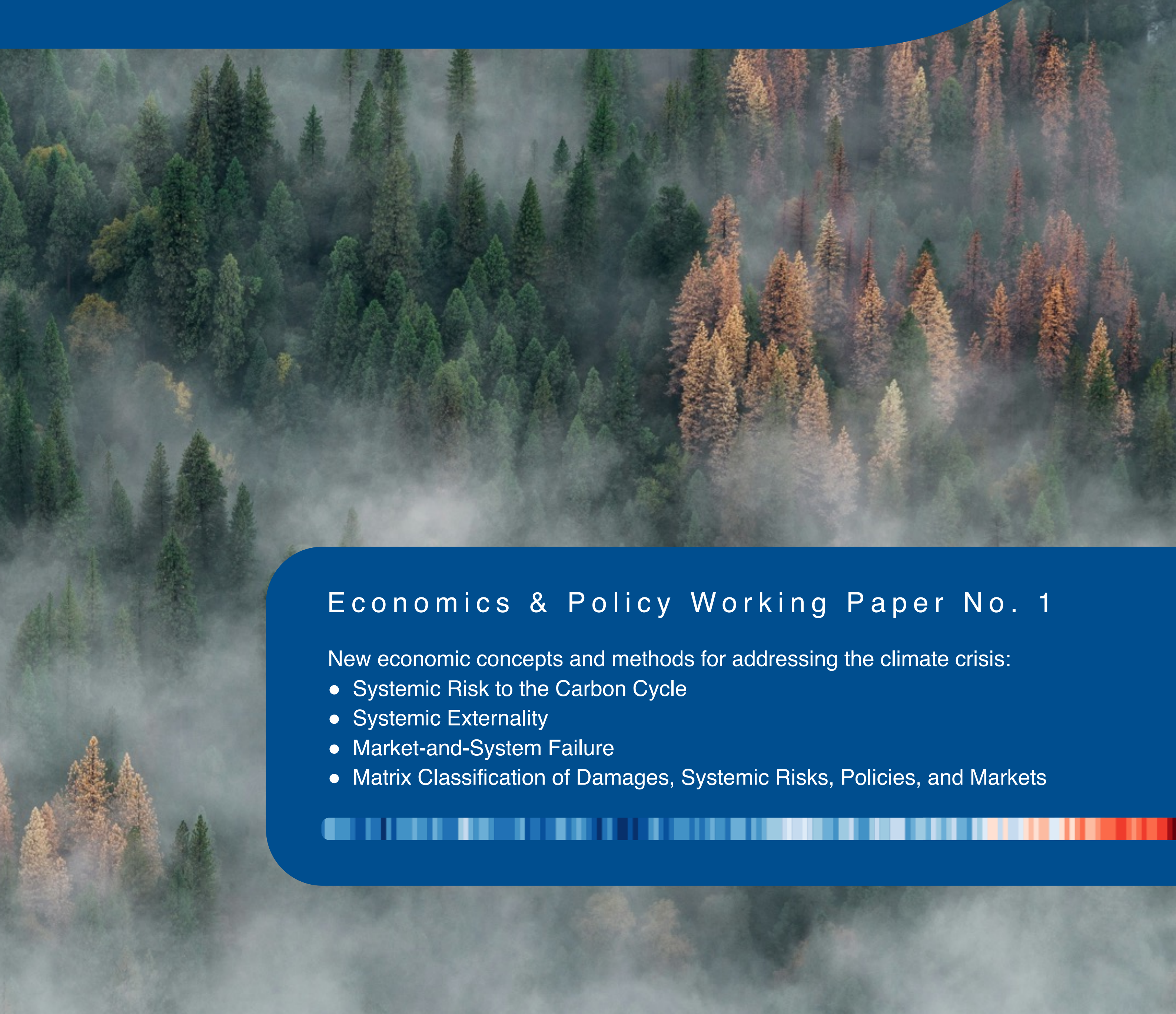
GLOBAL CARBON REWARD

Carbon Reward Policy:

An Economic Framework for Responding to Climate Damages & Systemic Risks

By Delton B. Chen
Global Carbon Reward
October 2025



Economics & Policy Working Paper No. 1

New economic concepts and methods for addressing the climate crisis:
- Systemic Risk to the Carbon Cycle
- Systemic Externality
- Market-and-System Failure
- Matrix Classification of Damages, Systemic Risks, Policies, and Markets

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Carbon Reward Policy:
An Economic Framework for Responding to Climate Damages & Systemic Risks*

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Abstract

The Paris Agreement's climate goals remain stalled by unpriced greenhouse gas (GHG) emissions, a multi-trillion-dollar finance gap, and disputes over cost-sharing. This working paper reframes the market failure in GHGs with new economic concepts and proposes a novel policy solution: the carbon reward. Included is a comprehensive new matrix-based classification of market outcomes, encompassing damages, systemic risks, and market policies.

The carbon reward policy is designed to address systemic risks to the carbon cycle. The reward instrument would function both as a positive financial incentive and as an investable asset with long-term price certainty, underpinned by central bank guarantees. Rewards would be provided as conditional grants to fund GHG removal, emission reductions, and avoidance, including the strategic early retirement of fossil energy assets and their substitution with clean energy.

The carbon reward requires the establishment of an international authority and central bank alliance. Operationally, it would finance projects at scale, attract private capital, and establish price certainty. Other policy advantages include the avoidance of carbon offsetting, valorisation of stranded assets, provision of debt relief, and support for co-benefits for communities, ecosystems, and industries. A preliminary assessment suggests that the policy-induced monetary inflation would be moderate if the policy is implemented as designed.

Keywords: carbon reward, systemic risk, systemic externality, climate finance, central bank, market failure, Paris Agreement, greenhouse gas mitigation

JEL Codes: Q54, Q58, Q51, E52, G38, H23, O44

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Table of Contents

List of Definition Boxes

List of Figures

List of Tables

List of Abbreviations

+1.5°C, +2.0°C, +1.75°C: Global mean temperature change targets relative to preindustrial levels

2×2: Two-by-two matrix (outcome matrix)

AMOC: Atlantic Meridional Overturning Circulation

AR6: Sixth Assessment Report (IPCC)

AT: Attribute (in matrices; A or B)

BAU: Business as Usual

BIS: Bank for International Settlements

CAT bonds: Catastrophe bonds

CBA: Cost-Benefit Analysis

CDR: Carbon Dioxide Removal

CEA: Carbon Exchange Authority

CES: Carbon Exchange Standard

CH_4: Methane

CQE: Carbon Quantitative Easing (central-bank program to defend the XCR price floor)

CO_2: Carbon Dioxide

CO_2e: Carbon Dioxide Equivalent

CPI (report context): Climate Policy Initiative

CPS: Carbon Price Support (UK)

CPF: Carbon Price Floor (UK mechanism)

DAC: Direct Air Capture

EROI: Energy Return on Investment

ETC: Energy Transitions Commission

EU ETS (EU-ETS): European Union Emissions Trading System

FX: Foreign Exchange (markets)

G7: Group of Seven

GDP: Gross Domestic Product

GDR: Gibbs free energy reaction classification context (ΔG matrix)

GFANZ: Glasgow Financial Alliance for Net Zero

GHG: Greenhouse Gas

$GtCO_2$: Gigatonnes of CO_2

IAM: Integrated Assessment Model

IEA: International Energy Agency

IMF: International Monetary Fund

IMO: International Maritime Organization

IPCC: Intergovernmental Panel on Climate Change

IRA (US): Inflation Reduction Act

ISO 4217: International standard for currency codes

ITMOs: Internationally Transferred Mitigation Outcomes

kg, t, Mt, Gt: Kilogram, tonne, megatonne, gigatonne

M0: Monetary base (bank reserves)

M1: Narrow money supply (cash + demand deposits, etc.)

M2: Broad money supply (M1 + term deposits, etc.)

M^*: Intermediate money supply ($M1 < M^* < M2$)

MAC (MACC): Marginal Abatement Cost (Curve)

MRV: Measurement, Reporting, and Verification

MSR: Market Stability Reserve (EU ETS)

NCQG: New Collective Quantified Goal on Climate Finance

NDCs: Nationally Determined Contributions

NGFS: Network for Greening the Financial System

NZAM: Net Zero Asset Managers Initiative

NZBA: Net-Zero Banking Alliance

NZIA: Net-Zero Insurance Alliance

OBBBA: One Big Beautiful Bill Act (US, 2025)

OECD (context via XCD): Organisation of Eastern Caribbean States code note (ISO list item)

PA: Paris Agreement

PPP: Purchasing Power Parity

R (reward multiplier): Dimensionless factor for XCR-based cost-effectiveness

RCC: Risk Cost of Carbon (anchors the ideal carbon reward for CDR and the XCR price floor)

RCP/SSP: Representative Concentration Pathway / Shared Socioeconomic Pathway (AR6)

R&D: Research and Development

SCC: Social Cost of Carbon (anchors the ideal carbon tax on GHG emissions)

SDR (finance): Special Drawing Rights (IMF)

SDR (economics): Social Discount Rate (context: Nordhaus–Stern debate)

SRM: Solar Radiation Management

tCO_2, tCO_2e: Tonne of CO_2, tonne of CO_2-equivalent

UNFCCC: United Nations Framework Convention on Climate Change

USD: United States Dollar

WG I/II/III: IPCC Working Group I/II/III

XAU, XAG, XDR, XCD, XTS: ISO 4217 'X' series codes (gold, silver, SDR, E. Caribbean, test)

XCC: Carbon Currency (earlier term for the instrument)

XCR: Carbon Reward (proposed code for the market instrument; not a carbon credit)

ΔG, ΔH, ΔS: Gibbs free energy, enthalpy, entropy changes (thermodynamics)

μ (mu): Annual percentage change ('yield') of XCR price floor

π (pi): Monetary inflation rate

θ (theta): Ratio of M^* to World GDP (in modelling)

Executive Summary

1. Carbon Reward Policy

This working paper presents a novel market policy—the **carbon reward**—along with an **expanded economic framework** that rationalises the policy's implementation. The carbon reward is designed to close the climate finance gap and resolve the market failure in greenhouse gas (GHG) emissions, thereby supporting the Paris Agreement's (PA) goal of limiting warming to well below 2°C, pursuing 1.5°C. It complements existing national carbon pricing measures by establishing a transparent and predictable international framework for pricing GHG removals, reductions, and avoidance, and a high-integrity alternative to carbon offsetting. The initiative will start with a small, voluntary coalition of countries and institutions, known as a 'climate club,' rather than requiring immediate global consensus.

2. Expanded Economic Framework

The expanded economic framework reframes the market failure in GHGs as a dual externality problem, consisting of:

- **Negative Externality (traditional):** The unpriced climate damages that impact society, caused by GHG emissions.

- **Systemic Externality (new)**: The unpriced systemic risks to the carbon cycle, caused by societal systems and earth systems.

The negative externality is a core concept in standard economics, while the systemic externality is newly proposed in this working paper. These externalities should be assessed and corrected (i.e., internalised) using the following metrics and price signals:

- **Social Cost of Carbon (SCC):** A time-discounted measure of social welfare loss caused by one additional tonne of CO_2e emissions and associated climate change. Internalising the SCC through negative pricing on GHG emissions is recommended to achieve **social efficiency**.

- **Risk Cost of Carbon (RCC)**: The marginal cost of atmospheric CO_2e removal to remain within a relatively safe carbon budget, and a measure of systemic risk. Internalising the RCC through positive pricing of full-spectrum decarbonisation is recommended to achieve **systemic safety**. This requires regenerative strategies that maximise the resilience and stability of communities, ecosystems, industries, and nations.

The systemic externality (and RCC) should be of particular concern because it can shrink the 'safe' carbon budget and amplify the negative externality (and SCC), with potentially catastrophic consequences.

The systemic risks that contribute to the systemic externality and RCC arise from two major system types:

■ **Societal Systems:** Increasing punitive prices on GHG emissions often trigger political resistance, creating self-reinforcing cycles of inaction—including gridlock over standard policies—that result in higher emissions and undermine the PA's climate goals.

■ **Earth Systems:** Non-linear climate dynamics, tipping-point risks, scientific uncertainties, and local-to-global instabilities further erode the safe carbon budget and threaten the PA's climate goals.

3. Matrix Classification of Damages, Systemic Risks & Policies

The expanded economic framework is organised into three matrices that together describe and correct the market failure in GHG emissions (see Figure ES-1):

(a) **Damage Matrix for Carbon:** The material and moral damages, including social welfare loss, natural capital loss, and subjective moral and environmental losses.

(b) **Risk Matrix for Carbon:** The systemic risks to the carbon cycle, including the climate finance gap, climate feedbacks, and financial and ecological instabilities.

(c) **Policy Matrix for Carbon:** The market policies for incentivising GHG mitigation, including carbon taxes, cap-and-trade, subsidies, and carbon rewards.

The above three matrices describe a 'market-and-system failure'—a situation that is much more challenging than a typical 'market failure' because societal and earth systems are perpetuating and amplifying the negative externality. The three matrices are theoretically linked together and they constitute a single coherent conceptual model. Important to note is that these matrices are linked 'diagonally.' In other words, Class 1 in the policy matrix is linked to the entire damage matrix, and Class 4 in the policy matrix is linked to the entire risk matrix.

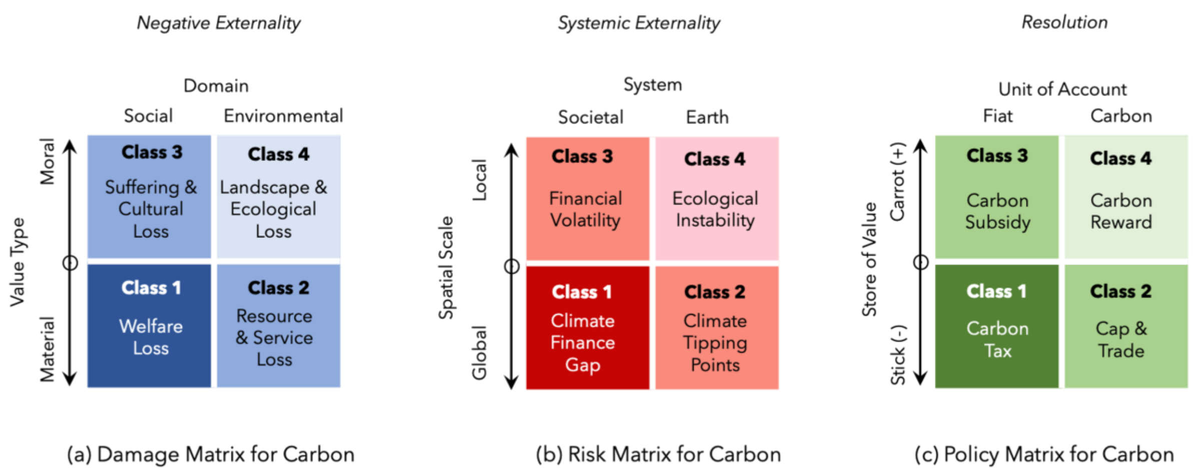

Figure ES-1. The expanded economic framework for the 'market-and-system' failure is comprised of three matrices: (a) damage matrix, (b) risk matrix, and (c) policy matrix.

The three matrices in Figure ES-1 are backward-compatible with the conventional theories articulated by Arthur C. Pigou (1920) in *The Economics of Welfare* and Ronald H. Coase (1960) in *The Problem of Social Cost*. A larger matrix, called the 'carbon market matrix,' was developed from the policy matrix in Figure ES-1(c) for classifying compliance carbon markets, voluntary carbon markets, carbon credits, and carbon offsetting.

4. <u>Layered Carbon Pricing for Meeting Two Objectives</u>

The recommended strategy is a layered system of 'carrot' and 'stick' incentives, as indicated in the policy matrix (Figure ES-1c). These policies include, carbon taxes, cap-and-trade, targeted subsidies, and a new carbon reward (also called mitigate-and-trade). This layered system would achieve the internalisation of the SCC and RCC, while improving political feasibility and international cooperation. The broader aim is to pursue two objectives:

- ■ **Social Efficiency (traditional):** The objective when responding to the negative externality with negative prices on GHG emissions, and

- ■ **Systemic Safety (new):** The objective when responding to the systemic externality with positive prices for GHG mitigation and regenerative co-benefits.

Achieving the above two objectives requires a deliberate trade-off, as some social efficiency would be forgone in the short- to medium term to achieve long-term systemic safety.

5. Carbon Reward Instrument (XCR)

The market instrument of the carbon reward policy is a carbon-linked sovereign-backed asset, called a 'carbon reward' or 'XCR.' The XCR is a positive incentive and tradeable asset. It is provided as conditional grants for verified GHG removals, reductions, and avoidance—without offsetting and without direct fiscal cost to governments or firms (see Class 4 in Figure ES-1c). A rolling XCR price floor, aligned with the RCC, anchors the XCR's long-term value and mobilizes private capital at scale. XCR will be issued as conditional grants through three channels:

■ **Reward Channel 1**: Carbon dioxide removal (CDR).

■ **Reward Channel 2**: Conventional GHG mitigation.

■ **Reward Channel 3:** Co-benefits for communities, ecosystems, and industries.

The carbon reward policy can provide XCR grants for the decarbonisation of all economic sectors, including the energy sector. Other important features of the carbon reward policy include:

■ Avoidance of carbon offsetting,

■ Use of XCR as a limited-risk financial asset for investors, and

■ No direct fiscal costs for governments, firms, or public.

6. How It Works

A **Carbon Exchange Authority (CEA)** sets a non-binding mitigation roadmap, administers the three reward channels, and manages 100-year durability contracts, milestones, and clawbacks for awardees in the carbon reward market. The mitigation roadmap is conceived as a 'landscape to be traversed,' rather than a single, legally binding emissions target. This approach recognizes that coalition-building among nations for rapid decarbonization first requires financial assurances to support such an ambitious transition.

An alliance of central banks guarantees the XCR price floor through **carbon quantitative easing (CQE)**, intervening only when XCR spot prices threaten to fall below the floor. The central bank guarantee is designed to foster investor confidence in XCR and limit governments' fiscal burdens. As trust in this mechanism grows, private investors may view XCR as a long-term store of value and a safe-haven asset—similar to gold—promoting sustained private demand and helping distribute mitigation costs.

7. What It Enables

The carbon reward policy includes some breakthrough strategies and initiatives for converting today's cycle of inaction into a cycle of participation and cooperation. These strategies and initiatives include (but are not limited to):

■ financially assisting developing countries,

■ protecting and regenerating communities, ecosystems, and industries,

■ valorising fossil energy assets that would otherwise become stranded,

■ retiring fossil energy assets by substituting them with clean energy,

■ avoiding deforestation at scale, and

■ decarbonizing hard-to-abate industries with performance-based rewards.

8. Preliminary Assessment

Thought-experiments suggest the carbon reward policy can be used to adaptively manage major systemic risks, including finance gaps, tipping points, and local instabilities (Figure ES-1b). Using the quantity-theory of money, preliminary estimates of monetary inflation from CQE suggest that this inflation would be modest and tolerable—especially if the private sector can be encouraged to invest in XCR, and if XCR grants can be used to leverage conventional finance.

9. What's New and Why It Matters

■ **Expanded Economic Framework:** Introduces a matrix-based classification of climate damages and systemic risks to the carbon cycle—corresponding to two externality types. This reframes the issue as a 'market-and-system failure' rather than a simple market failure.

■ **Carrots & Sticks:** Proposes a policy toolkit that combines traditional stick policies (taxes, cap-and-trade) with carrot policies (subsidies, carbon rewards) in a layered approach and across different geopolitical scales. This is to bypass political resistance and attract private investment and participation (Figure ES-1c)

■ **Carbon Reward Policy:** Innovates by creating a scalable carrot that is backed by central banks, long-term contracts, and transparent governance (Class 4 in

Figure ES-1c). The carrot is a tradable financial incentive (XCR), issued for verified GHG mitigation while avoiding carbon offsetting.

■ **XCR Price Floor:** Establishes a price signal for carbon dioxide removal (CDR) and conventional mitigation, and for mobilising private finance at speed and scale.

■ **New Central Bank Role:** Proposes an alliance of central banks to guarantee the XCR price floor over the long term. This would require a 'carbon mandate' for central banks so that they can deploy CQE to help manage the carbon cycle.

■ **Resolving Key Debates:** By treating social efficiency and systemic safety as two objectives (refer the SCC and RCC), several long-standing debates are resolved:

- **Nordhaus-Weitzman:** The RCC and carbon reward would address catastrophic risks much more effectively than the SCC and carbon tax.

- **Nordhaus-Stern:** The 100-year planning horizon of the carbon reward policy would balance short-term welfare with long-term safety, thereby resolving the inherent limitations of social time discounting.

- **Green Growth vs. Degrowth:** The framework proposes 'carbon-balanced agnostic-growth' as a development pathway that reconciles economic development with climate stability. It addresses a central pillar of the sustainability challenge by reframing the debate with a specific policy toolkit for agnostic-growth (i.e., agnostic to GDP growth); however, it is important to note that carbon-balanced agnostic-growth does not purport to resolve all concerns related to planetary boundaries and social sustainability.

10. Call to Action

This working paper calls for feasibility studies and stakeholder consultations guided by the expanded framework's three matrices. A climate club of nations will be needed to pilot the carbon reward policy, close the multi-trillion-dollar climate finance gap, and deliver co-benefits—particularly for vulnerable communities and ecosystems.

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Conflict of Interest Statement

There are no conflicts of interest to declare.

1. Introduction

1.1 Aims & Motivations

Global spending on climate mitigation is rising, but remains insufficient for meeting the 1.5°C objective of the 2015 Paris Agreement (PA) (United Nations, 2015). The Climate Policy Initiative (CPI) reported that annual climate finance reached nearly US$1.3 trillion in 2021/2022—just 1% of global GDP—while the amount needed will rise to US$9 trillion per year by 2030 and over US$10 trillion annually by 2050 (Naran et al., 2024). This leaves a substantial climate finance gap, which is a major barrier to approaching the 1.5°C target. In response, recent COP meetings have focused on finance. For example, at COP29 in Baku, various countries proposed to triple climate finance for developing nations to US$300 billion annually by 2035, and discussed scaling up this finance to US$1.3 trillion annually under the New Collective Quantified Goal on Climate Finance (NCQG) (Alayza & Larsen, 2025; UNFCCC, 2024).

The main motivation for writing this paper is to address the climate finance gap—on a worldwide basis—for achieving the PA's target of remaining well below 2°C and to pursue 1.5°C. The main aim is to present an expanded economic framework and new policy toolkit for bridging the climate finance gap and addressing the dual problems of (a) climate damages and (b) systemic risks. In doing so, a new policy—called a 'carbon reward'—is presented. This policy is specifically designed to respond to the systemic risks to the carbon cycle, thereby increasing the likelihood of remaining within a relatively safe carbon budget.

