivalence ratio with the average price per credit for each durability level.

		Total cost to obtain storage up to TH		
Durability	**Average price (single credit, $)**	**TH=1000**	**TH=5000**	**TH=10000**
AFF durability (100 years)	11.8	154.6	644.3	1806.6
Biochar durability (306 years)	171.5	720.3	3755.8	8523.5
High durability (assumed to be permanent)	843.7	843.7	843.7	843.7

In a market setup where permanence is valued and achieved through a vertical stacking approach, low-durability credits remain less expensive than those representing longer storage durations. While if a 1,000-year time horizon is adopted, the total price for biochar credits would approximate that of permanent credits. The price ratio between biochar credits and permanent credits aligns with the expected ratio for credits to achieve the same benefits as those associated with 1,000 years of storage.

Long durability credits are more expensive when considering the shortest time horizon (1,000 years). This is anticipated, as shorter time horizons tend to underestimate the benefits of long-term storage. Conversely, permanent credits become prohibitively expensive if the focus is solely on the near future.

4.4 Market consequences

The calculation exercise in section 4.3 highlights the distortions in financial incentives within VCMs, particularly the low cost of low-durability credits. As a result, in 2022, low-durability credits—primarily generated through nature-based activities—accounted for 99.88% of all removal credits, despite facing significant qualitative challenges. Current market prices discourage investment in medium- and high-durability credits, both of which are more likely to contribute to the goals of the Paris Agreement. For permanent storage technologies to become more affordable, substantial investments are necessary. However, the current pricing structure does not provide sufficient incentives for buyers to invest in high-durability credits. Even in a market where permanence is prioritized—defined as a minimum of 1,000 years and achieved through a vertical stacking approach—low-durability credits would still be more cost-effective.

These calculations are intended as an exercise rather than a policy recommendation. Ton-year approaches have been used to explore how equivalence ratios change when extended time horizons are applied. In fact ton-year approaches have been utilized in the past by initiatives such as the Climate Action Reserve (CAR) in their forestry and agriculture protocols, these

applications often served the opposite purpose—to issue partial credits from very short-term storage. Such short-term forestry storage, however, offers weak additionality, and the continued use of this ton-year approach is not recommended.

The economic perspective highlights that while temporary storage does not achieve physical equivalence to permanent storage, it offers value by delaying climate damage, thereby buying time for decarbonization and the development of more permanent CO_2 removal solutions. However, as explored in the cost-effectiveness framework, any carbon storage that ends before achieving the climate goal does not contribute to staying below the target temperature increase and thus holds zero value within this framework. Both perspectives are valuable but must be considered within a market context. Given the qualitative challenges of low-durability credits and the lack of regulatory power in voluntary markets compared to compliance markets, temporary credits—whose value, according to economic theory, lies in delaying damages—should be used for "buying time" claims. However, these credits are often misused as offsets, raising ethical concerns (as discussed in detail in section 2.3.1).

As a result, credits intended to buy time for decarbonization and the development of more affordable permanent removal solutions end up justifying delays in decarbonization efforts and fail to direct investments toward permanent removal technologies.

The current credibility crisis in VCMs, after more than two decades of operation, demonstrates that these markets still struggle to deliver on their promises. For all the reasons outlined above, we conclude that it is essential to shift from offsetting claims to claims focused on buying time or contributing to nature conservation. Removing the option to purchase cheap offsets would incentivize both direct decarbonization of one's emissions and investment in high-durability credits. VCMs can play a crucial role in channeling finance towards permanent storage technologies, making them more affordable and encouraging the market support for higher-durability credits.

5 Conclusion

This thesis has examined the value of temporary credits in VCMs by comparing theoretical perspectives with market realities. It contributes to the ongoing debate on the role of temporary carbon storage in achieving climate goals. By merging market insights with multiple economic perspectives, this study has demonstrated that such an integrated approach provides a more comprehensive and nuanced understanding of VCMs.

Chapter 2 provided an in-depth market perspective, shedding light on the quality of carbon credits, the current credibility crisis, and the inefficiencies that arise from the unregulated nature of these markets. It emphasized the challenges posed by the nature of credits as credence goods and the decentralized structure of VCMs, which contribute to the persistent credibility issues and distortions in the market.

Chapter 3 explored the economic perspective, particularly how the relationship between temporary and permanent credits evolves when long-term future damages are considered. The results offer an understanding of what price ratios an economic perspective would expect in different scenarios where society values future damages differently.

Finally, Chapter 4 analyzed current market prices, using the economic frameworks developed in Chapter 3 to interpret price signals. This chapter revealed significant discrepancies

between theoretical expectations and actual market prices, highlighting how current pricing mechanisms fail to reflect the temporal dimension of carbon storage adequately. These findings underscore the need for market reforms that better align prices with the true environmental value of both temporary and permanent carbon storage.

In conclusion, this thesis has proven that integrating market perspectives with economic approaches is more informative and necessary for addressing the challenges VCMs are facing. While temporary credits provide a means to delay climate damage, the market's current practices do not sufficiently incentivize long-term, durable carbon storage solutions.

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