In developing the expanded economic framework, the limitations of standard theories were critically examined to explain why traditional policies have fallen short. A major conclusion of this study is that standard theories are constrained by a definition of systemic risk that is conceptually limited by focusing too narrowly on financial stability issues. For example, the Network for Greening the Financial System (NGFS) views systemic risk only from a financial system perspective (NGFS, 2019). Our approach is to consider that the carbon balance also faces systemic risks, including political resistance to climate policies and non-linear climate dynamics. Subsequently, the expanded framework begins by reviewing the systemic risks to the carbon cycle and identifying a new externality, called a 'systemic externality.'

The expanded economic framework is structured by a matrix approach that is used to describe the market failure in much greater detail than the standard theory can provide. The matrix approach is used to classify a wide variety of moral and material damages, environmental losses, climate feedbacks, financial volatility, and social and ecological instability. The centrepiece of this framework is a policy toolkit that includes the (1) carbon tax, (2) cap-and-trade, (3) carbon subsidy, and the new (4) carbon reward. The carbon reward is the main focus of this paper, as it is designed to unlock scalable climate finance for a declared mitigation roadmap.

1.2 Organisation of this Working Paper

This working paper is organized to introduce and describe the carbon reward policy within the context of an expanded theory for market externalities. Section 1 begins by summarising standard market policies and past scholarship on the carbon reward. Sections 2 to 4 introduce an expanded economic framework for describing the damages, systemic risks, and market policies relevant to the market failure in greenhouse gases (GHGs). Section 5 is focused on describing the carbon reward policy in terms of the mitigation roadmap, reward channels, the market instrument and central bank role. In Section 6, the policy's capacity to mitigate systemic risks is assessed. The expanded economic theory is then verified in Section 7 in terms of its thermoeconomic plausibility. In Section 8, the carbon reward's main features are discussed in relation to the economic scholarship and recommendations are made for policy advancement. Finally, Section 9 provides concluding remarks to underscore the major new ideas of this working paper.

1.3 Definition of Key Terms

Prior to discussing the market failure and climate policies, the following key terms are defined below for clarity:

● **Mitigation:** is any "...human intervention to reduce emissions or enhance the sinks of greenhouse gases" (Calvin et al., 2023). In this paper, 'mitigation' excludes carbon offsetting, which is treated as zero-sum.

● **Conventional Mitigation:** is taken here to mean reducing or avoiding GHG emissions at the source of emissions. It excludes CDR and carbon offsetting.

● **Carbon Dioxide Removal (CDR):** is taken here to mean removing CO_2 from the atmosphere and storing it durably. Ideally, CDR would be used to address historical and residual CO_2 emissions because it is unlikely to replace conventional mitigation due to scalability challenges.

● **Carbon Offsetting:** is taken here to mean the purchase of carbon credits that represent the mitigation of GHGs in other locations. Carbon offsetting is a commercial transaction that is sometimes used by organisations to address their unabated GHG emissions.

● **Solar Radiation Management (SRM):** SRM or solar geoengineering is "...a set of proposed approaches to reflect sunlight to rapidly reduce global temperatures and counteract some of the effects of climate change... It would not directly reduce GHG concentrations in the atmosphere and thus would not counter other effects of rising GHG concentrations such as ocean acidification." (National Academies of Sciences, Engineering, and Medicine, 2021). While sometimes proposed as a supplement to greenhouse gas (GHG) mitigation, SRM remains controversial due to physical uncertainties and political risks. Importantly, the planetary energy imbalance interacts with the carbon cycle, meaning that GHG mitigation and SRM may need to be managed in concert as climate feedbacks evolve (IPCC WGI, 2023). Recent declines in global cloud cover and a rising planetary energy imbalance—both linked to increased warming—underscore the relevance of SRM to the market failure in GHG emissions (Blunden et al., 2025; Samset et al., 2025; Tselioudis et al., 2025; Yuan et al., 2024). For reasons of brevity and to simplify this working paper, the deployment of SRM is not explicitly considered.

1.4 Brief History of the Carbon Reward Policy

The seminal ideas for the carbon reward policy first appeared in a 2017 paper by Chen, van der Beek, and Cloud (2017). Since then, the policy has evolved, with significant updates to its underlying theory, rules, and terminology. Many of these developments are documented in subsequent publications (D. B. Chen, 2018; D. B. Chen et al., 2019; Lutz, 2022; Zappalà, 2018) and grey literature. The latest theory is presented in Sections 2–4 and 7-8, while the most recent version of the carbon reward policy is detailed in Sections 5–6.

Since 2017, the market instrument has undergone three name changes. Chen et al. (2017) originally called it a 'complementary currency for climate change' (4C), and Chen (2018) later referred to it as a central bank digital currency (CBDC). Between 2021 and 2025, it was presented in conferences as a 'carbon currency (XCC).' However, the instrument is neither a currency nor a CBDC from a technical perspective. The naming challenge reflects a semantic gap in the economics literature for this type of instrument (see Sections 5.2 and 8.3.1 for details). Technically, the instrument is a carbon-linked, sovereign-backed asset—and is not a currency. To avoid confusion with currencies, this working paper henceforth refers to the policy instrument as a 'carbon reward (XCR).'

K. S. Robinson's (2020) fictional novel about near-term climate change, *The Ministry for the Future*, was inspired by Chen et al.'s (2017, 2019) version of the carbon reward policy. In the novel, Robinson refers to the market instrument as the "carbon coin." While this term has gained some popularity in the mainstream media (e.g., Patterson, 2022), it is important to note that the instrument described in both the policy and Robinson's novel is not a cryptocurrency, as it would be backed by central banks (refer to Section 5).

1.5 Contemporary Policies & Initiatives for Climate Mitigation

A review of the literature was undertaken to examine the full range of policies and initiatives aimed at mitigating anthropogenic GHG emissions. It appears that such policies and initiatives can be divided into three broad categories for ease of presentation and analysis:

- **Market Policies:** This category includes carbon taxes, carbon subsidies, cap-and-trade, carbon credits and other similar policies that price carbon in compliance markets (Goodstein & Polasky, 2020).
- **Non-Market Policies:** This category includes nationally determined contributions (NDCs), laws, regulations, emission standards, work programs, and certain subsidies that don't price carbon.
- **Private and Institutional Initiatives:** This category includes concessional loans, green investing, climate bonds, debt cancellation, voluntary carbon offsetting, philanthropy, corporate net-zero pledges, corporate emissions reporting, public boycotts, divestment, and others.

Although the above policies and initiatives are often promoted by stakeholders, they face significant challenges related to political feasibility and scalability (Carattini et al., 2018, 2019; Davis et al., 2018; McCright et al., 2016; Michaud, 2024; Unruh, 2000). For instance, market-based policies and regulations often impose increasing costs on market participants, leading to political opposition. Financial sector efforts, meanwhile, may not be scalable if they cannot ensure the profitability of organisations after accounting for all project-related costs and risks. The risks include revenue uncertainty, interest rate risk, technical challenges, political risk, opportunity costs, etc. Among the above policies and initiatives, market-based policies are the main focus of this working paper because they are grounded in theories for understanding and correcting market failures.

2. Theory & Methodology

2.1 Standard Theory for Markets

Numerous economists, including Arthur Pigou, Francis Bator, Ronald Coase, James Buchanan, have contributed to the standard (neoclassical) theory for markets. However, for brevity, this article is focused on the work of Pigou (1920) and Coase (1960) because their theories are directly relevant to the expanded economic framework in Sections 2 to 5. Pigou described market failures as situations where private interests conflict with the welfare of society. This is exemplified by carbon emissions, where there is a divergence between private and social costs. Pigou recommended taxes and subsidies to internalize externalities (see Definition Box 1). When applying Pigou's theory to GHG emissions, the negative externality is codified as the social cost of carbon (SCC): the marginal welfare loss from one additional tonne of CO_2 equivalent and time-discounted to the present. While Pigou's theory points to the internalization of the SCC with a carbon tax, the Coase Theorem (1960) points to the internalization of the SCC with cap-and-trade. Cap-and-trade invites polluters to trade government-issued permits in order to discover a carbon price (Goodstein & Polasky, 2020). Success of cap-and-trade requires that the cap be prescribed, property rights be well-defined, and transaction costs be removed.

Definition Box 1. Market Failure (Standard Theory)

> According to Arthur C. Pigou (1920), in his book *The Economics of Welfare*, a market failure occurs when the private costs or benefits of a market activity do not reflect the costs or benefits experienced by society. The resulting discrepancies are not reflected in the market price of goods or services, and they are called externalities. Externalities may be negative or positive, and they indicate that the market is inefficient. A negative externality can be corrected with a tax, and a positive externality can be corrected with a subsidy.

2.2 Apparent Limitations of the Standard Theory

In this working paper, it is argued that Pigou's (1920) well-known theory for using taxes is inadequate when addressing GHG emissions because certain simplifying assumptions are violated. To set the context for this argument, consider that Pigou inferred that the negative externality is a price imperfection in the market that can be corrected with a tax as a technocratic solution. An unquestioning belief in the Pigouvian tax ignores the non-neutral dynamics of the economy, including political biases, institutional failures, information asymmetries, misinformation, conflicts of interest, and stochastic shocks of various kinds (Carattini et al., 2018, 2019). Pigou was actually aware of institutional failures, and public choice theory offers a sobering counterbalance to Pigou's simplifying assumptions.

In summary, the market failure in carbon appears to be characterized by the following major challenges that violate Pigou's simplifying assumptions by undermining the feasibility and effectiveness of the carbon tax:

- **Persistent Political and Social Resistance:** Efforts to implement the polluter pays principle—such as with carbon taxes or cap-and-trade—often encounter entrenched resistance from stakeholders with vested interests in carbon-intensive energy systems. This resistance is further reinforced by society's widespread dependence on existing carbon-based technologies and supply chains, which are deeply embedded into financial and social relationships. As a result, transitioning away from these systems may be perceived as too disruptive and costly, both politically and socially. These interconnected forms of resistance to decarbonization are called the 'carbon lock-in effect' after (Unruh, 2000).

- **Uncertain and Non-Linear Climate Dynamics:** The climate system exhibits non-linear, chaotic, and scale-dependent behaviour, leading to significant uncertainty in predicting future climate change, climate damages, and SCC. Key uncertainties include cloud feedbacks, tipping points, and the difficulty of translating global climate model outputs to local impacts. These factors result in a skewed risk profile, with the potential for extreme and poorly understood damages.

- **Propagation of Instabilities:** Social and biological systems sometimes experience stochastic instabilities that begin locally but can spread to cover large areas, even globally, ultimately disrupting efforts to mitigate GHG emissions. For example, an extreme weather event could trigger unexpected food price shocks, locust swarms, epidemics, or wars. Other examples are pandemics or financial crises that could result in a slowdown in renewable energy projects.

- **Self-Reinforcing Cycle of Inaction:** Here, it is claimed that the interplay between punitive policies (e.g., taxes, caps, standards, and regulations) and political resistance to these policies (e.g., lobbyist campaigns) results in a self-reinforcing feedback loop, which is named the 'self-reinforcing cycle of inaction' in this paper (see Figure 1). This cycle of inaction exists because worsening climate change results in a higher SCC, a steeper carbon tax, and a rising compliance cost for emitters, which then results in more intense political pushback. This self-reinforcing cycle of inaction is more dynamic than Unruh's (2000) concept of the carbon lock-in effect, because the word 'cycle' specifically refers to the periodic revision of the SCC estimate and the emergent political pushback against carbon taxes and similar policies.

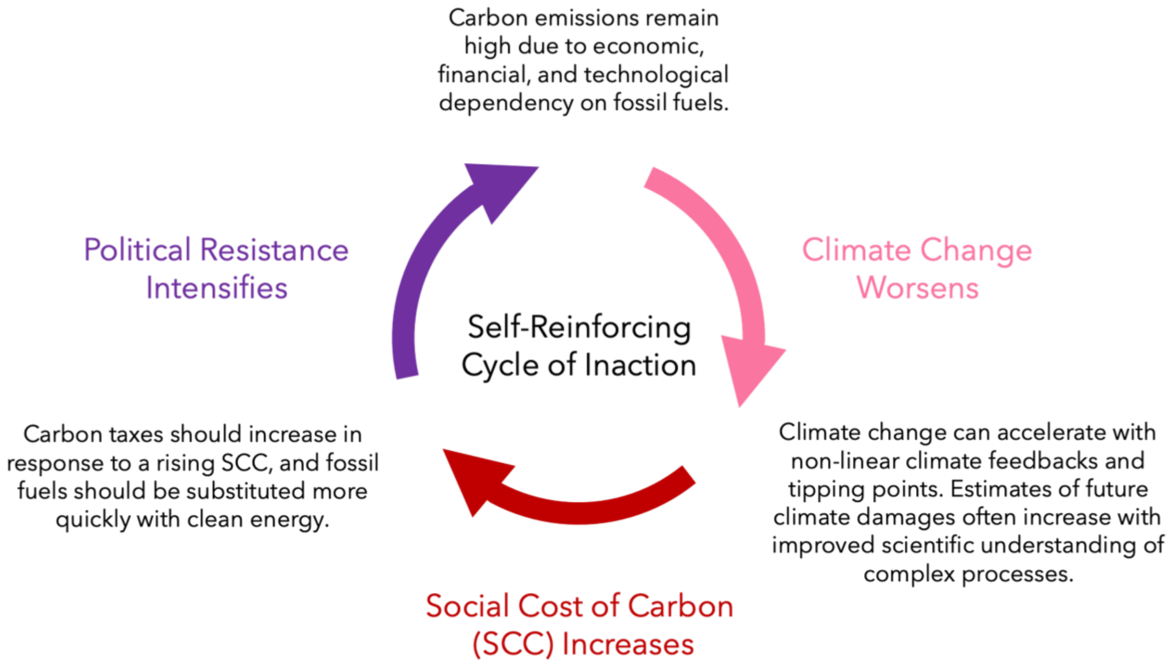


Figure 1. Self-reinforcing cycle of inaction (refer to Table 1 for evidence).

2.3 Expanding the Definition of Systemic Risk

The above critique of Pigou's tax was continued with a review of systemic risk in relation to staying within a relatively safe carbon budget and atmospheric GHG concentrations. The term 'systemic risk' typically refers to the susceptibility of the financial system to widespread disruption due to the collapse of a relatively small number of financial institutions (NGFS, 2019; see Definition Box 2). Systemic risks of this type are likened to the spread of a biological contagion, and are of major concern to macroprudential regulators (Kaufman & Scott, 2003). The global financial crisis of 2008 is a prominent example, where the failure of some large financial institutions—such as Bear Stearns, IndyMac Bank, and Lehman Brothers—rapidly transmitted shocks throughout the global financial system (Haas & Horen, 2012).

Definition Box 2. Systemic Risk to the Financial System

> "Systemic risk refers to the risk of a breakdown of an entire system rather than simply the failure of individual parts. In a financial context, it denotes the risk of a cascading failure in the financial sector, caused by linkages within the financial system, resulting in a severe economic downturn." (CFA Institute, 2022)

Why does the definition of systemic risk, shown in Definition Box 2, prevail in the economic discourse? It is argued here that the prevailing definition of systemic risk simply reflects the priorities and objectives of the parties that employ the definition. This implies that alternative definitions of systemic risk may be developed to address the specific needs of policymakers concerned with the anthropogenic carbon balance and climate change. To address this point, an alternative definition of systemic risk, called the 'systemic risk to the carbon cycle,' was developed, as shown in Definition Box 3. Evidence for the existence of this specific type of risk is presented in Table 1, and scholars are encouraged to review and expand Table 1.

Definition Box 3. Systemic Risk to the Carbon Cycle

> A systemic risk to the carbon cycle is defined as the likelihood of exceeding a safe greenhouse gas (GHG) emissions budget because of (a) societal systems that experience gridlock over standard mitigation policies, and (b) earth systems that produce uncertainties, amplifying feedbacks, and potential tipping points that shrink the allowable GHG emissions budget. Two examples within societal systems are political resistance to carbon taxes, and profit-seeking through fossil fuel extraction. Three examples within earth systems are intensifying permafrost thaw, wetland warming, and wildfire (processes that release more GHGs in response to global warming). If left unchecked, the systemic risk will worsen the climate damages and ultimately result in major irreversible disruption to the climate, biosphere, and economy.
>
> **Footnotes:**
>
> (a) Rising atmospheric CO_2 increases the acidity of oceans with major environmental implications.
> (b) The earth's changing albedo and the role of solar radiation management (SRM) would have an impact on the carbon cycle, but this topic is postponed for reasons of brevity.
> (c) The use of the singular term 'systemic risk' is referring to the collective systemic risk, and the plural term 'systemic risks' is equally valid.

Table 1. Evidence for Systemic Risks to the Carbon Cycle

1. Persistent Political and Social Resistance	
1.1	In 2014, Australia's carbon tax was repealed following intense opposition from fossil fuel industries and political actors (Chan, 2015); and in 2018, there was widespread public protests in France, called 'Yellow Vest', to oppose a fuel tax increase for reducing carbon emissions (Mehleb et al., 2021).
1.2	Between 2023-2025, some financial institutions withdrew from the following alliances due to political and legal risks. This includes the Glasgow Financial Alliance for Net Zero (GFANZ), Net-Zero Banking Alliance (NZBA), Net Zero Asset Managers Initiative (NZAM), and Net-Zero Insurance Alliance (NZIA) (Andrews, 2025; Asuene Inc., 2025; Wilkes et al., 2023)
1.3	The United States withdrew from the PA in 2017 (effective 2020) and 2025 for domestic political reasons (MacNeil, 2025).
2. Uncertain and Non-Linear Climate Dynamics	
2.1	There is potential for large amounts of CO_2 and CH_4 to be released to the atmosphere from thawing permafrost. This could amplify global warming in ways that are difficult to predict (Dean et al., 2018; Schuur et al., 2022).
2.2	The melting of the Greenland and West Antarctic ice sheets has accelerated in recent years, with potential for greater sea level rise in the short and long term (Otosaka et al., 2023; Stokes et al., 2025).
2.3	The Amazon has a changing hydrological balance and carbon balance due to deforestation and forest degradation, intensifying climate change impacts on a regional and global basis (Flores et al., 2024; Franco et al., 2025).
2.4	The destabilisation of the Atlantic Meridional Overturning Circulation (AMOC) has the potential to disrupt the global climate system with major implications for regional climates, water resources, ecosystems, and agriculture (Ditlevsen & Ditlevsen, 2023; Drijfhout et al., 2025a; Laybourn et al., 2023).

Table 1 (continued)

2.5	In 2025, James Hansen and colleagues estimated that the equilibrium climate sensitivity (ECS) could be 4.5°C, significantly higher than the IPCC's best estimate of 3°C, underscoring the significant uncertainty in climate models (Hansen et al., 2025).
3. Propagation of Instabilities	
3.1	The 2008 global financial crisis and the 2019 COVID recession resulted in financial instability and stalled investment in low-carbon projects (Zhang et al., 2025).
3.2	Extreme weather events have triggered food insecurity, social unrest, migration, and violence in the 2006–2009 Syrian drought and civil war (Kelley et al., 2015), 2011 Somalia drought and humanitarian crisis (Maxwell & Fitzpatrick, 2012), and 2019-2022 locusts plague in East Africa, Arabian Peninsula, and Indian subcontinent (Gebregiorgis et al., 2025).
3.3	Bark beetle outbreaks in the western United States have caused extensive tree mortality since the 1980s, decimating millions of acres of forests amid a warming climate. This has profound implications for carbon storage, water resources, timber production, and wildfire risks (Andrus et al., 2025).
4. Self-Reinforcing Cycle of Inaction	
4.1	In 2024, the mass-averaged global price on carbon emissions was only US$7.70 per tonne of CO_2e. This statistic is based on 24% of global emissions having a mass-averaged price of US$32 per tonne of CO_2e and the remaining 76% having no price. Recent estimates of the SCC place it as high as US$185 ($44-$413) per tonne of CO_2 (Rennert et al., 2022), or even as high as $1367 per tonne of CO_2 (Bilal & Känzig, 2024).

2.4 Introducing the Systemic Externality

The systemic risk to the carbon cycle was introduced in the previous section (see Definition Box 3). By theorizing that this systemic risk should be priced into the economy with a dedicated policy, the possibility emerges that a 'systemic externality' could exist. The systemic externality concept differs from Pigou's (1920) negative and positive externalities, because the systemic externality is associated with system dynamics, and not with market inefficiencies. By introducing the systemic externality, this working paper differs from the approach of Chen et al. (2019) who considered the cost of managing climate systemic risk to be a positive externality. A technical definition of the systemic externality was developed as part of this study (see Definition Box 4), and a policy for correcting it was also developed (see Section 5) using the policy ideas of Chen (2018) and Chen et al. (2017, 2019) as inspiration.

Definition Box 4. Systemic Externality

A systemic externality is defined here as the unpriced systemic risk in a market failure. In the case of GHG emissions, it refers specifically to the unpriced systemic risk to the carbon cycle (see Definition Box 3). The systemic externality arises from the dynamics of societal and earth systems that make the negative externality unmanageable when relying solely on standard policies. The systemic externality is potentially hazardous because it can cause the negative externality to become unbounded and extreme. An expanded policy toolkit is needed to address both the systemic and negative externalities in order to correct the market failure.

The systemic externality, as defined in Definition Box 4, is a new type of externality that does not appear as a core concept in Pigou's externality framework. This newly theorized externality accounts for the self-reinforcing cycle of inaction in Figure 1, and other systemic risks to the carbon cycle. The idea that the standard economic theory does not adequately address the scale or complexity of the market failure in GHG emissions is not new. For instance, N. H. Stern (2014), in his 'Stern Review' to the UK government, recommended further research into the topic, highlighting the need for new approaches to inform policy and decision-making.

In Sections 3 to 4, an expanded economic framework is presented that includes a policy toolkit for addressing and correcting both externalities: the negative and the systemic. The systemic externality defined in Definition Box 4 is further clarified in Section 7 with a system-level verification. Included in this verification is a system-level diagram (Figure 13) showing the role of international institutions in responding to the systemic externality.

2.5 Two-by-Two Matrix for Classifying Market Outcomes

An iterative-abductive methodology was adopted to produce the findings of this working paper. This involved trial-and-error testing of a variety of economic frameworks. The aim was to develop an expanded economic framework and policy toolkit that could potentially resolve the market failure in carbon by addressing important knowledge gaps. Through this process, the two-by-two (2×2) outcome matrix shown in Figure 2 was developed as a 'pattern recognition tool' for analysing the market failure in carbon (see Appendix A for additional details concerning this 2×2 outcome matrix). The matrix in Figure 2 was ultimately adopted because it was found to be useful for analysing the market failure in carbon while also providing a major new opportunity to build on previous economic scholarship and without contradicting established economic theories.

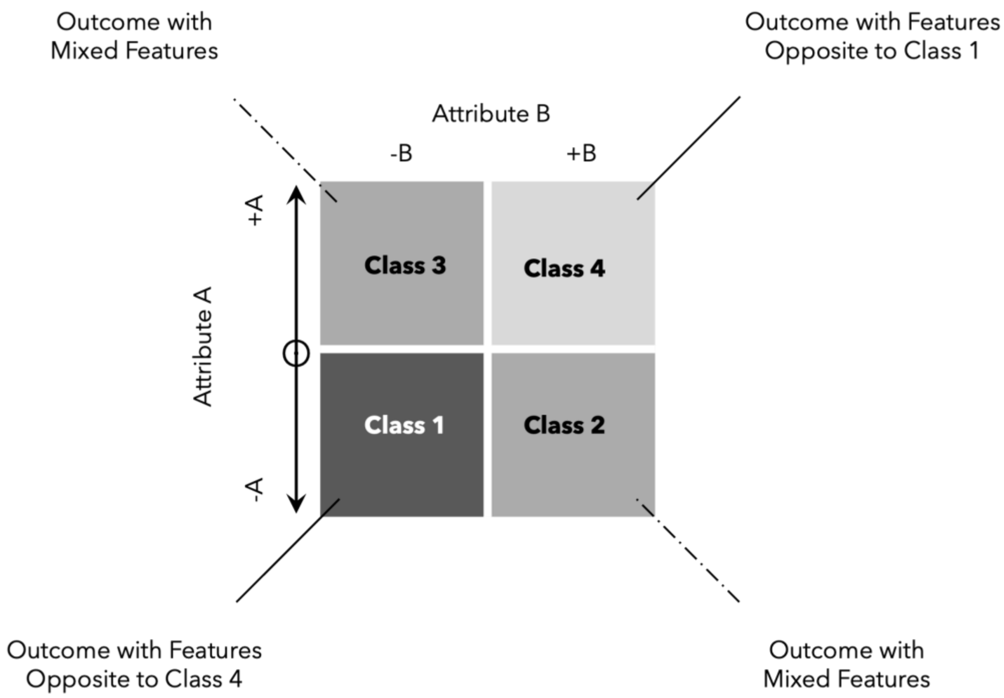


Figure 2. The 2×2 outcome matrix for the market failure in carbon.

The 2×2 matrices in Figure 2 and Figure A1 (Appendix A) are widely-used in the social sciences to compare outcomes, strategies, and options. Notable examples include:

- Fourfold classification of goods (Mankiw, 2012; see Figure A2)
- Eisenhower matrix (Covey et al., 2003; see Figure A3)
- NGFS systemic risk scenario matrix (Richters et al., 2022; see Figure A4)
- Corporate Ansoff matrix (Meldrum & McDonald, 1995)
- Growth-share matrix (C. W. Stern et al., 2006)
- Porter's generic strategies matrix (Porter, 1998).

The above examples demonstrate the versatility of the 2×2 matrix in the analysis of a variety of emergent and complex social systems however this matrix approach has not previously been used to examine the market failure in carbon.

As indicated in Figure 2, the utility of the 2×2 outcome matrix is dependent on the system of interest having two attributes: Attribute A should have two opposing numeric or ordinal value categories, and Attribute B should have a binary option. The 2×2 matrix in Figure 2 is applicable when interactions between attributes A and B result in four distinct outcome classes. Important, is that outcomes in Classes 1 and 4, although emerging from complex interactions, should exhibit opposite features due to the compounding influence of Attributes A and B. Outcomes in Classes 2 and 3, on the other hand, should exhibit mixed features because the compounding effect is absent.

The 2×2 matrix in Figure 2 was used to develop a damage matrix, a risk matrix, and a policy matrix for the market failure in carbon, as described in Sections 3 to 4. The expanded economic framework of this paper, including the carbon reward policy itself (refer to Section 5), was developed by linking these three matrices together in a unified conceptual model.

The example 2×2 matrices listed above do not constitute proof that this matrix approach (refer to Figure 2) is the optimal pattern recognition tool for the market failure in carbon, and so partial validations and partial verifications were also undertaken with some promising results. The expanded economic framework was partly validated by undertaking a preliminary assessment of the carbon reward policy (see Section 6). The expanded framework was also partly verified by undertaking a thermoeconomic review (see Section 7) and resolving two well-known theoretical conundrums related to Pigou's approach (see Section 8.2).

The partial verification of the expanded economic framework includes a possible resolution to two prominent debates in the economics of climate change: a debate between W. D. Nordhaus and M.L. Weitzman (Weitzman, 2009; refer to Section 8.2.5), and a debate between W. D. Nordhaus and N. H. Stern (Nordhaus, 2007; refer to Section 8.2.6). The thermodynamic review examines Gibbs free energy, which is naturally structured by a similar 2×2 matrix, as shown in Figure A5. The analysis of Gibbs free energy was undertaken to better understand the 2×2 matrix from a system-level perspective, and to develop a possible new epistemology for the economics of carbon (refer to Section 7.3.3). These partial validations and verifications add weight to the matrix approach of this study however further work, including policy feasibility assessments and piloting, is needed to validate the expanded economic framework presented in the remainder of this working paper.

3. Expanded Economic Framework for the Market Failure in Carbon

3.1 Damage Matrix for Carbon

The standard theory for the market failure in carbon (refer to Section 1.3.2) emphasizes the negative externality resulting from unpriced carbon emissions. This externality is quantified as the SCC in economic assessments (Rennert et al., 2022). However, the SCC has notable limitations, including the subjectivity of the social time discount rate, and the insensitivity of the SCC to many moral and environmental damages. For example, the monetary value of a sacred religious artifact, iconic species, ecosystem, or beautiful landscape may be impossible to determine. To address these challenges, a number of faceted classifications were tested with the 2×2 outcome matrix in Figure 2 (see Appendix A for background on the 2×2 matrix). The preferred result is the damage matrix for carbon, as shown in Figure 3. This matrix categorizes damages based on two attributes: (A) value type, and (B) domain type. The two rows of the matrix refer to damages with (-A) material value, and (+A) moral value. Material value is tangible and usually monetizable, and moral value is intangible and usually non-monetizable. The two columns refer to damages within (-B) a social domain, and (+B) an environmental domain.

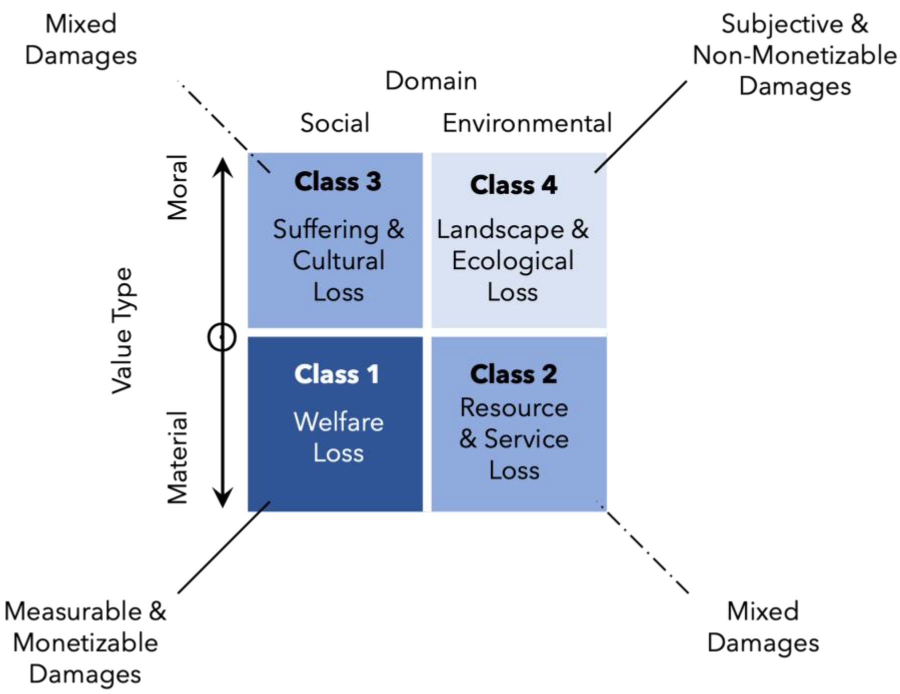


Figure 3. Damage matrix for carbon (see main text for Class 1–4 definitions).

The four classes of damage in Figure 2 are defined as follows:

● **Class 1 Damage:** this class refers to any social welfare loss that is tangible, quantifiable, monetizable, and readily incorporated into estimates of the SCC and GDP. This may include damage to infrastructure, loss of property, asset depreciation, service disruptions, productivity declines, healthcare costs, etc.

● **Class 2 Damage:** this class refers to degraded or lost natural resources and ecosystem services—collectively known as natural capital. These damages are a combination of monetizable and non-monetizable losses, and they are partially captured in SCC and GDP estimates. The non-monetizable feature of these damages results from inherent ambiguities when attempting to estimate the monetary value of natural capital and ecosystem services.

● **Class 3 Damage:** this class refers to any intangible moral damage, such as cultural heritage destruction and human suffering, grief, and psychological trauma. This class of damage is only partially captured in SCC and GDP estimates because the damage has a non-monetizable component given that only some moral damages are linked to compensation claims and insurance payouts.

● **Class 4 Damage:** this class refers to moral damages tied to unwanted changes in landscapes and ecosystems that comprise humanity's natural heritage. These damages are typically non-monetizable and are poorly reflected in SCC and GDP estimates. Examples include biodiversity loss, species extinction, ecosystem degradation, and alterations to iconic landscapes. These moral damages may be more acute for indigenous and rural communities whose cultures are intimately connected to the land, water, and ecosystems.

The damage matrix for carbon, shown in Figure 1, was not developed to improve the accuracy of SCC or GDP estimates, but rather to improve our general understanding of climate-related damages. The matrix highlights a key limitation of the standard theory, which is that various kinds of moral and environmental damage are impossible to monetize or include in SCC estimates. Scholars and researchers are encouraged to critically evaluate the damage matrix in Figure 3 by proposing additional examples, comparing it with (IPCC WGII, 2023) classifications, and testing its general adequacy.

3.2 Risk Matrix for Carbon

The 2×2 outcome matrix in Figure 2 was used to classify the systemic risks to the carbon cycle (refer to Definition Box 3). These systemic risks include:

● political and social resistance to standard policies (e.g., (Carattini et al., 2018)

● technological dependency on fossil fuels (e.g., Unruh, 2000),

● uncertain and non-linear climate dynamics (e.g., Drijfhout et al., 2025)

● propagation of social and ecological instabilities (e.g., Zhang et al., 2025), and

● a self-reinforcing cycle of inaction (Figure 1).

After testing various options, the 'risk matrix for carbon', shown in Figure 4, was adopted. This matrix classifies systemic risks according to two attributes: (A) spatial scale and (B) system type. The two rows of the matrix denote (-A) global scales and (+A) local scales, and the two columns denote (-B) societal systems and (+B) earth systems. Societal systems include financial, monetary, legal, political, educational, cultural systems, etc. that contribute to the structure of economies and associated markets. Earth systems include the hydrosphere, cryosphere, biosphere, lithosphere, and atmosphere. The (-A) global scales generally refer to systemic risks that are continental or planetary in scope. For example, negotiations under the UNFCCC have planetary implications. The local spatial scales refer to systemic risks that appear in organizations, communities, cities, states, and nations.

The four classes of systemic risk in Figure 4 are defined as follows:

● **Class 1 Risk:** this class refers to global-scale systemic risks caused by societal systems (i.e. political economy) by preventing or delaying policies and plans for decarbonization. A headline metric for this class of risk is the 'climate finance gap' (Naran et al., 2024). Other metrics for this risk are the SCC, the global mass-averaged carbon price, Nationally Determined Contributions (NCDs), and projected investment in renewable energy versus fossil fuel extraction. Subjective indicators of Class 1 risk are political gridlock, free-riding, political discord, and conflict. Reducing this risk requires international conferences, diplomacy, policy discussions, agreements, laws, and good governance.

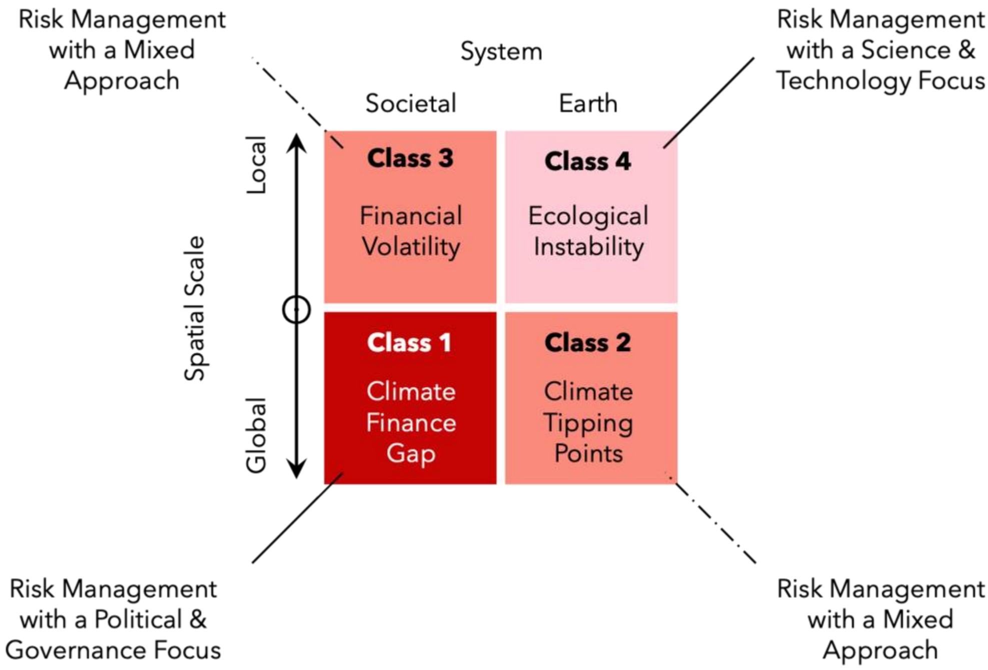


Figure 4. Risk matrix for carbon (see main text for Class 1–4 definitions).

- **Class 2 Risk:** this class refers to global-scale systemic risks caused by the non-linear dynamics of earth systems, and uncertainties in climate change forecasting. The headline issue is the risk of passing climate tipping points by following an unsafe emissions trajectory. Tipping elements include rainforest dieback in the Amazon, ice sheet destabilization, sea ice melt in the polar regions, thermohaline circulation disruption in the Atlantic Ocean, and others. Uncertainties regarding the science of climate change could potentially result in the overestimation of the available carbon budget. For example, if the equilibrium climate sensitivity or aerosol cooling effect were to be underestimated. Reducing these systemic risks will require a mix of policies, governance, new technologies, and scientific research.

- **Class 3 Risk:** this class refers to systemic risks caused by instability in societal systems, beginning within organisations, communities, institutions, markets, and governments. This risk exists when a localised instability spreads to become a regional or global problem—potentially slowing or reversing economic decarbonization. The headline issue is 'financial volatility' because this is a common measure of societal instability. Two sources of financial instability, according to the NGFS, are transitioning to a low-carbon economy, and climate-related damages (see Figure A3). Other possible sources of instability are insurance failures, network failures, cybercrime, bank runs, economic recessions, geopolitical tensions, trade wars, terrorism, and hot wars. These risks could amplify other risks, and managing them will require a mix of new technologies, stakeholder consultation, diplomacy, policies, standards, regulations, laws, and good governance.

● **Class 4 Risk**: this class refers to systemic risks caused by instabilities in the biosphere that begin at a local level but propagate, potentially undermining attempts to decarbonize the economy. The headline issue is ecological instability. One example is the loss of pollinator insects, such as bees, that are vital for agriculture. Other examples are deforestation causing water stress, wildfire risk, invasive species risk, contagious disease, and new viruses. The direct impacts could include falling agricultural productivity, food insecurity, human migration, and pandemics. These risks could amplify other risks, and managing them will require a toolkit of standards, controls, technologies, policing, and scientific research.

The risk matrix for carbon (see Figure 4) highlights that there are diverse risks to the carbon cycle. Striking, is that the risks on the major diagonal (Classes 1 & 4) have opposite features, with Class 1 being more focused on politics and governance, and Class 4 being more focused on science and technology.

3.3 Dual-Externality Thesis for the Market Failure in Carbon

In previous sections the market failure in carbon was described in terms of unpriced climate damages (Figure 3) and unpriced systemic risks to the carbon cycle (Figure 4). These two market failings are synthesized in Figure 5, revealing a multidimensional market failure unaddressed by Pigouvian theory. This is called the dual-externality thesis, and it posits that two distinct externalities have emerged: (1) a negative externality of unpriced damages, and quantified with the SCC metric, and (2) a systemic externality of unpriced systemic risks to the carbon cycle, and quantified with the RCC metric. A technical guide for understanding and applying the SCC and RCC metrics is provided in Appendix B.

Figure 5 is a metaphorical illustration, showing the dual-externality thesis as the two sides of a coin. This duality raises critical policy questions: Can carbon taxes alone address both externality types? Are all damages and risks quantifiable? How can policymakers mitigate systemic risks? This complexity is addressed in Section 4 with the development of an expanded policy toolkit and by moving beyond single-instrument solutions.

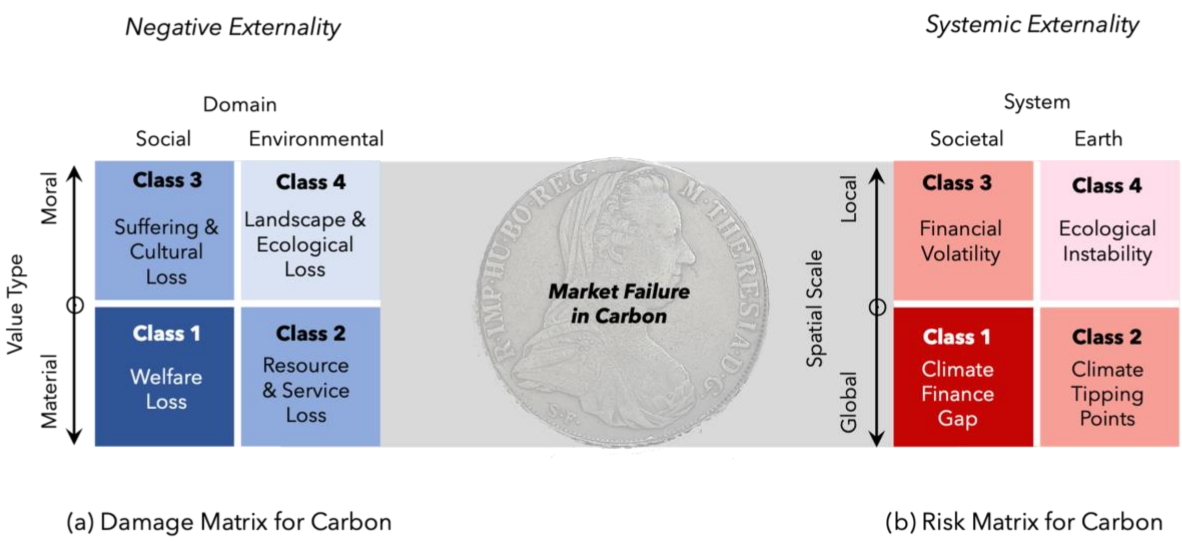


Figure 5. The dual externality thesis as a metaphorical coin, with one side representing the negative externality and the other representing the systemic externality.

4. Potential Resolution to the Market Failure in Carbon

4.1 Policy Matrix for Carbon

The dual-externality thesis, presented in the previous section, is based on the damage and risk matrices for carbon, presented in Figures 3-5. The development of this thesis was the first major step towards developing an expanded economic framework that could potentially resolve the market failure in carbon. The second major step was to develop a suitable policy toolkit. This involved developing a 2×2 outcome matrix specifically for market policies. After some trial-and-error testing, a 2×2 matrix with the following attributes was adopted: (A) store-of-value for the market instrument with either (-A) a negative value ('stick'), or (+A) a positive value ('carrot'); and (B) unit-of-account for the market instrument as either (-B) a sovereign currency ('fiat'), or (+B) a carbon mass ('carbon').

The resulting 2×2 matrix, shown in Figure 6, is named the 'policy matrix for carbon.' It was adopted because it appears to be effective at classifying policies and resolving the market failure. The four classes of the policy matrix are described as follows:

- **Class 1 Policy:** this class refers to the carbon tax, which is a government-imposed fee on carbon emissions. The ideal tax is defined by the social cost of carbon (SCC), determined through cost-benefit analysis (Metcalf, 2019). Carbon-intensive goods and services would become more expensive, and producers and consumers would then respond by adopting cleaner alternatives. Illustrative examples include Sweden's nationwide carbon tax, first levied in 1991 at €22 per tCO_2 and gradually increased to about €134 per tCO_2 by 2025 (Government Offices Sweden, n.d.). Another example is British Columbia's province-wide carbon tax, introduced at CA$10 per tCO_2 in 2008 and gradually increased to about CA$80 per tCO_2 by 2024—but was abolished on in April 1, 2025 (Carbon Tax Act, 2008). Class 1 also includes hybrid carbon taxes, such as fee-and-dividend and feebates.

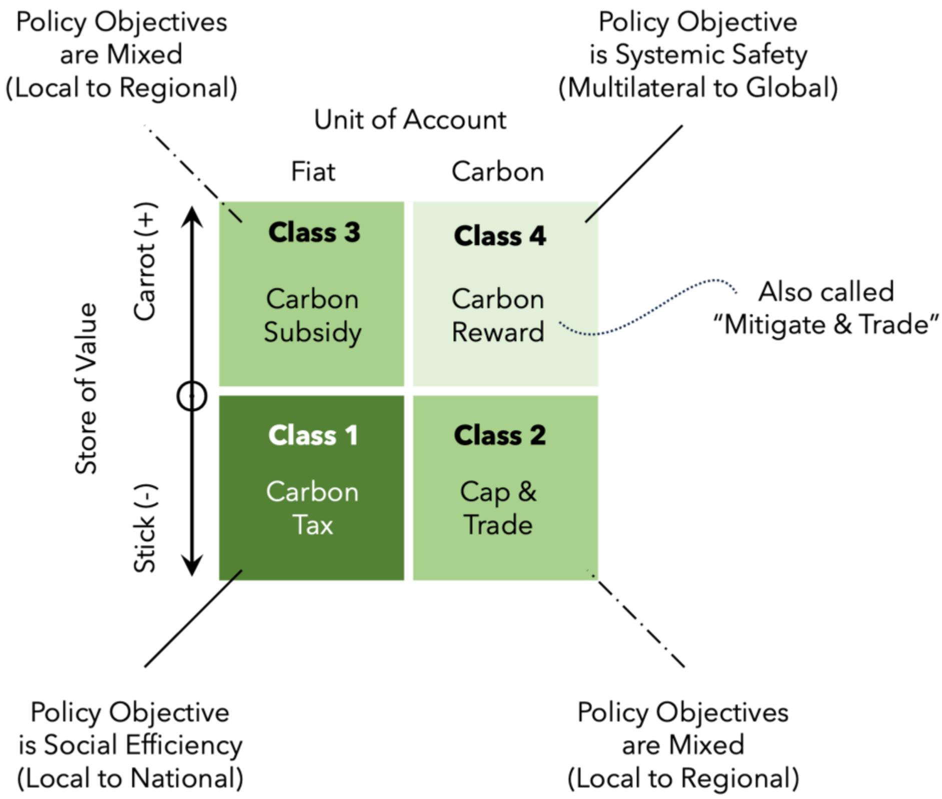


Figure 6. Policy matrix for carbon (see main text for Class 1–4 definitions).

● **Class 2 Policy:** this class refers to cap-and-trade systems, which involve government-imposed caps on the total GHG emissions, typically for a specific industry or sector (see Appendix C for a summary description of this policy type). Polluters receive or purchase GHG emission permits corresponding to the declared cap, and individual polluters who produce less emissions than their GHG permits allow, may sell their excess permits. This creates a market for permits, and Coasean bargaining should follow to reach Pareto optimality. An example is the European Union Emissions Trading System (EU-ETS), which launched in 2005 and has significantly reduced carbon emissions in the EU (Bayer & Aklin, 2020). Class 2 also includes hybrid cap-and-trade policies, such as baseline-and-credit (i.e. issuing tradable credits to organizations for reducing their GHG emissions below a baseline) and carbon takeback (i.e. imposing a declining GHG cap specifically for fossil fuel producers).

● **Class 3 Policy:** this class refers to carbon subsidies, which include government funded positive incentives, grants, or tax credits for supporting technologies and projects that mitigate GHG emissions by removal, reduction, or avoidance.

Subsidies are managed through fiscal means, with no Coasean bargaining, although tax credits may be sold in open markets at a discount. A prominent example is the United States' Inflation Reduction Act (IRA), enacted in 2022 (Bistline et al., 2023). The IRA represents the largest climate investment in U.S. history, allocating nearly US$400 billion for a suite of subsidies for decarbonization. The IRA expanded tax credits for clean energy and industrial decarbonization, including up to US$85 per metric ton of CO_2 captured and stored from industrial facilities, and US$180 per metric ton for direct air capture projects (Naran et al., 2024). The IRA is no longer fully active due to the passage of the One Big Beautiful Bill Act (OBBBA) in 2025, which weakened the IRA by phasing out key tax credits for solar and wind energy, which are crucial for reducing emissions (Cavanaugh et al., 2025).

- **Class 4 Policy:** this class refers to a novel policy type called a 'carbon reward' or 'mitigate and trade.' The objective of the carbon reward is to positively price mitigation for overcoming the systemic risks to the carbon cycle. These risks are quantified in terms of the risk cost of carbon (RCC)—a metric that was first coined by Chen et al. (2017, 2019) but is refined in Section 5 and Appendix B of this paper. Unlike most other policies, the carbon reward is a 'no sticks' policy because it avoids imposing fiscal costs on market actors and governments. The market instrument, a carbon-linked financial asset, is used to create positive prices for verified GHG mitigation, including CDR. A price floor is set under the market instrument, and this floor is guaranteed by central banks using monetary programs. This guarantee is to stabilise the reward price and attract private investment in the instrument. This private demand, based on Coasean bargaining, would crowd-out other investments and channel private capital into mitigation. No other Class 4 policies were considered in this study, and there were no real-world examples at the time of writing. For further information, see Sections 5 and 6.

A few governments have augmented cap-and-trade (Class 2) by introducing a price floor on emissions permits through fiscal methods, such as 'buybacks.' For instance, the United Kingdom established a Carbon Price Floor (CPF) and Carbon Price Support (CPS) mechanism in 2013 to ensure a minimum carbon price within the EU ETS framework (Hirst, 2018). Alternatively, the EU ETS Market Stability Reserve (MSR), operational since 2019, adjusts the supply of emissions permits based on thresholds, to prevent price collapses (Borghesi et al., 2023). These Class 2 price floors are supported by fiscal interventions and so differ fundamentally from the Class 4 price floor, which is supported by monetary programs. For a detailed comparison of Class 2 and Class 4 policies, see Appendix C.

4.2 Expanded Economic Framework: Potential Resolution

The policy matrix presented in Figure 6 serves as the foundation for a potential resolution to the market failure in GHG emissions. The carbon reward policy (Class 4) is particularly notable for its potential to address the systemic risks to the carbon cycle—risks that extend beyond traditional market failures. Notable, is that the 2×2 policy matrix includes new interpretations concerning the objectives and geo-political feasibility of each policy class based on the compounding effect of policy attributes. More specifically, the objective and geopolitical feasibility of the carbon reward (Class 4) are opposite and complementary to those of the carbon tax (Class 1). These opposing features of Class 4 and Class 1 policies are presumed to have major implications for resolving the market failure and improving climate governance (see Section 8.2.4 for a discussion).

While standard market policies such as carbon taxes and cap-and-trade have achieved some progress, they have only achieved a globally-averaged price of US$7.70 per tCO_2e according to World Bank (2024) data. This price falls significantly below the aspirations of the PA. In response, the 'expanded economic framework,' illustrated in Figure 7, integrates three analytical matrices: (1) the damage matrix (Figure 3), (2) the risk matrix (Figure 4), and (3) the policy matrix (Figure 6). This expanded framework provides a thorough characterization of the market failure, encompassing the related damages, systemic risks, and corresponding policy responses. At its core, the policy matrix functions as a toolkit designed to balance the dual objectives of social efficiency and systemic safety, thereby offering a resolution to an otherwise intractable problem (Figure 5).

The recommended policy response is to implement all four policy classes shown in Figure 6 while leveraging their geopolitical strengths. This means deploying carbon pricing in complementary layers, with Classes 1 & 2 providing a layer of sticks, and the Classes 3 & 4 providing a layer of carrots. The carbon tax (Class 1) will likely be the least popular because it is the most punitive, and will thus require the most favourable political conditions. The cap-and-trade (Class 2) and subsidy (Class 3) would likely be more popular than the carbon tax (Class 1), and efforts should be made to deploy them locally, nationally, and regionally. Finally, it is presumed that the carbon reward (Class 4) has geopolitical feasibility for international deployment because there are no fiscal costs, given that costs will be directed into financial markets and central bank balance sheets (refer to Section 5).

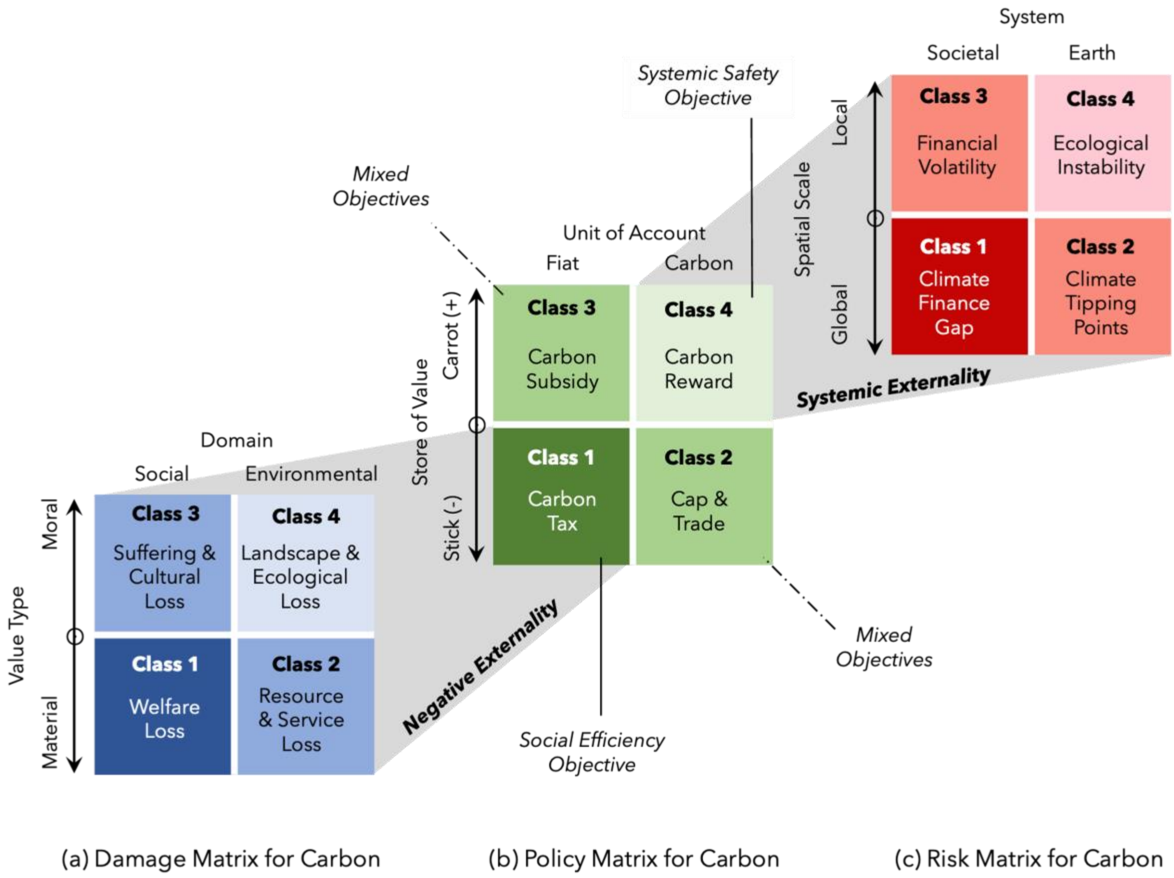


Figure 7. Expanded economic framework for the market failure in carbon.

Referring to Figures 6 & 7, the policies in the top row offer carrots that would encourage mutual cooperation amongst stakeholders based on financial self-interest. For example, the U.S. Inflation Reduction Act, provides a suite of subsidies, tax credits, and production incentives for decarbonisation. Meanwhile, policies in the right column, Classes 2 and 4, are Coasean in nature, because they invite private bargaining: a form of mutual cooperation that leads to Pareto optimality (i.e. when no party can be made better off without making another worse off). By contrast, the carbon tax (Class 1) seeks to improve social efficiency by internalising the SCC into the economy. Taxes alone are not ideal for promoting cooperation, and this point is critically important because it underscores the claim made here that a strategic combination of carrots and sticks is required to promote strong cooperation. In this working paper, the carbon reward is recommended as an international carrot and complement to other market policies.

4.3 Carbon Market Matrix

An understanding of carbon markets under Article 6 of the Paris Agreement is essential for effective climate action, but these markets are sometimes bewildering because they're comprised of a variety of compliance markets, voluntary markets, pricing instruments, mitigation standards, and offsetting mechanisms. To help make sense of this complexity, the policy matrix for carbon in Figure 6 was expanded to provide the 'carbon market matrix' shown in Figure 8. This larger matrix, with three rows and four columns (3x4 matrix), is designed to distinguish and classify compliance markets, voluntary markets, carbon credits, and offsetting. It also clarifies the difference between pricing emissions at the source versus elsewhere.

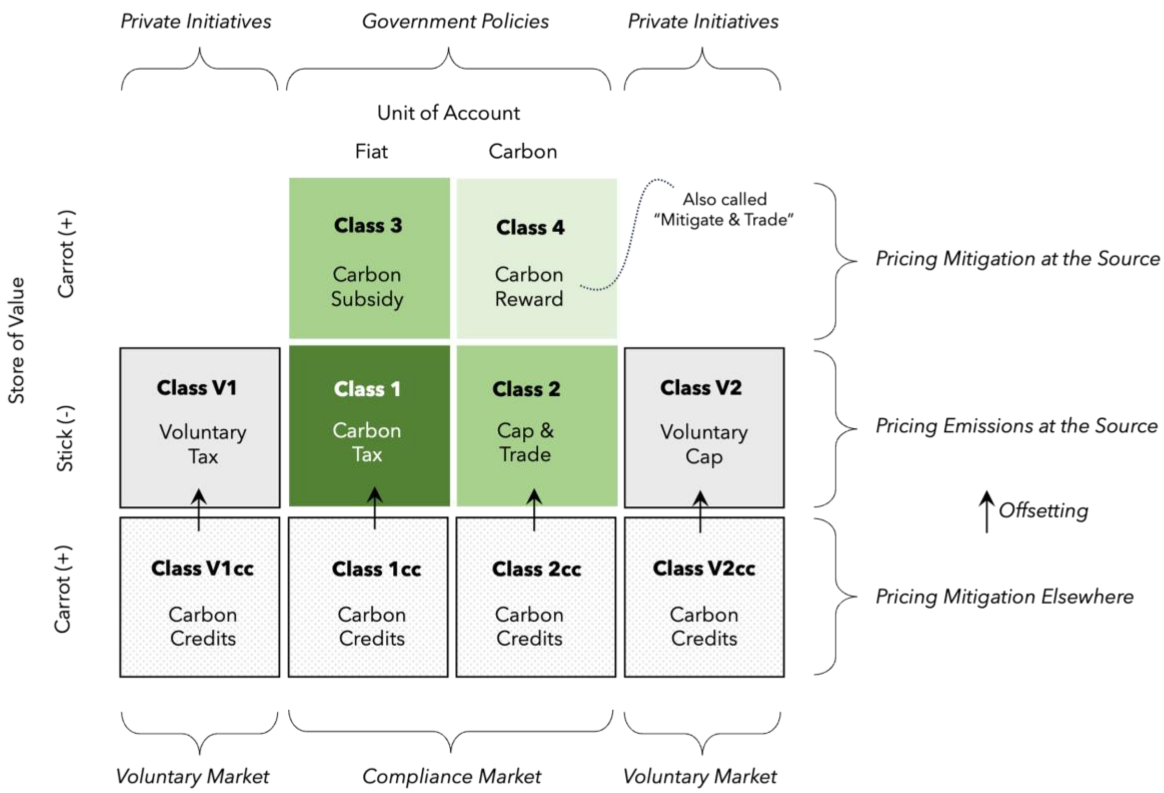


Figure 8. Carbon market matrix.

Looking closely at Figure 8, voluntary taxes (Class V1) include 'shadow' carbon pricing by corporates. They also encompass voluntary purchases of carbon credits without offsetting, and voluntary consumer spending on low-carbon goods and services that are more expensive than their high-carbon counterparts. Voluntary caps (Class V2) include net-zero pledges (usually by firms) that are defined by a year when net-zero emissions are to be reached.

Referring to Figure 8, some market participants may wish to voluntarily offset some of their emissions—rather than reduce them at the source—and this gives rise to voluntary markets for generating carbon credits that can be used to offset emissions (Classes V1 & V1cc, and Classes V2 & V2cc). Noteworthy is that Figure 8 shows that the carbon reward (Class 4) does not link to carbon credit markets and does not involve offsetting.

Practitioners in carbon markets are encouraged to review Figure 8 and consider it for use as a taxonomy under Article 6 of the PA. Scholars are also encouraged to review Figures 7 & 8 in terms of their implications for voluntary carbon markets. Here it is suggested that voluntary markets (i.e. Classes V1, V2, V1cc and V2cc) have mixed utility based on their attributes, and would be insufficient on their own to correct either of the two externalities. The main strengths of voluntary markets appear to be in fostering innovation and participation with the private sector especially where/when co-benefits are obvious, such as with some nature-based solutions. Their main weaknesses are a zero-sum impact when offsetting, limited financial scalability, and vulnerability to greenwashing. Romm et al. (2025) found that many offsetting projects have intractable quality problems.

4.4 Renaming the Market Failure

It is proposed here that the market failure in carbon be renamed to align with the expanded economic framework in Figures 7 & 8. The recommended new name is 'market-and-system failure,' because the market failure extends beyond markets and includes the unwanted effects of systems. A market-and-system failure in GHG emissions is defined in Definition Box 5.

Definition Box 5. Market-and-System Failure

A market-and-system failure is defined here as an extreme kind of market failure that involves a systemic externality in addition to a negative externality. For the market failure in greenhouse gas (GHG) emissions, the systemic externality refers to unpriced systemic risks to the carbon cycle. These systemic risks include policy-gridlock, climate feedbacks, and resulting amplification of the negative externality. Correcting a market-and-system failure requires a broader policy toolkit that can manage the unwanted effects of societal and earth systems, as well as correct the negative externality.

5. Carbon Reward Policy

5.1 Policy Type

The expanded economic framework of the previous section assumes that the carbon reward policy can—as part of a larger policy toolkit—be used to price and correct the systemic risks to the carbon cycle. This policy is most accurately called 'mitigate-and-trade' because it uses a tradable market instrument to incentivize GHG mitigation and to voluntarily distribute the mitigation cost with the support of a central bank guarantee (see Definition Box 6).

Before describing the carbon reward policy (also known as mitigate-and-trade) in more detail, it may be helpful to consider that the policy was developed with a 'no sticks' approach. In other words, the approach was to develop a positive incentive system (carrot) that can scale globally through voluntary participation. This is the opposite of cap-and-trade, which enforces limits on emissions through permits and policing (sticks). The carbon reward instead establishes a minimum price for carbon dioxide removal (CDR) and adaptive prices for conventional mitigation. It then invites countries to support the policy to target a non-binding mitigation roadmap. A summary description of this policy, based on this 'no stick' approach, is provided in Definition Box 6.

Definition Box 6. Carbon Reward Policy (Mitigate-and-Trade)

The 'carbon reward' is a market policy, also called mitigate-and-trade, that does not create any direct costs for market actors or governments. It offers a positive incentive for additional GHG mitigation, and it has the following key features:

- Systemic Externality: The externality of interest is the unpriced systemic risk to the carbon cycle, and the objective is to achieve systemic safety by pricing this risk (Definition Boxes 3 & 4).
- Policy Objective: The objective is to remain within a relatively 'safe' GHG emissions budget, and this objective would be agreed by the parties in the form of a declared mitigation roadmap (Figure 9).
- Asset Supply: The market instrument is a carbon-linked financial asset that would be issued for carbon dioxide removal (CDR). It would also be issued for cost-effective conventional mitigation across the sectors and industries that need financial support to align with the declared mitigation roadmap (Section 5.3).

Definition Box 6 (continued)

The carbon-linked asset would be supplied to mitigators under long-term contracts that roll forward in time.

● Asset Demand: The policy would require central banks to act as the 'market makers' for the carbon-linked asset, guaranteeing the price floor as necessary. This means that central banks would buy the asset whenever its spot price threatens to fall below the floor. This price floor would be calibrated to achieve a minimum required rate of CDR, and it would be the price signal for markets to respond (Figure 10; Section 5.4 & Appendix B).

● Price Discovery: Mitigators may sell their carbon-linked assets to investors or to central banks, allowing price discovery. This trading would occur in foreign exchange (FX) markets, resulting in Coasean bargaining (Appendix D). This bargaining in the FX would be encouraged to crowd-out other financial assets, thereby distributing the mitigation cost across financial markets for a Pareto optimal outcome.

5.2 Naming the Market Instrument

When choosing a name for the market instrument of the carbon reward policy, the intention was to differentiate the instrument from carbon credits, given that the new instrument (a) would not transfer the ownership of mitigated carbon, and so could not be used to offset GHG emissions; and (b) would be tradable in financial markets, including foreign exchanges (FX). In other words, the instrument only conveys economic value, and not the ownership of the mitigated carbon. Previously, the instrument was called a 'carbon currency (XCC).' This naming convention was adopted during the policy's development, however, 'carbon currency' is an unsatisfactory name because it incorrectly refers to the instrument as a currency. To avoid possible confusion, the instrument is henceforth called a 'carbon reward,' as proposed in Table 2. The instrument is also abbreviated 'XCR,' which appears suitable for registration in ISO 4217 (ISO, 2015). The prefix 'X' aligns with the 'X series' in ISO 4217, which includes precious metals, supranational units, specialized monetary operations, and test codes. To illustrate this point, Table 2 presents five examples of registered X codes. The term 'carbon reward' or 'XCR' is used in the remainder of this working paper and it is also recommended for future policy discussions for clarity and to distinguish the carbon reward from carbon credits and other market instruments.

Table 2. Naming the Carbon Reward Instrument and Examples from ISO 4217

Carbon Reward Instrument		
Name	Code	Description
Carbon Currency	XCC	A placeholder name for the policy instrument during its development, including in papers and presentations predating this working paper.
Carbon Reward	XCR	The recommended name for the policy instrument in this working paper and for future policy discussions, publications, feasibility studies, stakeholder consultations, piloting, and official implementation under international agreements.
Examples from ISO 4217 (ISO, 2015)		
Name	Code	Description
Gold	XAU	Code for one troy ounce of gold, and used as a standard of value in international finance.
Silver	XAG	Code for one troy ounce of silver, and used as a standard of value in international finance.
SDR	XDR	Special Drawing Rights, an international reserve asset created by the IMF, based on a basket of major currencies.
Eastern Caribbean Dollar	XCD	Currency of all seven full members and one associate member of the Organisation of Eastern Caribbean States (OECS).
Reserved for Testing	XTS	Reserved for testing purposes.

5.3 Mitigation Roadmap & Reward Channels

The carbon reward policy would target a declared mitigation roadmap, like that shown in Figure 9, and ideally to align with the Paris Agreement's climate goals (targeting well below +2°C, ideally below +1.5°C). This roadmap would be comprised of a maximum feasible rate of conventional GHG mitigation, a minimum feasible rate of residual GHG emissions, and a minimum required rate of carbon dioxide removal (CDR). The CDR is needed to neutralize the residual emissions and may be needed to counteract historical emissions (refer Figure 9).

Country parties would need to agree in principle to the declared mitigation roadmap (Figure 9) while acknowledging that the roadmap is not legally binding. Market actors (i.e. organizations) who wish to participate in the carbon reward market, would need to agree in principle to the roadmap by declaring a portfolio of mitigation projects that covers their entire operations. Each individual project would be assessed and rewarded through Reward Channel 1 or 2, as shown in Figure 9.

- **Reward Channel 1:** This channel would finance CDR projects in a level-playing field based on a global reward price. CDR may include engineered, natural, and hybrid methods that meet certain criteria for good governance. Although the CDR rates shown in Figure 9 are hypothetical, the total CDR requirement in Figure 9 is within the IPCC's estimate for remaining within the +1.5°C limit (i.e., 100-1000 $GtCO_2e$ for the period 2020-2100). Reward Channel 1 is complementary to Reward Channel 2 because both channels are needed to achieve global net-zero emissions and global net-negative emissions under the roadmap.

- **Reward Channel 2:** This channel would finance conventional mitigation projects with rewards that are adjustable to achieve cost-effective outcomes. This channel would aim to reduce fossil fuel extraction and consumption, and reduce CO_2e emissions from electricity generation, transportation, primary industry, manufacturing, and all other sectors. This channel would also be used to avoid CO_2e emissions through the preservation of natural carbon stores, including in forests, soils, peatlands, wetlands, kelp forests, etc.

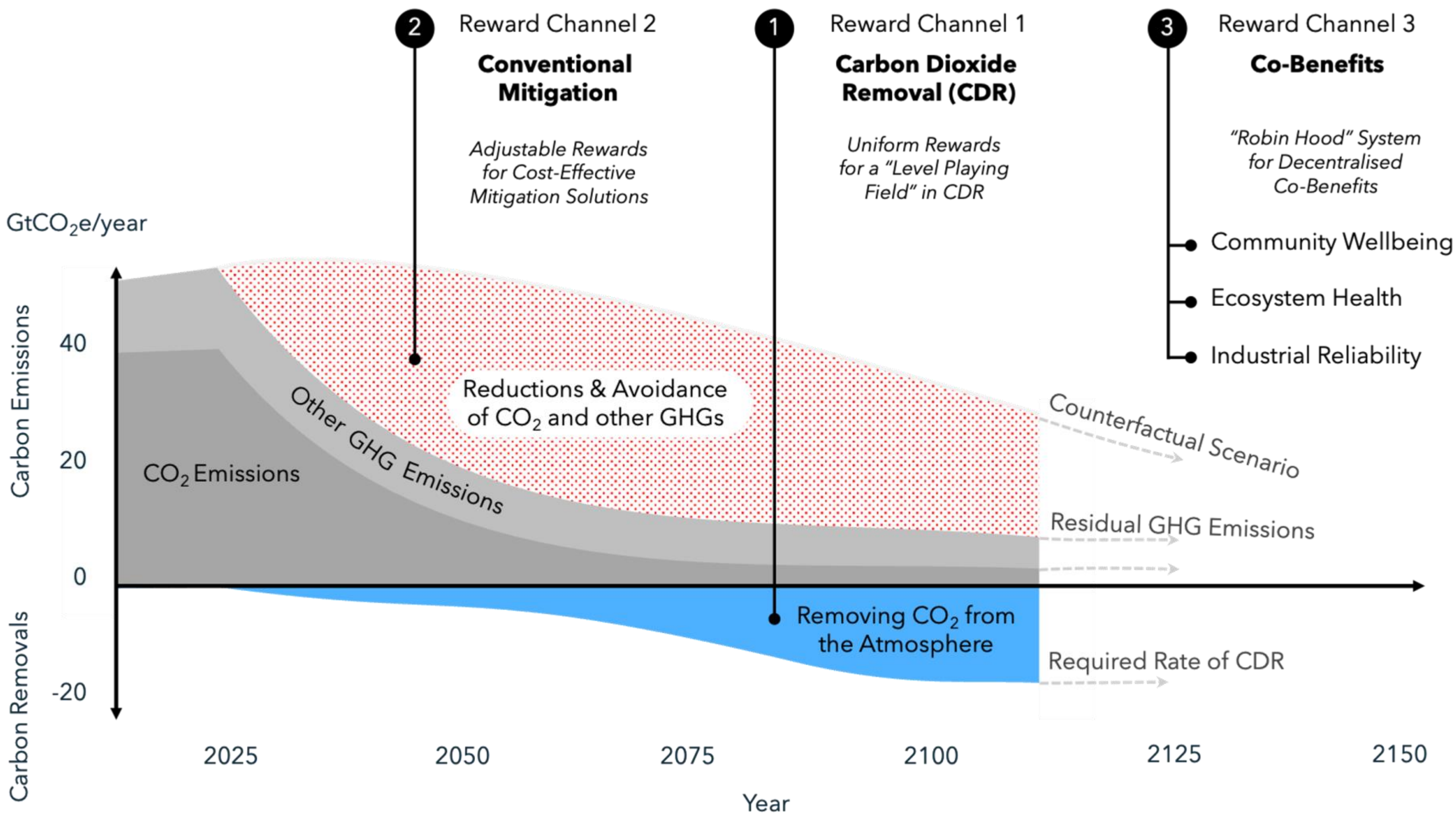


Figure 9. Declared mitigation roadmap (hypothetical).

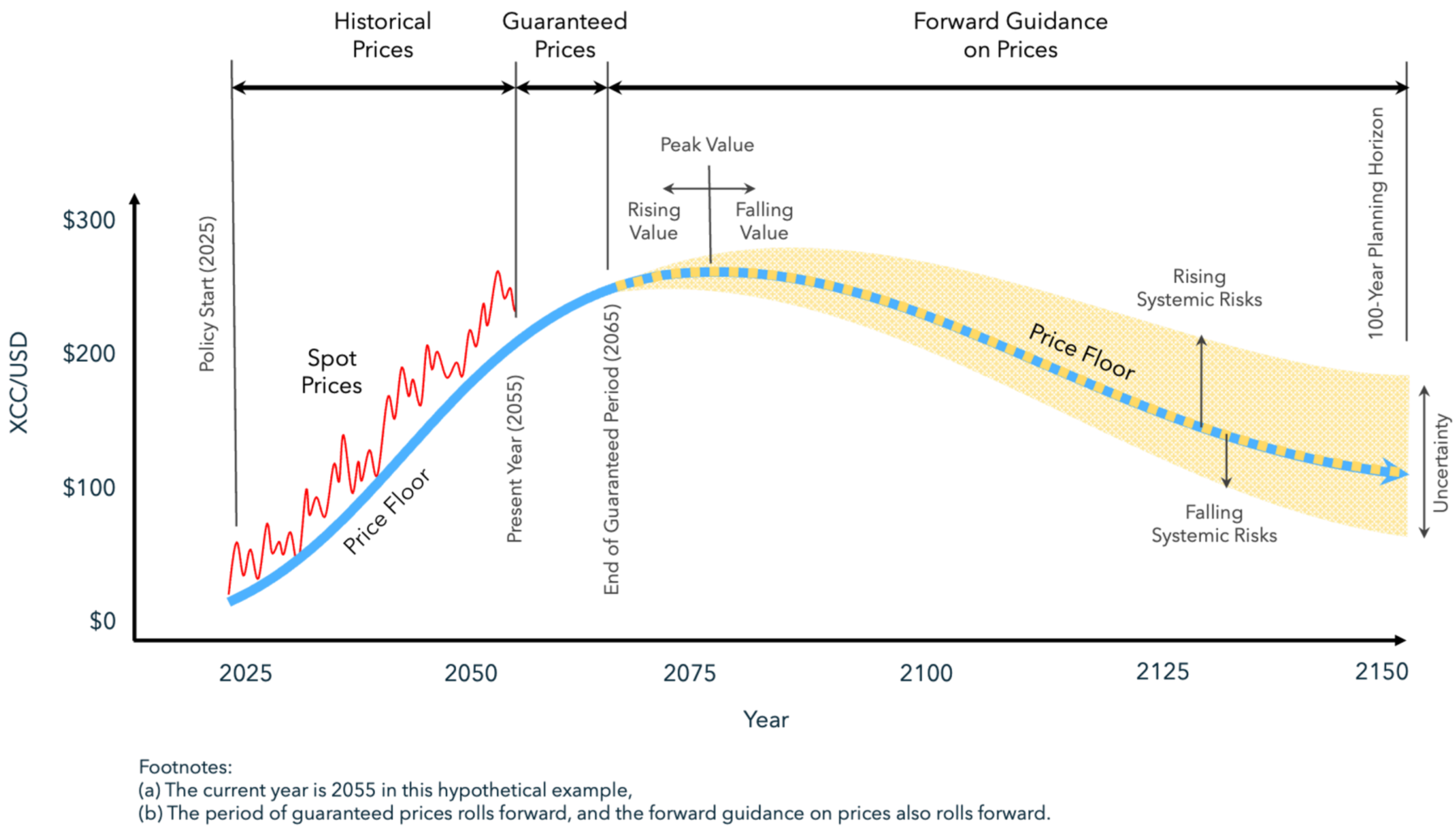


Figure 10. XCR price floor (hypothetical; aligns with Figure 9).

Many mitigation projects will likely produce a mix of positive and negative side-effects, some unexpected. To promote sustainable development and social cohesion, these projects may be directed into Reward Channel 3 at the discretion of the countries that are parties to the policy (see Figure 9)

- **Reward Channel 3:** This channel incorporates stakeholder management platforms—called 'Robin Hood' systems—to incentivize the owners of mitigation projects to reduce harms and maximize co-benefits for stakeholders. These harms and co-benefits would be defined by the stakeholders themselves. Some hypothetical examples are a reforestation project that improves food security, a renewable energy project that creates employment, and a CDR project that protects biodiversity. To help structure Reward Channel 3, three stakeholder types would be recognized: (Type 1) representing community wellbeing, (Type 2) representing ecosystem health, and (Type 3) representing industrial reliability. The various Robin Hood systems would allow stakeholders to compare mitigation projects in terms of harms and co-benefits. This information would be used to facilitate a periodic redistribution of XCR amongst projects to dis-incentivize harms and incentivize co-benefits. The ideal Robin Hood systems under Reward Channel 3 would be decentralized, open-source, and democratic to promote regeneration and resilience.

5.4 Economic Driver: XCR Price Floor

The carbon reward's price floor (XCR price floor) functions as the fundamental economic driver of the carbon reward policy (see Figure 10). In this policy, it is recommended that central banks guarantee the XCR price floor, as explained in Section 5.7.2. The ideal XCR price floor is termed the risk cost of carbon (RCC), as defined in Definition Box 7 and Appendix B. Unlike traditional carbon price floors that primarily impose costs on emitters, the XCR price floor establishes a guaranteed positive incentive for CDR and conventional mitigation. With a guaranteed XCR price floor, the carbon reward market would align profit motives with climate objectives, potentially mobilizing far greater financial capital and economic cooperation for climate action than traditional fiscal policies could achieve.

Definition Box 7. Risk Cost of Carbon (RCC)

> The risk cost of carbon (RCC) is defined here as the globally-averaged marginal cost of carbon dioxide removal (CDR) that is sufficient (i.e. the minimum required) for remaining within a relatively safe carbon budget. The RCC is used to set the XCR price floor in Figure 10. The RCC is based on the assumption that conventional mitigation will proceed at a vigorous rate. The RCC would be estimated by a Carbon Exchange Authority (see Section 5.7.1), and would be revised periodically to account for new climate science, GHG trends, technological advances, and other developments that influence the available carbon budget.
>
> **Footnote:** See Appendix B for technical guidance on the RCC.

The XCR price floor consists of three temporal components, as illustrated in Figure 10, namely: (a) historical prices, (b) approximately 10 years of guaranteed prices that roll forward annually, and (c) approximately 90 years of forward-guidance that also roll forward. This structure provides both immediate certainty and long-term visibility for market participants and investors. A peak in the XCR price floor could occur mid-century, with the actual timing being a function of technological progress and numerous other factors impacting the RCC (refer Definition Box 7).

XCR should not be confused with government bonds. XCR would trade in secondary markets, just like bonds, and so their market prices vary in response to supply and demand. While bond prices can move above or below par, XCR prices would only move above the XCR price floor. This price floor is policy-driven, with a rolling 10-year guarantee and 100-year guidance (Figure 10). The XCR price floor has a corresponding yield advertisement (annual % change) however realized returns will depend on the actual path of XCR spot prices relative to the price floor. XCR's yield is distinct from government bond yields because the XCR floor is anchored to the globally averaged marginal cost of CDR required for the mitigation roadmap (Figure 9). Government bonds, on the other hand, have a coupon rate set by the issuer, and a yield to maturity (YTM) that departs from the coupon rate under market forces. Bond payments rely on issuer credit, whereas the XCR can always be sold to private buyers or central banks via CQE.

5.5 Unit of Account

Deciding on the unit of account for the XCR was a pivotal step in the development of the carbon reward policy. This is because the unit of account impacts the design of the reward rules and entire financial mechanism. After considering various options, a unit of account for the XCR was defined to represent the removal of 1 tonne of CO_2e from the atmosphere and its durable storage (for 100 years or more) using a carbon dioxide removal (CDR) method or technology. The unit of account is rather unusual, however, because it also refers to the mass of CO_2e that can be conventionally mitigated at the same marginal cost of CDR. This benchmarking of the XCR's unit of account to the marginal cost of CDR is explained further in Definition Boxes 8 & 9.

Definition Box 8. Unit of Account of XCR

The unit of account for the carbon reward (XCR) is defined as:

1 XCR = 1/R tonnes of mitigated CO_2e with durability of 100 years or more,

where:

- R is fixed at 1 for carbon dioxide removal (CDR) projects (R=1),
- R is adjusted over time for conventional mitigation projects (R>0), and
- R is the reward multiplier for reporting the cost-effectiveness of mitigation projects relative to the marginal cost of CDR for remaining within a relatively safe carbon budget.

Footnote: See Definition Box 9 for a more detailed description of R.

The XCR unit of account consists of three key components: a unit of time, a unit of mass, and a reward multiplier (R). The unit of time is set at 100 years to ensure that mitigation outcomes are representative of the true global warming potential of GHGs. There is some flexibility in the adopted unit of time, however 100 years was chosen for simplicity. For mass, 1 tonne of CO_2-equivalent (CO_2e) mitigated is used, reflecting the standard metric in climate science. The reward multiplier, R, is a dimensionless factor that enables the provision of adjustable rewards for conventional mitigation under Reward Channel 2 (refer to Figure 9). R should be used to adjust and fine-tune the rewards that are offered to mitigation projects, it should also be used to describe and compare mitigation costs between projects, industries, and sectors.

When inspecting Definition Box 7, it is important to note that XCR is not a carbon credit and cannot be used to offset emissions. Therefore, XCR's unit of account does not need to represent a single standardized CO_2e mass. The reward multiplier, R, is introduced so that each unit of XCR can be adjusted to represent a 'cost-effective mass' of CO_2e mitigated (not a fixed mass). This innovation allows for adjustable rewards and greater financial flexibility while using just one instrument. This approach is recommended because the overarching goal of the policy is to deliver a relatively 'safe' carbon balance—not merely to track the mitigated mass of GHGs. The utility of R is clarified in Definition Box 9 and in the following section.

Definition Box 9. Reward Multiplier (R)

> The reward multiplier, R, is defined as a non-dimensional factor for adjusting the carbon rewards (XCR) issued to mitigation projects in a mitigate-and-trade market. The benchmark reward (R=1) refers to the globally-averaged marginal cost of carbon dioxide removal (CDR) that conforms to a declared mitigation roadmap (see Figure 10). R values should be adjusted to ensure that conventional mitigation projects receive sufficient finance to achieve milestones and outcomes that align with the declared mitigation roadmap. R values may be used to compare the cost-effectiveness of a conventional mitigation project with other projects or with other technologies, industries, sectors, or the average cost of CDR (R=1).

5.6 Carbon Reward Accounting

Organizations that participate in the carbon reward market will be required to meet certain standards, including standards for carbon reward accounting. A preliminary framework for this carbon reward accounting was developed to address the XCR's unit of account (see Definition Boxes 8 & 9), to support the century-scale ambition for mitigation, and to provide pragmatic financial support for mitigation projects. This preliminary accounting framework includes the following concepts:

(a) project portfolios for organizations,
(b) cost-effectiveness reporting with R,
(c) time-split rewards,
(d) milestone-driven rewards,
(e) pro-rata rewards, and
(f) clawback provisions.

5.6.1 Project Portfolios for Organisations

Each participating organisation will be required to manage their entire operation as a portfolio of mitigation projects, with each project having a dedicated carbon reward account. Project accounts will be inter-linked for tracking carbon that moves within the same organisation, thereby limiting the risk of greenwashing. Project accounts will be required to undergo periodic updates, audits, validation with real-time monitoring, and data tracking. For consistency, these accounts—including the reward revenue—would be denominated in a national currency (not in

XCR). By using a national currency, the risk of accounting errors involving the reward multiplier (R) would be minimised, as explained below.

5.6.2 Cost-Effectiveness Reporting with R

Of note, is that all project accounts will be required to meet the accounting standards of the carbon reward policy, and this includes denominating the accounts in a national currency, and not in R. This is to avoid accounting errors. R is intended as a cost-effectiveness indicator, such as when comparing expected with actual costs, or when comparing project costs with industry averages (refer to Definition Boxes 8 & 9).

To clarify, consider a simple hypothetical example of three mitigation projects that progress in parallel to align with the declared mitigation roadmap. To simplify this hypothetical, the guaranteed value of 1 XCR is assumed to be US$100. First, consider a CDR project:

- A CDR project, operating in a common global market, is offered 1 XCR or US$100 per tonne of CO_2e removed with durability of 100+ years (i.e. R=1).

Next, consider two conventional mitigation projects that have undergone careful evaluation to determine their most cost-effective rewards:

- A reforestation project is offered US$75 per tonne of CO_2e mitigated with durability of 100+ years, resulting in 1 XCR paid per 1.33 tonnes of CO_2e mitigated; and
- A coal-to-solar project is offered US$150 per tonne of CO_2e mitigated with durability of 100+ years, resulting in 1 XCR paid per 0.67 tonnes of CO_2e mitigated.

Referring to the above projects, the CDR project has an R=1 because it can only receive the reward set by the XCR price floor (US$100 in this example). The coal-to-solar project received the largest reward per unit mass because it faced the highest additional cost, resulting in R=1.5. The reforestation project received the lowest reward per unit mass because it faced the least additional cost, resulting in R=0.75. In each case, the R value reveals the relative cost of mitigation on a mass basis in relation to the XCR price floor (refer Figure 10) and the declared mitigation roadmap (refer Figure 9).

5.6.3 Time-Split Rewards

To help project owners manage their finances across the 100+ year durability requirement, XCR grants may be time-split between ex-ante and ex-post mitigation, as follows:

● Ex-ante rewards would help cover project establishment and running costs but would be tied to verifiable milestones (refer Section 5.6.3); and

● Ex-post rewards would be issued after periodic verification of carbon stocks, ensuring adherence to durability targets.

Such time-splitting of rewards would be designed to incentivize a long-term commitment from project owners while providing liquidity for operational continuity. For example, a mangrove restoration project might receive 30% ex-ante rewards for upfront capital expenditure, such as site preparation, and 70% ex-post rewards distributed over decades as carbon stocks mature during its operation.

5.6.4 Milestone-Driven Rewards

XCR grants that are paid ex-ante would be structured by milestones that commit project owners to responsible project management. In other words, rewards may be offered in tranches, corresponding to the completion of project feasibility, site selection, permitting, design, financing, procurement, construction, commissioning, operation, maintenance, closure, decommissioning, etc. These milestones would act as temporal checkpoints for:

● ensuring responsible management by linking rewards to performance,

● reducing project risks by staging reward payments to reflect progress,

● reducing uncertainty in financial planning and debt finance arrangements, and

● allowing for renegotiations based on external factors.

5.6.5 Pro-Rata Rewards

Recognizing that most mitigation projects will need reward revenue before their mitigated carbon fully matures (i.e. full maturity requires 100 years), or may need financial support due to unexpected costs—for example damages caused by extreme weather, political crises, pandemics, etc.—the authority may provide partial reward payments through pro-rata calculations. These calculations will determine a fair reward for mitigation periods less than the 100-year durability standard (refer Definition Box 7). This pro-rata mechanism will be used to:

- help maintain the financial viability of projects, or
- help facilitate the early closure of mitigation projects when circumstances demand.

5.6.6 Clawback Provisions

The carbon reward accounting will be linked to clawback provisions that may be invoked in case of: (1) mitigation backsliding that is unintentional but has resulted in the overpayment of XCR grants; (2) poor management, negligence, accounting errors, or misconduct; and (3) profit ceilings on individuals and organizations to avoid undue XCR grants.

5.7 Institutions & Alliances

5.7.1 Carbon Exchange Authority

To ensure the effective oversight and administration of the carbon reward market, a dedicated international institution—called the Carbon Exchange Authority (CEA)—is proposed. The CEA would serve as a technocratic body, established and mandated by countries supporting the carbon reward policy and the PA. The CEA would require robust governance systems, including clear decision-making processes and safeguards to maintain the effectiveness and integrity of the reward market. The CEA would be staffed by experts nominated by the parties. Its core structure would consist of specialized working groups responsible for designing the declared mitigation roadmap (refer Figure 9) and the detailed strategies, rules, guidelines, and contracts, all tailored to the decarbonization of economic sectors and industries.

Within the carbon reward marketplace, the CEA would offer and issue XCR grants to organizations under Reward Channels 1, 2 & 3, as illustrated in Figure 9. Sector-specific working groups of the CEA would be tasked with the long-term monitoring, evaluation, and rewarding of mitigation projects within their assigned domains. For CDR projects, under Reward Channel 1, working groups would maintain a level playing field accessible to all participating countries. For conventional mitigation projects, under Reward Channel 2, working groups would adjust the grant levels to ensure cost-effectiveness within the context of geographic variability. To accommodate this geographic context, CEA working groups may be subdivided by region, country, state, or city. All working groups would report to an executive body responsible for aligning the reward market with the declared mitigation roadmap.

The CEA would be self-financed through a percentage-based fee on XCR grants, ensuring its financial sustainability and independence. The CEA would invite third parties (consultants) to undertake project assessments based on XCR commissions. Participating organizations and third-party assessors would need to undertake specific training and certification under a proposed Carbon Exchange Standard (CES). Organizations that create technical standards, including for measurement, reporting, and verification (MRV), would need to be accredited under the CES. The CEA would adjudicate over these standards and would resolve disputes.

From the perspective of market participants (organizations), the attractiveness of the carbon reward market will depend on the specific details of the long-term contracts with the CEA. The objective of these contracts should be to guide and support organizations in achieving cost-effective mitigation outcomes. For this reason, contracts with the CEA should include a comprehensive set of milestones, mitigation targets, and formulas for XCR grant disbursement (refer to Section 5.6.1).

The CEA should collaborate with country parties to ensure that international and domestic laws are sufficient to support and enforce the long-term contracts provided by the CEA. This alignment is needed to clarify applicable legal jurisdictions; ensure the enforceability of provisions related to material breaches, insolvency, and dispute resolution, and establish robust provisions for force majeure and succession.

5.7.2 Central Bank Monetary-Carbon Alliance

Central bank alliances have historically formed to provide international financial stability, exemplified by the creation of the Bank for International Settlements (BIS) in 1930 and international agreements, such as the Tripartite Agreement in 1937 (Harris, 2021), Gold Pool in 1961-68 (Bordo et al., 2019), and Federal Reserve swap lines in 2007-9 (Jack, 2023). In the context of the carbon reward market, a central bank monetary-carbon alliance is needed to implement the XCR price floor that is illustrated in Figure 10. This alliance would be connected to the CEA through a monetary board that would be mandated to determine and revise the XCR price floor (refer Figure 10) for delivery to the central bank monetary-carbon alliance.

The central bank monetary-carbon alliance would act as the 'market maker' by maintaining the XCR price floor with the application of carbon quantitative easing (CQE) (see Definition Box 10). Only when the XCR spot price threatens to fall below the floor would the alliance be required to purchase XCR with bank reserves (M0, base money) using CQE. The new M0 would be deposited in the commercial bank accounts of the relevant XCR exchanges, directly expanding M1 (narrow money) and subsequently increasing M2 (broad money) through the banking system and stimulating clean investment without burdening governments. Most central banks would likely need explicit legal authority to undertake CQE as they currently lack mandates to support carbon market interventions. As Tamez et al. (2024) note, central bank actions are governed by mandates set by national laws.

CQE would be designed in such a way that it supports international equity. This implies allocating XCR purchase requirements to each central bank according to a formula that can produce minimal disruption to currency exchange rates and acceptable levels of monetary inflation. Meanwhile, the CEA would encourage carbon rewards to be directed to developing economies to help them develop more sustainably. Stakeholders may view the CQE-driven monetary inflation (see Section 6.6 for an estimate of this inflation) and the partial loss of central bank sovereignty as acceptable trade-offs if the approach can avoid hazardous climate change.

Definition Box 10. Carbon Quantitative Easing (CQE)

Carbon quantitative easing (CQE) is defined here as an internationally coordinated monetary program for central banks that belong to a monetary-carbon alliance. Each central bank of the alliance is required to participate in the CQE program with the aim of guaranteeing the XCR price floor in international markets. CQE requires member banks to purchase XCR with new bank reserves and in volumes defined by a common CQE formula. CQE does not involve creating or issuing XCR, and central banks only play the role of guarantor for the XCR price floor. CQE would be designed to achieve fairness and minimise unwanted monetary effects, such as monetary inflation and exchange rate volatility. Unlike traditional QE, CQE is long term, strategic, and does not involve buying government bonds, green bonds, or other securities.

Footnote: The XCR price floor is determined by a Carbon Exchange Authority (see Definition Box 7).

In summary, the central bank alliance would be mandated for the following:

- **Establishing Reliable Value:** By guaranteeing the XCR price floor, the XCR becomes a carbon-linked sovereign-backed asset with reliable long-term value for addressing critical sustainability issues (refer Figures 9 & 10).

- **Creating Investment Confidence:** The XCR price floor with a rolling 10-year guarantee enables project developers to secure debt and equity financing based on their XCR earnings estimates (refer Figure 10).

● **Facilitating Market Liquidity:** By establishing XCR trading and the XCR price floor in the FX, currency traders, pension funds, and investors will be attracted to the XCR because of its liquidity and its limited downside risk. On a global scale, the resulting redistribution of financial capital could exceed US$3 trillion per year with the aim of bridging the climate finance gap (refer Section 1.1).

● **Improving Systemic Stability:** During market turbulence, risk-averse investors can hedge their investment positions with XCR holdings, thereby redirecting financial capital towards decarbonization and giving the financial system some anti-fragility.

5.8 Potential Breakthroughs with Carbon Rewards

Reward Channel 1 of the carbon reward policy, introduced in Section 5.3 and Figure 9, represents a breakthrough in climate finance by proposing a global market for CDR based on a universal carbon price, financial scalability, and a level-playing field (refer to Figure 10). Reward Channel 2 of the policy (see Figure 9) complements Reward Channel 1 with unmatched flexibility for financing conventional mitigation projects across all sectors and industries that generate significant GHG emissions.

The policy options for applying Reward Channel 2 are vast. To illustrate the breakthrough potential of a carbon reward market, three examples are described below: (a) energy asset exchanges, (b) avoided deforestation initiatives, and (c) proactive decarbonization of hard-to-abate sectors. These examples exemplify the policy's capacity to address complex challenges, including the geopolitics of fossil fuel dependency, the need to stabilise natural carbon reservoirs, and the need to coordinate evolving clean technologies. The potency of Reward Channels 1 & 2 is based on their ability to bypass traditional fiscal constraints by mobilizing XCR grants and leveraging on cooperative opportunities. Policymakers and scholars may wish to explore other potential breakthroughs besides the three described below.

5.8.1 Energy Asset Exchanges

Energy asset exchanges are a major feature of the carbon reward policy because they are designed to circumvent the political, financial, technological, and institutional gridlock that is blocking the decarbonization of the energy sector (Unruh, 2000). Energy asset exchanges are a structured financial mechanism for transitioning from fossil fuel dependency to a resilient, clean energy system. The approach avoids fiscal burdens, avoids stranding assets, and transforms systemic risks into cooperative opportunities. For fossil-dependent corporates and governments, they would represent an orderly exit strategy.

At their core, energy asset exchanges operate by offering XCR grants as incentives for energy producers to retire fossil fuel assets and simultaneously construct new clean energy infrastructure of equivalent market value. This dual commitment is formalized through service contracts that specify a rolling 100-year retirement schedule for designated coal, oil, or gas reserves, alongside clear requirements for the deployment of clean energy assets tailored to sectoral demand or regional grid readiness.

Energy asset exchanges would address various Class 2, 3, and 4 risks outlined in the risk matrix for carbon (Figure 4). To give context to the Class 2 risk, consider that the International Energy Agency's net-zero roadmap for +1.5°C requires "No new oil and gas fields approved for development; no new coal mines or mine extensions" by 2021 (IEA, 2021). Yet, recent COP29 negotiations reveal that fossil fuel producers are reluctant to align with these targets (Mathiesen & Weise, 2024). A distinguishing feature of the Class 2 risk is the possibility of passing climate tipping points as a result of sustained fossil fuel extraction and combustion (Armstrong McKay et al., 2022; Lenton et al., 2019; Wunderling et al., 2021).

To address the Class 2 risk, energy asset exchanges would be offered to fossil fuel producers—state and private—to accelerate the clean energy transition. Strategic working groups within the CEA, comprised of representatives from both energy-producing and energy-consuming sectors, would coordinate their planning efforts to match energy supply with demand across sectors. This coordination would aim to ensure that the reduction in fossil fuels being supplied is matched by a commensurate increase in clean energy capacity, thereby averting price rebounds in fossil energy markets, and more generally to avoid energy price shocks during the transition.

The recommended strategy for managing these energy asset exchanges is to rank fossil energy reserves in terms of their size, quality, market value, expected rent/profit, socio-ecological externalities, and the clean energy asset of approximate equal value. The CEA would then target these fossil energy reserves with cost-effective energy asset exchanges. Reverse auctions would be used if competitive bidding can improve their cost-effectiveness. The CEA might elect to enter into direct negotiations with energy producers to expedite energy asset exchanges. The main focus of negotiations would be estimating the fair value of the fossil energy reserves, setting the reward multiplier (R), and scoping new clean energy assets. The reverse auctions and negotiations would be managed by specialist and cross-sector working groups who would guide the project R values and design of contracts. Meanwhile, energy demand forecasts provided by energy-intensive sectors would guide the siting and timing of new clean energy assets, ensuring that energy systems remain balanced and resilient throughout the transition.

To mitigate Class 3 risks—such as project insolvency—XCR grants would consist of (a) ex-ante grants that are tied to the completion of project milestones, spanning from feasibility assessments through to commissioning and long-term monitoring, and (b) ex-post grants that are tied to verifiable carbon mitigation outcomes. The milestone-driven payment structure would secure future XCR revenues and would foster responsible project management, mitigate financial volatility for asset owners and investors, attract debt and equity financing, and reduce the risk of project delays or abandonment. To further mitigate Class 3 risks, the energy asset exchanges would be prioritized for developing countries that would most benefit from technology transfer, sustainable development, and debt relief.

To mitigate Class 4 risk—local, societal and ecological instabilities—XCR grants would be prioritized for fossil energy reserves that could cause significant ecological damage if extracted. XCR grants would be tied to ecological safeguards, introduced to govern site selection for new renewable energy assets, thereby avoiding biodiversity loss, water stress, and community displacement. Beyond harm avoidance, the R value of projects would be adjusted to encourage regenerative innovations. For example, supporting the restoration of pollinator habitats near solar farms or other ecosystem resilience initiatives. This approach ensures that the transition delivers tangible benefits to local communities and ecosystems.

5.8.2 Avoided Deforestation Initiatives

Protecting large rainforests in the Amazon, Congo Basin, and other regions is a critical global priority due to their role as carbon stores, biodiversity hubs, and climate regulators (Rosa et al., 2016; Scheidel & Gingrich, 2020). Avoiding deforestation—primarily driven by logging for cattle, palm oil, and soybean agriculture—requires adaptive policies, as traditional approaches often fail due to enforcement gaps, financing issues, and carbon leakage (Bueno et al., 2021; Ritchie, 2021). The carbon reward policy addresses this by offering XCR grants (Reward Channel 2) for avoided deforestation initiatives based on 100-year rolling contracts and top-down and bottom-up risk management strategies. These strategies would move beyond traditional carbon markets by responding to the Class 2, 3 and 4 risks in Figure 4.

In relation to Class 2 risks—such as non-linear climate feedbacks, deforestation-induced water scarcity, and forest-to-savanna transitions—the CEA would respond with a top-down approach of providing (a) XCR grant allocations per km^2 and covering large areas, (b) XCR grants supporting ecosystem regeneration and integrity, (c) XCR grants adapting to protect high-risk zones, such as at rainforest edges and near roads, and (d) avoiding carbon offsetting. When addressing Class 3 & 4 risks, the CEA would adopt a bottom-up risk management approach, including:

- **Integrated Landscape Approaches:** Encouraging proposals that combine forest protection with sustainable agriculture, non-timber forest products, regenerative land management, biodiversity protection, and community development, thereby reducing the underlying drivers of deforestation and forest degradation (e.g., Waeber et al., 2023).

- **Dynamic Threat Assessments:** Using real-time remote sensing to adjust rewards as threats evolve, ensuring that incentives remain effective as deforestation frontiers shift (e.g., Liu et al., 2025).

- **Transparent, Open-Source Monitoring:** Making all transactions, methodologies, and monitoring data publicly available to build trust, enable independent verification, and foster global cooperation (e.g., Reed et al., 2023).

The CEA would invite proposals from traditional land stewards, indigenous groups, communities, and conservation organisations, and the reward contracts would be offered to the most credible and cost-effective initiatives. The outcomes of these mitigation projects would be validated through remote sensing and ground-truthing. If preventable deforestation were to occur within a project area, then clawed-back provisions would apply to some rewards. On the other hand, if unpreventable deforestation were to occur, the mitigation project would be reviewed and strengthened with a more targeted strategy.

5.8.3 Proactive Decarbonisation of Hard-to-Abate Sectors

Decarbonizing hard-to-abate sectors, including heavy industry (e.g., steel, cement, and chemicals) and long-distance transport (e.g., shipping and aviation), is inherently difficult because emissions are coupled to the high-temperature and high-power chemical processes that underpin these sectors (Bataille et al., 2018; IRENA, 2024). Decarbonizing long-distance transport is additionally constrained by just-in-time logistics (IPCC WGIII, 2022; McKinnon et al., 2015). Decarbonising these sectors requires replacing or retrofitting heavy-duty, long-lived equipment to operate with low-carbon energy sources (e.g., renewable fuels) resulting in high capital costs (IEA, 2020; IPCC WGIII, 2022; IRENA, 2024), and overall, contributes to Class 1, 2 and 3 Risks (refer to Figure 4). Some emerging low-carbon technologies may also increase operating costs, impair performance, pose safety challenges, or create supply chain risks, especially when untested at commercial scale (IPCC WGIII, 2022).

The carbon reward policy presents a transformative solution for overcoming the financial barriers and coordination challenges (i.e., the coordination of new technologies and changing logistics) that have long hindered decarbonization in these sectors (a Class 3 risk; see Figure 4). The CEA (Section 5.7.1) would assume a proactive role by convening expert working groups to directly engage each hard-to-abate industry. Industry-specific working groups within the CEA would design mitigation roadmaps and reward contracts suited to the unique challenges of each industry. This is to ensure that incentives are cost-effective, aligned with the declared mitigation roadmap, and to avoid fragmented or duplicative efforts. By providing long-term contracts—based on conditional XCR grants underpinned by a guaranteed price floor—the policy provides the financial certainty needed to unlock investment in capital-intensive mitigation projects.

Unlike conventional carbon pricing, which imposes costs, the carbon reward policy provides positive financial incentives, coordinated by the CEA and underpinned by central bank guarantees. By distributing the costs of decarbonization across global financial markets, rather than concentrating them on consumers, industry, or governments, this approach could break the inertia of entrenched emissions-intensive infrastructure (Unruh, 2000) and address Class 1 & 3 Risks (refer to Figure 4). As participation in the carbon reward market grows and as technologies mature, costs are expected to decline (Bataille et al., 2018; IEA, 2020), creating a reinforcing cycle that would enable more ambitious sectoral targets.

Through open calls for proposals, the CEA will assess the technological, financial, and logistical feasibility of decarbonization projects. Tailored carbon reward contracts will be developed collaboratively, offering XCR grants based on a mix of milestones and mitigation outcomes. These contracts will feature periodic reporting, third-party verification, and provisions for adjusting rewards as technology costs fall or supply chain challenges are resolved. Organizations will assemble portfolios of mitigation projects, each receiving XCR grants sufficient to cover the expected additional costs. Examples include (ETC, 2020; IMO, 2021):

- A steelmaker phases in green hydrogen direct reduction (H-DRI) with electric furnaces in regions with abundant low-cost renewables, targeting full primary steel decarbonisation as electrolyser costs fall and clusters provide shared hydrogen and power infrastructure:

- A cement producer deploys high-capture CCS on kilns while increasing clinker substitution with alternative binders and supplementary cementitious materials to cut both process and fuel emissions at scale.

- A global shipping operator retrofits vessels for efficiency and transitions from oil to zero-carbon fuels by adopting ammonia or e-methanol on deep-sea routes, supported by green fuel bunkering hubs and IMO-consistent fuel pathways.

- An aviation company scales sustainable aviation fuels (advanced biofuels and power-to-liquids) for long-haul while electrifying short-haul and regional operations as batteries improve, anchored by airport green-energy hubs and offtake contracts.

Grants will combine upfront (ex-ante) rewards for milestones—such as infrastructure build-out and supply chain scaling—and performance-based (ex-post) rewards linked to emissions reductions. The reward multiplier (R) will be calibrated to reflect the higher costs and risks of early-stage projects, then reduced as technologies mature and scale. The approach allows organizations to secure debt and equity financing anchored by the reliable, multi-decade XCR price floor, justifying both capital investment and ongoing operational costs over the 100-year durability standard. Competitive mechanisms such as reverse auctions may be used to ensure that rewards are allocated efficiently, driving innovation and accelerating the adoption of breakthrough technologies.

In summary, the adaptive, contract-based carbon reward policy delivers the financial certainty, coordinated planning, and market-driven incentives required for mitigating the systemic risks associated with carbon-intensive heavy industries and long-distance transportation. By aligning profit motives with climate objectives, the policy could transform hard-to-abate sectors from laggards into inspirational leaders of a net-zero transition.

6. Preliminary Assessment of the Carbon Reward Policy

6.1 Assessment Approach

Section 6 presents a preliminary assessment of the carbon reward's capacity to manage the systemic risks previously identified in the risk matrix (Figure 7c). The assessment approach has two parts. The first part (see Sections 6.2-6.5) examines the policy's risk management potential with hypothetical scenarios. The assessment considers: Class 1 Risk (global, societal), Class 2 Risk (global, earth-system), Class 3 Risk (local, societal), and Class 4 Risk (local, earth-system). This part of the assessment highlights how the policy's reward channels can be adapted to manage a diverse spectrum of climate threats, ranging from geopolitical gridlock and tipping points to local instabilities in communities and ecosystems. The second part of the assessment (see Section 6.6) provides a preliminary estimate of the policy-induced monetary inflation (π) that can arise when central banks apply carbon quantitative easing (CQE) to guarantee the XCR price floor. The methodology for estimating π is based on the quantity theory of money and assumptions regarding the financial pathway for spanning the climate finance gap reported by the Climate Policy Initiative (Naran et al., 2024). Appendix D details the formulas, data sources, assumptions, and calculations adopted in the estimation of π.

6.2 Management of Class 1 Risk

Class 1 Risk refers to global, societal systemic risks to the carbon cycle (refer Figure 4). Five examples are presented in Table 3, including geopolitical gridlock in climate finance and north-south economic disparity. These Class 1 risks are matched with responses focused on debt-free finance, pragmatic agreements, and mutual cooperation.

Table 3. Management of Class 1 Risk with Carbon Rewards: Validation Examples

<table>
<tr><th>Global, Societal Systemic Risks</th><th>Recommended Policy Responses</th></tr>
<tr><td>(a) The Paris Agreement's (PA) climate goals are inhibited by political gridlock, and there is a climate finance requirement of about US$9 trillion annually by 2030, and rising thereafter.</td><td>Offer carbon rewards as long-term conditional grants for implementing a declared mitigation roadmap, and without imposing direct costs on private or public stakeholders, including governments.</td></tr>
<tr><td>(b) The world economy is structurally dependent on fossil fuels, including associated financial flows, contractual agreements, infrastructure, and supply chains.</td><td>Offer carbon rewards for energy asset exchanges (see Section 5.8.1) and sectoral decarbonisation, under Reward Channel 2, and in a manner that balances energy supply with energy demand.</td></tr>
<tr><td>(c) Historical fossil fuel use and carbon emissions are unequal at the country level, resulting in an unfair burden on developing countries, especially developing countries that experience relatively high costs for trying to decarbonise.</td><td rowspan="2">● Carbon rewards are debt-free and convertible with hard currencies, and so can reduce debt stress.
● Projects that are suitable for developing countries can be developed under Reward Channels 1 & 2. For example, CDR projects that use natural methods might improve soil health, crop yields, and provide decentralised revenue for rural communities.
● Develop 'Robin Hood' systems in developing countries under Reward Channel 3 to incentivise social, ecological, and industrial co-benefits. For example, to promote technology transfer and sustainable employment.</td></tr>
<tr><td>(d) Dollar-denominated loans are common in developing countries, contributing to exchange rate risk, debt stress, austerity in essential services, and consequently a reliance on extractive primary industries that can have harmful social impacts.</td></tr>
<tr><td>(e) Trade barriers, trade tariffs, geopolitical blocks, and wars can act as barriers to international decarbonisation efforts.</td><td>Seek legally binding international agreements that mandate central banks to guarantee the XCR price floor for managing the carbon balance and helping to stabilise the climate.</td></tr>
</table>

6.3 Management of Class 2 Risk

Class 2 Risk refers to global, earth-system risks to the carbon cycle (refer Figure 4). Two examples are presented in Table 4. These examples are the likely the most obvious in relation to earth systems, because they refer to the available carbon budget for avoiding climate thresholds and tipping points (IPCC WGIII, 2022). These Class 2 risks are matched with pragmatic responses, including the development of an adaptive mitigation roadmap tied to emerging scientific knowledge.

Table 4. Management of Class 2 Risk with Carbon Rewards: Validation Examples

<table>
<tr><th>Global, Earth-System Risks</th><th>Recommended Policy Responses</th></tr>
<tr><td>(a) The available carbon budget for avoiding dangerous global warming and ocean acidification is shrinking.</td><td rowspan="2">● Periodically update the declared mitigation roadmap and price floor to correspond to a relatively ‘safe’ carbon balance.
● Embed explicit risk tolerances in the mitigation roadmap and price floor to reflect tipping point uncertainty.
● Deploy complementary market and non-market policies, including a combination of carrot-and-stick incentives (Figures 6 & 8).
● Undertake a global media campaign to encourage the public and private sectors to invest in XCR.
● Broaden the reward market to include more industries and technologies.</td></tr>
<tr><td>(b) The available carbon budget for avoiding dangerous thresholds and climate tipping points is finite and difficult to forecast.</td></tr>
</table>

6.4 Management of Class 3 Risk

Class 3 Risk refers to local, societal systemic risks to the carbon cycle (refer Figure 4). Four examples are presented in Table 5, including two examples related to financial instabilities, and the second two referring to communities and mitigation projects. These Class 3 risks are matched with policy responses that are micro-financial, flexible, and invite bottom-up solutions.

Table 5. Management of Class 3 Risk with Carbon Rewards: Validation Examples

<table>
<tr><th>Local, Societal Systemic Risks</th><th>Recommended Policy Responses</th></tr>
<tr><td>(a) Financial markets are exposed to transition risks, such as from new policies, new regulations, rising compliance costs, and stranded assets.</td><td rowspan="2">● Establish the XCR as a highly-trusted asset by ensuring that all central banks are backing the XCR price floor.
● Minimise the transaction costs for wholesale and retail XCR investing, and thus attract broad participation in the XCR market for hedging against financial volatility while supporting climate mitigation at the same time.</td></tr>
<tr><td>(b) Financial markets are exposed to physical risks, such as climate damages, rising insurance costs, lost revenue, supply-chain shocks, and insolvencies.</td></tr>
<tr><td>(c) Low-carbon projects, such as for clean energy, can be destabilised by weather extremes, financial volatility, technological change, and supply-chain disruptions.</td><td>Offer milestone-based, conditional XCR grants under Reward Channel 2, calibrated to be cost effective and inclusive of project insurance costs.</td></tr>
<tr><td>(d) Communities can be destabilised by poverty, lost productivity, food or water insecurity, lack of essential services, diseases, ecosystem breakdown, etc.</td><td>Provide stakeholders with some ability to redistribute carbon rewards under Reward Channel 3 to incentivise and improve community wellbeing and adaptability.</td></tr>
</table>

6.5 Management of Class 4 Risk

Class 4 Risk refers to local, earth-system risks to the carbon cycle (refer Figure 4). Three examples are presented in Table 6, with references to forests, ecosystems and agriculture. These Class 4 risks are matched with policy responses that are micro-financial, flexible, and invite bottom-up solutions and regenerative practices—analogous to putting out a bushfire before it spreads.

Table 6. Management of Class 4 Risk with Carbon Rewards: Validation Examples

Local, Earth-System Risks	Recommended Policy Responses
(a) Deforestation and forest degradation are major contributors to ecosystem instability, carbon emissions, and biodiversity loss.	Offer carbon rewards for reforestation under Reward Channel 1, and avoided deforestation under Reward Channel 2. Use Reward Channel 3 to incentivise regenerative practices and local resilience.
(b) Ecosystems can be destabilised by many factors linked to resource extraction, pollution, deforestation, degradation, and climate change.	Enable the redistribution of carbon rewards amongst projects, under Reward Channel 3, to incentivise ecosystem protection and regeneration.
(c) Agricultural productivity can be destabilised by changing rainfall and temperature regimes, weather extremes, biodiversity loss, financial volatility, and other factors.	Offer carbon rewards, under Reward Channel 2, for reducing and avoiding carbon emissions with improved agricultural management. Introduce Reward Channel 3 to further support regenerative practices and adaptability.

6.6 Policy-Induced Monetary Inflation

6.6.1 Background

Important to note, is that XCR issuance does not expand monetary aggregates because it is not a currency; however, the carbon reward policy introduces a novel monetary dimension through its reliance on central bank guarantees for the XCR price floor based on carbon quantitative easing (CQE). If central banks deploy CQE, they would create M0 to purchase XCR in order to prevent the XCR spot price from falling below the price floor. The CQE process would create new bank reserves, M0 (base money) for the XCR purchases that would directly credit the bank deposit accounts of XCR sellers at their commercial banks. This would immediately increase M1 (narrow money) and subsequently expand M2 (broad money) through the banking system, creating policy-induced monetary inflation (π). Overall, the XCR exchanges and their clients would hold higher deposit balances, reflecting the expansion of M1 and M2. The details of how π was estimated in this study are provided in Appendix D.

This section examines the XCR price floor's role as an economic driver and provides a preliminary estimate of π that could result from the expansion of M0, M1, and M2 through CQE. This analysis was carried out for just one policy scenario: reaching +1.75°C by 2100, the mid-point of the PA climate goal. The analysis is based on a conservative measure of the aggregate money supply, intermediate between M1 and M2 (refer to Appendix D2.1).

6.6.2 Financial Pathways

The preliminary analysis includes the following two financial pathways to explore the sensitivity of π to the total volume of XCR issued for additional GHG mitigation:

- XCR is leveraged by conventional debt and equity finance on a 1:1 leverage, halving the XCR required for the same investment volume (as per Naran et al.'s 2024 estimate); and
- XCR fills 100% of the climate finance gap (as per Naran et al.'s 2024 estimate).

In the above two financial pathways, CDR is fully funded with XCR. This is based on a simplifying assumption that CDR will be unprofitable due to high input costs and lack of saleable products.

Other financial pathways were also considered based on hypothetical levels of private demand for the XCR in response to the price floor. This price floor is the policy's core economic driver, because it would provide a reliable price signal and attract private investment demand (refer to Figures 10 and D1). The XCR's yield, μ (annual percentage change in the price floor), is anchored to the globally averaged marginal cost of CDR required under the roadmap. This yield acts as the 'advertisement' to private investors, influencing investment and trading in XCR (see Figure D1).

As illustrated in Figure D1 (Appendix D), the estimated XCR price floor has three major phases: (1) a high yield phase (2025-2040) with $\mu > 5\%$, likely drawing strong private demand and crowding out other investments, like bonds; (2) a moderate yield phase (2040-2060) with $5\% > \mu > 0\%$, sustaining moderate demand; and (3) a late-century depreciation phase (c. 2060-2100) with

μ < 0%, reducing private interest and increasing reliance on central banks as 'buyers of last resort' via CQE. Beyond 2100, the price floor might stabilize ($\mu \approx$ 0%) if CDR is needed to neutralise a continuous stream of residual GHG emissions.

The ratio of the private ownership share, α (with the central bank share being 1-α), is used to parameterise alternative financial pathways. Lower values of α imply higher central bank ownership, and thus greater M1 (narrow money) and M2 (broad money) expansion via CQE. In all financial pathways, α in the high yield phase is assumed to be 100%, but after the high yield phase α is assumed to decline at a constant rate until reaching a minimum value in 2100. Four minimum α values, 80%, 60%, 40% and 20%, are considered for the year 2100 (see Table 7).

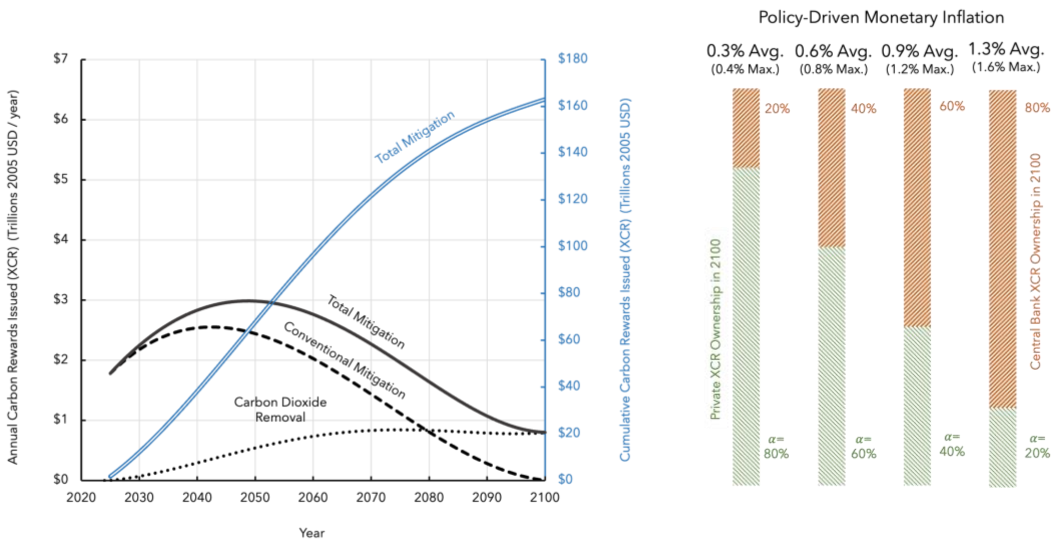
6.6.3 Preliminary Estimate

Monetary inflation (π) that results from CQE-induced monetary expansion was estimated using the quantity theory of money and a measure of the aggregate money supply intermediate between M1 and M2 (Appendix D2.1). The methodology, data, and key assumptions are described in Appendix D. Table 7 reports average annual π and maximum annual π over 2025-2100 under each pathway. Figures 11-12 depict annual XCR issuance for CDR and conventional mitigation, and the cumulative total (Trillions 2005 USD). XCR outlays are expressed in constant 2005 USD (i.e., not in XCR units). The annual volume of XCR units issued equals the annual reward issuance (see Figures 11-12) divided by that year's XCR price floor (see Figure D1).

Table 7. Estimated monetary inflation (π) for the Policy Scenario of +1.75°C by 2100.

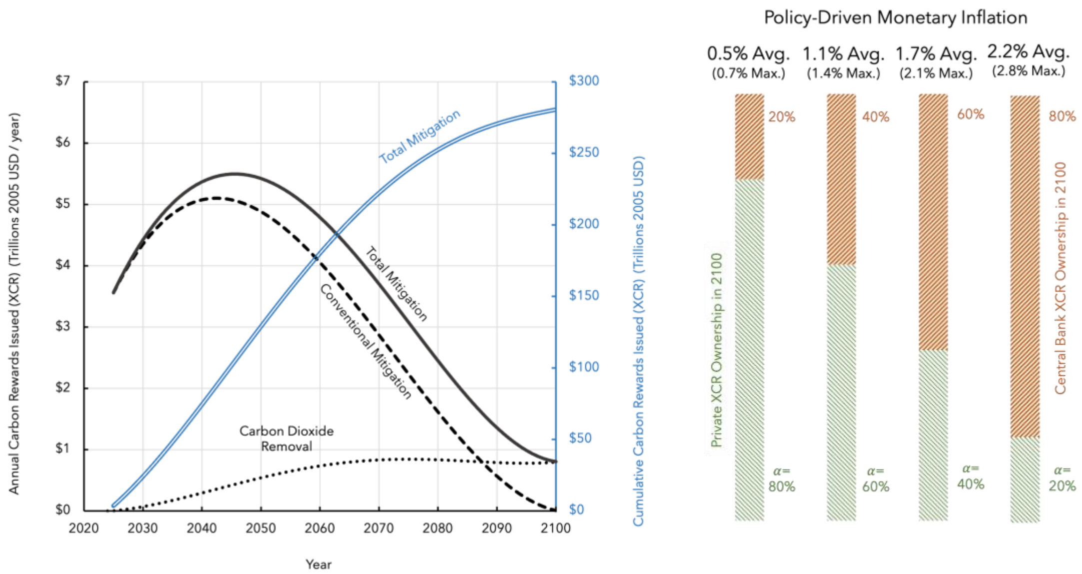
Min. Private Ownership[(a)] α (%)	XCR Filling ~50% of the Finance Gap		XCR Filling 100% of the Finance Gap	
	Avg. π (%)	Max. π (%)	Avg. π (%)	Max. π (%)
80%	0.3	0.4	0.5	0.7
60%	0.6	0.8	1.1	1.4
40%	0.9	1.2	1.7	2.1
20%	1.3	1.6	2.2	2.8

Footnotes:
(a) Refers to the assumed minimum level of private ownership, which occurs in year 2100.
(b) Years with zero π are ignored in the statistical averaging of π, and π estimates are based on smooth-curve interpolations of key economic variables (2025-2100) as described in Appendix D.
(c) See Figures 11-12 for XCR issuance over time (Trillions 2005 USD).



(a) XCR for filling ~50% of the climate finance gap (b) Monetary inflation estimates

Figure 11. Policy scenario for +1.75°C by 2100 and assuming XCR fills ~50% of the climate finance gap.



(a) XCR for filling 100% of the climate finance gap (b) Monetary inflation estimates

Figure 12. Policy scenario for +1.75°C by 2100 and assuming XCR fills 100% of the climate finance gap.

In the financial pathway that relies on XCR to fill 50% of the climate finance gap, cumulative XCR issuance reaches \$163T (2005 USD) by 2100, funding ~\$1.8-2.5T annually for conventional mitigation before 2050 (see Figure 11). After 2050, this annual cost is assumed to decline, reaching zero by 2100. On the other hand, CDR scales to ~10 $GtCO_2e$/year by 2100 to address residual GHG emissions, costing below \$0.90T annually (2005 USD). Average π ranges from 0.3% (80% private ownership) to 1.3% (20% private ownership), with corresponding peaks of 0.4-1.6% (see Table 7).

When XCR is used to fill 100% of the climate finance gap, the issuance of XCR nearly doubles to ~\$280T (2005 USD) by 2100, resulting in an average π of between 0.5% (80% private ownership) to 2.2% (20% private ownership) and corresponding peaks at 0.7-2.8% (see Table 7 & Figure 12).

6.7 Main Findings of the Assessment

This preliminary policy assessment—including hypothetical scenarios for risk management (Sections 6.2-6.5) and estimation of monetary inflation (Section 6.6)—suggests that the carbon reward policy is suitable for managing the systemic risks to the carbon cycle, described in Tables 3–6. The policy's design, including its reward channels and adaptive pricing mechanisms, appears capable of addressing Class 1 through Class 4 Risks based on the policy advice in Tables 3-6.

The preliminary analysis of monetary inflation (π)—while lacking an uncertainty analysis—indicates that π could remain modest, particularly if XCR issuance is leveraged with equivalent conventional finance, or if private ownership of XCR is relatively stable and exceeds 60%. Under these conditions, π appears to be less than one standard deviation of global inflation variability between 2000–2024 (averaged 3.9%; standard deviation 1.4%) according to data from the World Bank Group (2025). This suggests that π could represent a tolerable trade-off for avoiding hazardous climate change, especially when weighed against alternative scenarios that could include climate tipping points and far greater damages.

The π estimates in Table 7 are conservative by assuming an aggregate money supply that is only 50% of World GDP (M2 was 140% of World GDP in 2024; Table D1) and no monetary tightening (e.g., central bank balance-sheet management). Central banks, acting as market makers, would be required to defend the XCR price floor with CQE during low-demand periods, thereby expanding the money supply (M0, M1 and M2) and inducing π. To minimize reliance on CQE, central banks could also promote the investment appeal of XCR by developing new applications for XCR. Possible applications include XCR collateral eligibility, safekeeping accounts, stablecoins, and remittance services, and positioning XCR as an alternative to precious metals and cryptocurrencies. Overall, higher private ownership (>60%) would keep π within tolerable levels (0.6–1.1% average), as markets would absorb more costs through voluntary XCR purchases. Lower private ownership increases reliance on CQE, elevating π but distributing π and mitigation burdens equitably across economies.

These findings are mostly theoretical and warrant verification and validation. Policymakers, stakeholders, and scholars across the spectrum of the climate change debate are invited to review Tables 3–7 and Figures 11-12, propose new case studies, and pursue evidence-based research.

7. System-Level Verification

7.1 Thermoeconomics

The fields of thermodynamics and economics were historically regarded as distinct, with economics positioned as a social science and thermodynamics as a natural science. However, this separation is increasingly recognized as limiting, and a multidisciplinary field known as thermoeconomics has emerged to integrate the two (Frangopoulos & UNESCO, 2009; Glucina & Mayumi, 2010; Picallo-Perez et al., 2021). Thermoeconomics applies thermodynamic principles—especially concepts such as exergy, entropy, and energy efficiency—to economic analysis, enabling deeper insight into issues like the market failure in GHG emissions (e.g., Garrett, 2012, 2014) and systemic sustainability (e.g., Herbert et al., 2023).

The market failure in GHG emissions has a distinct thermodynamic character due to it being largely caused by the combustion of fossil fuels in the production of goods and services. In thermodynamic jargon, this production is the 'useful work' of 'heat engines.' Consequently, a thermoeconomics analysis was undertaken to partially verify the three matrices in Figure 7, including the damage matrix, risk matrix, and policy matrix. The key results are presented in Sections 7.2-7.4 below.

7.2 Markets as Open Systems

The first step in the system-level verification was to define the thermoeconomic systems relevant to the market failure and its correction with the carbon reward policy. The results are shown in Figures 13 & 14, with Reward Channels 1 and 2 presented in separate diagrams for visual clarity. For reasons of brevity, Figures 13 & 14 do not show Reward Channel 3 or any other market policy, initiative, law, or standard that might be needed for global decarbonisation.

In Figures 13 & 14, markets are represented as open systems, also called 'dissipative structures' after Prigogine & Stengers (1984). Three system types are shown: (A) heat engine, (B & C) negentropy engines (i.e., negative-entropy after Schrödinger (1944) and Brillouin (1953)), and (D) carbon-neutral engine. Definitions of these engine types are provided in Definition Boxes 11, 12 & 13, respectively. The two columns of the damage matrix and risk matrix in Figure 7 are partly verified by noting that the columns of the damage matrix (social vs. environmental domains) and risk matrix (societal vs. earth systems) correspond to the duality of system vs. surroundings, as shown in Figures 13 & 14.

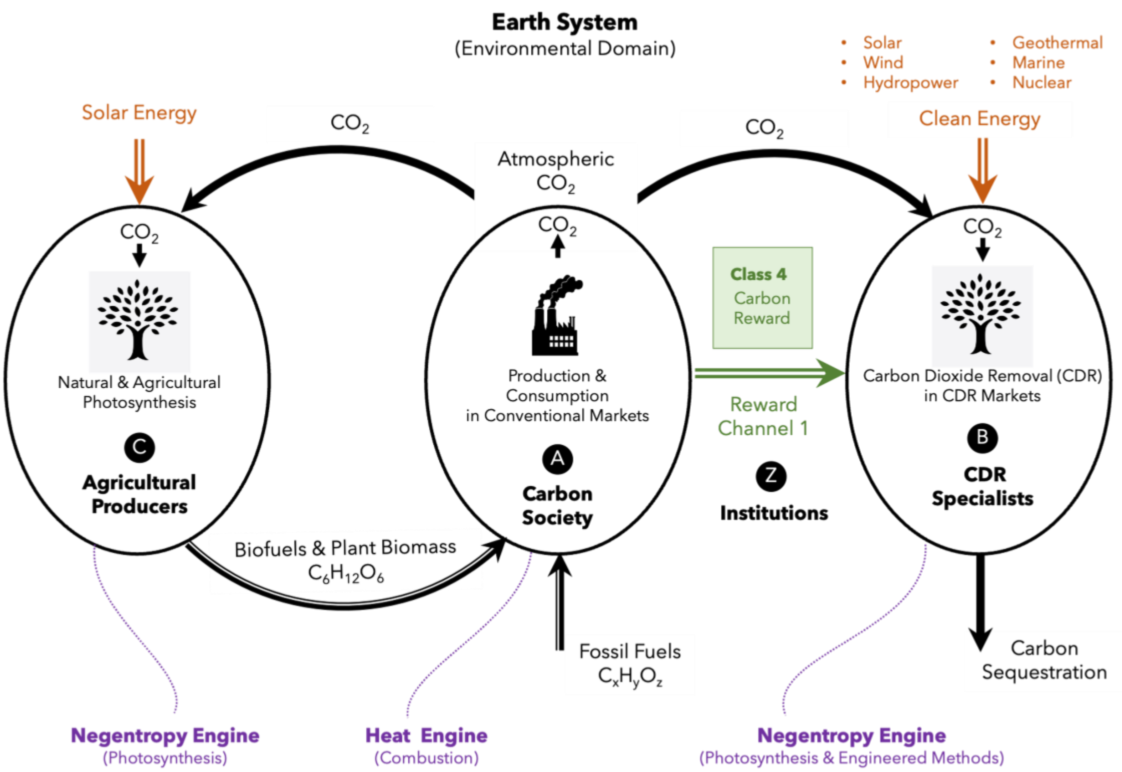


Figure 13. Markets shown as open systems, including (A) heat engine and (B, C) negentropy engines. Reward Channel 1 of the carbon reward policy is designed to redirect resources to B.

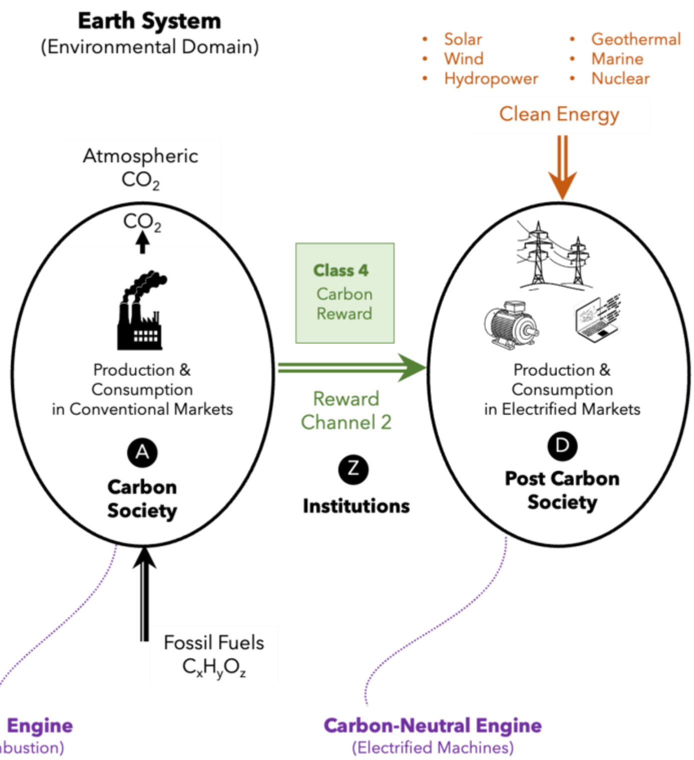


Figure 14. Markets shown as open systems, including (A) heat engine and (D) carbon-neutral engine. Reward Channel 2 of the carbon reward policy is designed to redirect resources to D.

Definition Box 11. Heat Engine

"A heat engine may be defined as a device that operates in a thermodynamic cycle and does a certain amount of net positive work as a result of heat transfer from a high-temperature body to a low-temperature body. Often the term heat engine is used in a broader sense to include all devices that produce work, either through heat transfer or combustion, even though the device does not operate in a thermodynamic cycle." (Van Wylen & Sonntag, 1986, p.159)

Footnotes:

(a) This type of engine is contextualised by the oxidation of fossil fuels and biofuels.

(b) The fossil fuels and biofuels are considered internal to the heat engine (an open system).

Definition Box 12. Negentropy Engine

A negentropy engine is defined here as an open system that absorbs external sources of clean energy, such as electricity and sunlight, to capture atmospheric CO_2 and store it in stable biomass and other durable forms. The negentropy engine creates a 'pocket' of ordered carbon within the open system, but at the cost of increasing the disorder (entropy) of the environment.

Footnotes:

(a) 'Negentropy engine' is not a standard scientific term (adapted from Brillouin, 1953)

(b) The archetypical negentropy engine is photosynthesis in the chloroplast of plants.

(c) Systems B & C in Figure 13 are negentropy engines.

Definition Box 13. Carbon-Neutral Engine

A carbon neutral engine is defined here as an open system that absorbs external sources of clean energy, such as electricity and sunlight, to do useful work on natural resources (matter) for creating goods and services. This useful work aims to produce goods and services that are attractive to consumers, and thus the notion of 'useful work' is socially framed. This useful work involves both the ordering and disordering of matter within the open system, and it results in increasing the disorder (entropy) of the environment.

Footnotes:

(a) The term 'carbon-neutral engine' is used in the transport sector (e.g., Y. Liu et al., 2025)

(b) System D in Figure 14 is a carbon-neutral engine.

The heat engine (see System A in Figures 13 & 14) represents market activities that combust carbon-based fuels and emit CO_2 to produce goods and services (e.g., Garrett, 2012, 2014). For visual clarity, all fossil fuel- or biofuel-dependent activities are lumped into System A (refer to Definition Box 11).

The negentropy engine (B in Figure 13) represents CDR activities that sequester and durably store CO_2 using clean energy (e.g., Keith et al., 2018). This CDR market would be needed to counteract residual CO_2 emissions and eventually achieve net-zero or net-negative CO_2 emissions (Definition Box 12).

The negentropy engine (C in Figure 13) represents photosynthesis that is involved in the production of biofuels and biomass for consumption (Definition Box 12).

The carbon-neutral engine (D in Figure 14) represents market activities that utilise clean energy to produce goods and services, and this open system is mostly structured by electrified machines. For reasons of simplicity and for visual clarity, all goods and services that are lumped into this system are assumed to produce zero CO_2 emissions (Definition Box 13).

The interaction of the three system types—the heat engine (A), two negentropy engines (B & C), and carbon-neutral engine (D)—is the foundation of a meta-system solution that is unique to this working paper. In this meta-system solution, net-zero or net-negative anthropogenic CO_2 is achieved by managing the CO_2 sources and sinks of Systems A, B, C, and D. This would require incentivizing CDR with Reward Channel 1, and conventional mitigation with Reward Channel 2. These financial incentives would have the effect of transferring resources from the heat engine (A) to the negentropy engine (B) and carbon-neutral engine (D), thereby 'shrinking' the heat engine over time.

7.3 Perceptions of Damage, Risk, and Reward

The second step in the system-level verification was to compare the various perceptions of damage, risk, and reward in Figures 13 & 14 with the damage matrix, risk matrix, and carbon reward policy:

- **(A) Carbon Society**: Actors in System A include organisations, firms, and members of society who produce or consume carbon intensive goods and services. Their perspectives are reflected in the damage matrix, referring to social welfare and material/moral values. These actors have an individual, rather than system-wide, perspective of risk. Thus, actors in System A are not associated with the risk matrix. Mitigators in System A may be eligible for carbon rewards via Reward Channel 2. These actors move into System D when they have fully decarbonised.

● **(B) CDR Specialists:** Actors in System B are CDR specialists, focused on CO_2 removals and storage, and are eligible for rewards via Reward Channel 1. The perspective of these actors is reflected in the damage matrix, but not in the risk matrix, similar to the actors in System A.

● **(C) Agricultural Producers:** Actors at this position include loggers and agricultural producers whose organic commodities can be sold to System A. Most of the organic carbon contained in these commodities is re-emitted to the atmosphere when consumed. Certain of these actors can receive rewards via Reward Channel 1 by repurposing biomass for CDR, resulting in some of these actors moving to System B. Certain of these actors can receive rewards via Reward Channel 2 for avoided deforestation. The perspective of these actors is reflected in the damage matrix, but not in the risk matrix, similar to the actors in System A.

● **(D) Post-Carbon Society:** Actors at this position include organisations, firms, and members of society who produce or consume zero-carbon goods and services. Their perspectives are reflected in the damage matrix, referring to social welfare and material/moral values. These actors have an individual, rather than system-wide, perspective of risk, similar to the actors in System A. Since there are no polluters in System D, these actors are not eligible for rewards.

● **(Z) Institutions:** Actors at this position would include institutions administering the carbon reward market. These institutions are external to Systems A, B, C and D, and they are best situated for addressing the systemic risks detailed in the risk matrix (Figure 4) because they can administer the carbon rewards as a meta-system solution. These institutions may charge commissions on the rewards that they administer to ensure financial independence and continuity of the reward market. Actors at Z do not relate to the damage matrix because they are governing institutions and not firms or individuals.

To summarise, the expanded economic framework (Figure 7) is partly verified by comparing it with the thermoeconomic system diagram (Figures 13 & 14) and by showing that:

● the damage matrix corresponds to the actors at positions A, B, C, and D,

● the risk matrix is addressed by the institutional actors at position Z,

- mitigators at B may be eligible for rewards under Reward Channel 1, and
- mitigators at A and C may be eligible for rewards under Reward Channel 2.

7.4 Matrix Correlation for Policies and Energy

The third step in the system-level verification was to verify the policy matrix for carbon (see Figure 15c) by comparing it with the thermoeconomic system diagram (Figures 13 & 14) and Gibbs free energy (ΔG) (see Figure 15d). Gibbs free energy is widely used in chemistry and engineering to determine whether a reaction can proceed spontaneously at constant temperature and pressure (Atkins & De Paula, 2006). A reaction is considered spontaneous when $\Delta G < 0$, meaning it can proceed without external energy input (Atkins & De Paula, 2006). More precisely, ΔG represents the maximum amount of useful work obtainable from a chemical reaction under specified conditions. A reaction is non-spontaneous when $\Delta G > 0$, meaning it requires external energy to proceed.

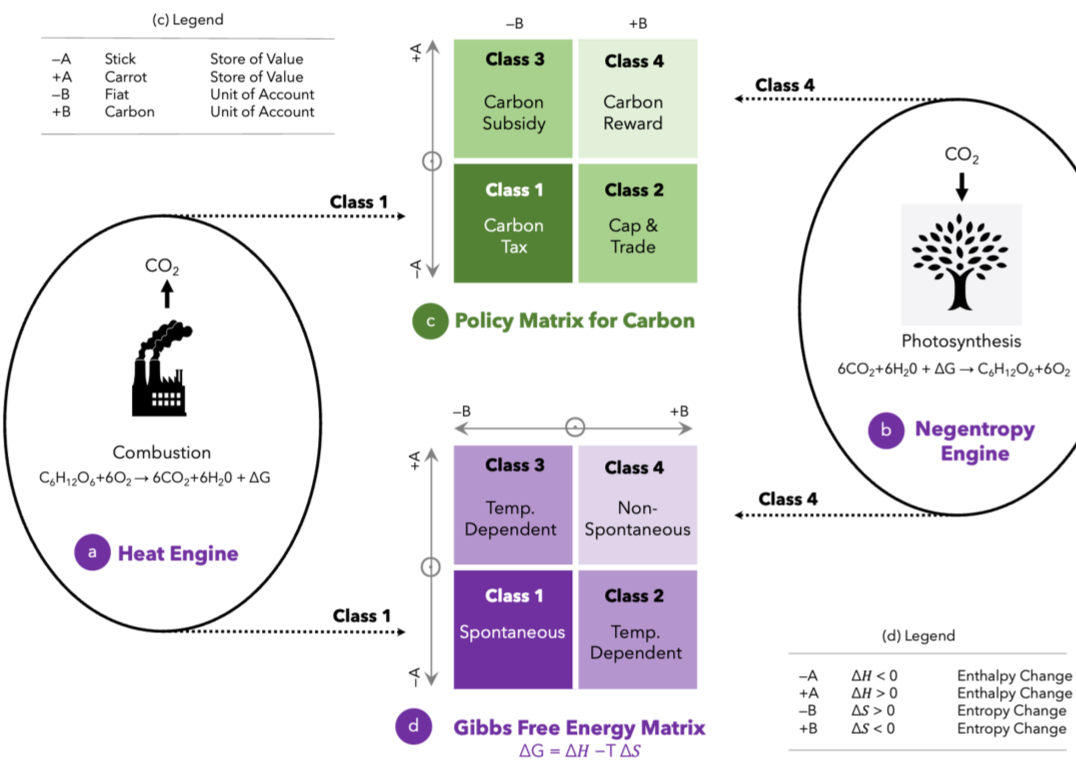


Figure 15. Policy matrix for carbon and Gibbs free energy matrix: (a) heat engine correlation, and (b) negentropy engine correlation.

Importantly, the outcomes of all chemical reactions can be classified within the ΔG matrix—based on the attributes of enthalpy change (ΔH) and entropy change (ΔS)—as shown in Figure 15d and Figure A5 of Appendix A. Within this ΔG matrix:

- Class 1 (ΔG < 0) corresponds to spontaneous reactions, where energy is released and can be used to do 'useful work.'
- Class 4 (ΔG > 0) corresponds to non-spontaneous reactions, which require external energy inputs to proceed.
- Classes 2 and 3 describe intermediate cases where spontaneity depends on temperature, leading to 'mixed' results.

The 2×2 policy matrix was compared with the 2×2 ΔG matrix to investigate their respective thermodynamic and economic outcomes (see Figure 15). Of particular interest are the Class 1-Class 1 and Class 4-Class 4 correlations. These correlations exist because both matrices identify the same emergent outcomes but through different methods: through market-based pricing in the case of the policy matrix, and spontaneity of reactions in the case of the ΔG matrix. Classes 2 and 3 of the two matrices do not appear to be correlated.

The Class 1-Class 1 correlation refers to a heat engine, as shown in Figure 15a and defined in Definition Box 11. Heat engines rely on spontaneous combustion reactions (ΔG < 0) to generate thermal gradients for doing mechanical work. These are not confined to historical steam engines, as the concept extends to the vast diversity of machines that burn organic fuels, as well as to organisms that respire using oxygen, such as humans, animals, and fungi. All of these rely on ΔG being negative: to release the stored chemical energy to do useful work.

Spontaneous combustion reactions (ΔG < 0) logically link to the carbon tax, Class 1 in the policy matrix, because a carbon tax is applied in markets that combust carbon-based fuels and emit CO_2, establishing a direct connection to ΔG. Moreover, the Pigouvian logic behind the tax is to internalize the SCC with the goal of maximising social welfare. This logic has a hidden thermodynamic meaning. Maximising social welfare in this context implies prioritising the goods and services that result in less CO_2 emissions, thereby reducing climate damages and increasing social welfare. In this respect, the goal of Pigou is to increase the energy efficiency of the heat engine in terms of doing 'useful work' that produces fewer harmful side effects and more social welfare.

By contrast, Class 4 outcomes are associated with negentropy engines, like that shown in Figure 15b and defined in Definition Box 12. A negentropy engine reduces entropy within its boundaries by drawing useful energy from outside its system boundary to overcome an internal energy barrier ($\Delta G > 0$). Common examples include chloroplasts in plant cells (photosynthesis), refrigerators and air-conditioning systems that create cooled spaces, and computers that organise information by reducing local entropy.

When reinterpreted through a thermoeconomic lens, the relevant negentropy engines are those that remove and sequester atmospheric CO_2 by generating internal order as CO_2 is stored at the expense of external energy inputs. Photosynthesis is the archetypal CDR approach: it removes CO_2 from the atmosphere and organises it into biomass using sunlight. Many engineered CDR technologies—such as direct air capture (DAC) using potassium hydroxide chemistry or electrochemical separation methods—also fall within this category. Consequently, most CDR processes are non-spontaneous at the system level, and require significant external energy inputs to overcome positive ΔG's. This thermoeconomic logic corresponds to the carbon reward, Class 4 in the policy matrix, by targeting and financially rewarding non-spontaneous CO_2 removal processes that require external energy ($\Delta G > 0$). A positive incentive—a carrot—is required for negentropy engines precisely because they need energy to overcome their non-spontaneous chemistry. Without dedicated financial support, CDR will not achieve scale due to this energy cost.

The comparison suggests that the two rows of the policy matrix exist to ensure that the sign of the policy incentive (carrot or stick) matches the sign of ΔG, as follows:

- Heat engines ($\Delta G<0$, spontaneous) correspond with CO_2 emissions and negative incentives (carbon tax and cap-and-trade).
- Negentropy engines ($\Delta G > 0$, non-spontaneous) correspond with CO_2 removal and storage and positive incentives (carbon subsidy and carbon reward).

Similarly, the two columns of the policy matrix align the unit of account with what is valued:

- For heat engines, the relevant outcomes are goods and services valued in society, most effectively denominated in fiat currencies.
- For negentropy engines, the relevant outcome is the sequestration of CO_2 itself, best valued in a dedicated carbon unit (refer to Definition Boxes 8-9).

The above interpretations partly verify the policy matrix by showing that it is consistent with the thermodynamic and economic constraints of the real world.

8. Discussion

8.1 Implementing a Carbon Reward Market

8.1.1 'Climate Club' Scenario

The political feasibility of a carbon reward market cannot be verified until implementation is attempted. Nonetheless, the following three-phase implementation scenario was developed based on hypothetical storylines.

- **Pilot Launch (Phase 1):** A few countries form a climate club for piloting the carbon reward policy, including running tests on reward contracts, XCR price floor and private XCR trading. The first pilot is a high-visibility energy asset exchange (Section 5.8.1) launched in Ecuador's Yasuní National Park, aligning with Ecuador's commitment to halt oil and gas extraction in its biodiverse rainforests (Laastad, 2024). Subsequent pilots focus on avoided deforestation initiatives in Southeast Asia and the Congo Basin, targeting regions with significant carbon stocks and biodiversity value (IPCC WGII, 2023; Section 5.8.2).

- **Institutional Development (Phase 2):** By the fourth year, the Phase 1 pilots demonstrate success and attract global media attention, the climate club grows to include a dozen new member countries, among them a G7 nation. This expansion prompts the development of digital platforms to ensure transparency and scalability, as well as the establishment of key governing institutions: the Carbon Exchange Authority (CEA) and Central Bank Monetary-Carbon Alliance (Section 5.7). In parallel, UNFCCC guidance clarifies how Article 6 of the PA applies to the carbon reward market, clarifying the reward's role in valorising Nationally Determined Contributions (NDCs) and possible links to Internationally Transferred Mitigation Outcomes (ITMOs) and other carbon markets (United Nations, 2015; Figure 8).

- **Mainstream Adoption (Phase 3):** By the sixth year, the policy gains significant traction, driven by the economic incentives offered through XCR grants, which are a new source of foreign exchange revenue for participating countries. Crucially, the opportunity to valorise the early retirement of fossil fuel assets and financially de-risk investment portfolios attracts the support of some major energy companies and fossil fuel exporters. Additionally, grassroots demand from businesses and investors, motivated by the profit opportunities of carbon rewards, propels the policy into the political discourse and UNFCCC negotiations. The demonstrated potential of the policy to finance CDR and accelerate decarbonization in hard-to-abate sectors—such as heavy industry, agriculture, and energy production—further strengthens its appeal. Within a decade, the climate club expands to represent 80% of the world economy, setting humanity on a new trajectory for rapid, orderly decarbonization.

8.1.2 Optimism Bias or Objective Policymaking?

Achieving the Paris Agreement's (PA) climate goals, of targeting below 1.5-2°C of warming, necessitates rapid global decarbonization given that only 250–1,200 $GtCO_2$ (50% C.I.) remain for meeting PA goals (Lamboll et al., 2023). Compounding the urgency of the situation, global emissions reached a record 41.6 $GtCO_2$ in 2024 (Friedlingstein et al., 2025). Atmospheric CO_2 also rose by a record 3.75 ppm in 2023 (Lindsey, 2025), implying that the +1.5°C target is implausible without a temporary overshoot (Calvin et al., 2023). Despite these challenges, the carbon reward market would follow a non-binding mitigation roadmap, including a presumption that CDR can scale-up to neutralize future residual GHG emissions. This raises the question: is the policy troubled by optimism bias?

This paper contends that the policy's non-binding mitigation roadmap should be viewed, metaphorically, as a 'landscape to be traversed' and not a 'specific pathway.' This landscape metaphor acknowledges that coalition-building is essential for such a journey. The core argument is that countries and market actors need more economic certainty—assurances of financial viability—before they can commit to rapid decarbonization. Thus, by focusing on carbon rewards and a non-binding roadmap, rather than insisting on binding emissions targets, international cooperation is more likely to emerge.

Supporting the carbon reward policy does not obviate the need for binding limits on GHG emissions. Such limits are presumed to become more feasible once the carbon reward market has operated long enough to exert a political and cultural influence and to widen the Overton window. Seen within this context of emergent cooperation, the non-binding mitigation roadmap of the carbon reward policy reflects pragmatic objectivity—not naïve optimism.

8.1.3 Recommended Strategy for Carbon Dioxide Removal

Scientific forecasting of future GHG emissions affirms that large-scale CDR is indispensable for neutralizing residual CO_2 emissions and ultimately for achieving global net-zero for all GHG emissions (IPCC WGIII, 2022). Yet the implementation of CDR faces major challenges, including moral hazards, scalability risk, impermanence, side effects, and poor governance. In response to these challenges, the carbon reward policy deploys a three-pronged strategy, shown in Table 8, including (a) incentive alignment, (b) price-driven scalability, and (c) safeguards. This three-pronged strategy is neither optimistic nor pessimistic. Rather, it is objective because it accepts the need for large-scale CDR while responding to challenges with pragmatic responses.

Table 8. Carbon Reward Policy: Recommended Reponses for Carbon Dioxide Removal (CDR)

Challenges	Recommended Policy Responses
<u>Moral Hazards</u> ● CDR could be used as an excuse to delay conventional mitigation (Merk et al., 2019).	<u>Incentive Alignment</u> ● Polluting industries will be incentivised with flexible XCR grants via Reward Channel 2 (Section 5.3) to achieve vigorous decarbonisation rates. ● CDR providers will be incentivised with a global XCR price floor and proportional grants via Reward Channel 1 (Section 5.3) to achieve sufficient CDR rates. ● In summary, the reward rules will be designed to achieve a vigorous level of conventional mitigation and a minimal level of CDR for supporting the declared mitigation roadmap (Figure 9).
<u>Scalability Risk</u> ● CDR technologies are nascent, relatively expensive, and face technical challenges for overcoming thermodynamic and logistical barriers (IPCC WGIII, 2022).	<u>Price-Driven Scalability</u> ● The XCR price floor will be calibrated to attract a minimal but sufficient level of CDR, taking into account technological progress, natural resource constraints, and other variables likely to impact the cost of CDR into the future (Figure 10; Definition Box 7; Appendix B). ● A global R&D effort will be incentivised by the XCR price floor, thereby increasing the likelihood of significant technological advances that lower the cost of CDR and improving its scalability.

Table 8 (continued)

<table>
<tr><th>Challenges</th><th>Recommended Policy Responses</th></tr>
<tr><td><u>Impermanence</u>

● The long-term durability of CDR, especially nature-based CDR, is a concern (Matthews et al., 2023).</td><td rowspan="3"><u>Safeguards</u>

● The Carbon Exchange Authority (CEA) will develop and publish an official Carbon Exchange Standard (CES) for the measurement, reporting, accounting, and assessment of CDR outcomes (Section 5.7.1). The CES will be a composite standard, utilising other standards when effective and efficient.

● The adopted carbon reward accounting will include time-sensitive rules to ensure that CDR outcomes are measured in terms of a 100-year durability target (Section 5.5). This will include time-split rewards, milestone-driven rewards, pro-rata rewards, and clawback provisions (Section 5.6).

● A global R&D effort for improving the scalability and permanence of CDR will be incentivised by the XCR price floor (Figure 10).

● The CEA will provide good governance to avoid unsafe CDR and to limit the unwanted side-effects of CDR (Section 5.7.1).

● Reward Channel 3 of the policy—managed as ‘Robin Hood’ systems—will disincentivise harms and incentivise co-benefits to improve community wellbeing, ecosystem health, and industrial reliability (Section 5.3; Figure 9).</td></tr>
<tr><td><u>Side-Effects</u>

● Certain kinds of CDR require significant energy, land, and water resources, potentially leading to resource scarcity (Adun et al., 2024).</td></tr>
<tr><td><u>Poor Governance</u>

● CDR lacks international standards and oversight (Mace et al., 2021).</td></tr>
</table>

8.2 Possible Advances on Standard Economics

8.2.1 Carrots & Sticks for Cooperation

The expanded economic framework of this paper (Sections 3-4) is unique by presenting a policy toolkit that includes carrot-and-stick carbon pricing for a range of geopolitical scales, from local to global (see Figure 6). This framework includes an explicit claim that a carbon reward market would accelerate decarbonisation through its scalable financial mechanism. This claim rests on a hypothesis that carrot-and-stick carbon pricing can unlock profound levels of political and economic cooperation. Supporting this theory are the following deductions and observations:

- businesses and governments would not be fiscally burdened by a carbon reward market, potentially ending the self-reinforcing cycle of inaction (Figure 1);
- market participants that receive the carbon reward would, by design, have sufficient finance to manage the costs and risks of their mitigation projects (Section 5.3);
- scientific evidence indicates that starting with carrots and then adding sticks, will increase group cooperation, compared with other incentive options (Andreoni et al., 2003; X. Chen et al., 2015; Hilbe & Sigmund, 2010); and
- empirical evidence shows that policy mixes, especially those including price-based instruments, are the most successful in driving climate action (Stechemesser et al., 2024).

Standard (neoclassical) market theory overlooks the synergy of combining carrots and sticks, and lacks the scope to evaluate the carbon reward policy. Policymakers and scholars may wish to explore this synergy effect with policy studies and field trials, and especially with the aim of creating a self-reinforcing cycle of participation for GHG mitigation (Figure 1).

8.2.2 Recognising Systems as a Source of Risk

A unique and central feature of the expanded economic framework is the systemic externality (Definition Box 4). This new type of externality was introduced to account for political inertia that prolongs the market failure, and amplifying climate feedbacks that intensify the climate damages. With the introduction of the systemic externality, the market failure in carbon is actually considered to be a market-and-system failure (Definition Box 5).

The systemic externality, in terms of its social dimension, is evocative of the problem that Donella Meadows called ‘system traps’ (Meadows & Wright, 2009). A system trap refers to a political stalemate over a policy as a result of stakeholders having competing objectives. The systemic externality, as it applies to societal systems, is also relatable to a John Nash’s equilibrium in competitive games (Nash, 1950). This social equilibrium in games results when players are making self-interested strategic decisions based on what other players are doing—but no player being able to benefit by changing their own strategy.

Evidently, the idea that systems can block solutions is not new, however the potential breakthrough is to recognise that the standard economic theory cannot explain why the market failure in carbon is so hazardous in regards to persistent political obstruction and amplifying climate feedbacks. The following subsections explain how the systemic externality complements Pigou's (1920) market theory and the Coase Theorem (1960).

8.2.3 Coase Theorem in Risk Management

To illustrate how Coasean bargaining (Coase, 1960) can be used in risk management, let’s consider (a) temperature futures (Dorfleitner & Wimmer, 2010), (b) catastrophe bonds (CAT bonds) (Coval et al., 2009), and (c) the carbon reward (Section 5). In a temperature futures contract, the right to receive payment for an unusual temperature event becomes a tradable asset. Similar logic applies to CAT bonds, where investors receive high returns unless a predefined catastrophe (like a major hurricane) occurs—in which case invested funds are redirected to cover the losses of insured parties. The first two instruments invite market actors to Coasean trading with these instruments. Stakeholders exposed to climate risks can transfer financial liability to investors, to insure themselves from weather extremes. The Coase Theorem holds that when property rights are well defined and transaction costs are low, market actors can negotiate and trade to reach Pareto efficient outcomes (Coase, 1960). Temperature futures and CAT bonds operationalize this principle by making insurance tradable.

The carbon reward market differs from temperature futures and CAT bonds in regards to the goal and who hedges. The goal of the carbon reward is physical mitigation (prevention) to remain within a relatively safe carbon budget (Section 5.3). The Carbon Exchange Authority (CEA) offers and issues XCR to achieve a certain amount of additional mitigation on aggregate (see Figure B4). Central banks provide the financial hedging by guaranteeing the XCR price floor with XCR purchases (see Figure 10). The voluntary trading of XCR in the FX, an example of Coasean bargaining, distributes the mitigation cost across the global financial system. This mitigation cost may also be viewed as a type of preventive insurance (see Section 8.3.2 for details).

8.2.4 Building on Pigouvian and Coasean Approaches

The policy matrix for carbon, reproduced in Figure 16, is part of the expanded economic framework for resolving the market-and-system failure in greenhouse gas (GHG) emissions (Definition Box 5). Important questions are whether the policy matrix complements Pigou's (1920) original theory on externalities and the Coase Theorem on property rights (Coase, 1960), and whether the matrix can enhance the functioning of the economy. To address these questions, the externalities and objectives of the policy matrix were scrutinised to provide the following interpretations, but without a formal proof (see Figure 16 and Table 9).

The policy matrix in Figure 16 and Table 19 is comprised of Pigouvian policies (taxes and subsidies) and Coasean policies (cap-and-trade and carbon rewards). The policy matrix in Figure 16 builds on Pigou’s (1920) theory by proposing the existence of two concurrent externalities and emergence of primary and secondary objectives. These concurrent externalities are (a) the social cost of carbon (SCC) and (b) the risk cost of carbon (RCC). The corresponding objectives are: (a) maximizing social efficiency and (b) achieving systemic safety. Shifting from Pigou’s single objective approach to the current dual-objective model in Figure 16 aligns with common economic practice, where multi-objective optimizations are almost always managed as trade-offs. Trade-offs are needed when multiple objectives exist, because multiple objectives make it impossible to optimize all objectives simultaneously (Ehrgott et al., 2025; Petchrompo et al., 2022; Roy et al., 2023). When correcting this market failure, some social efficiency would be traded off to achieve greater systemic safety. A technical guide for the SCC and RCC, and the required trade-off, is provided in Appendix B.

The cap-and-trade policy (Class 2 in Figure 16) was originally developed by economists John Dales in 1968 (Dales, 2002) and W. David Montgomery (1972) by utilising the Coase Theorem. While Coase did not explicitly identify the cap-and-trade policy, his theorem asserts that with well-defined property rights and low transaction costs, a Pareto optimality will result regardless of the initial allocation of pollution permits in a cap-and-trade market. The carbon reward (Class 4 in Figure 16) also invokes the Coase Theorem by attracting voluntary XCR investing and trading. The carbon reward policy—with the XCR price floor being the advertised price signal—is designed to stimulate long-term private sector investment in XCR, thereby transferring private financial capital into GHG mitigation.

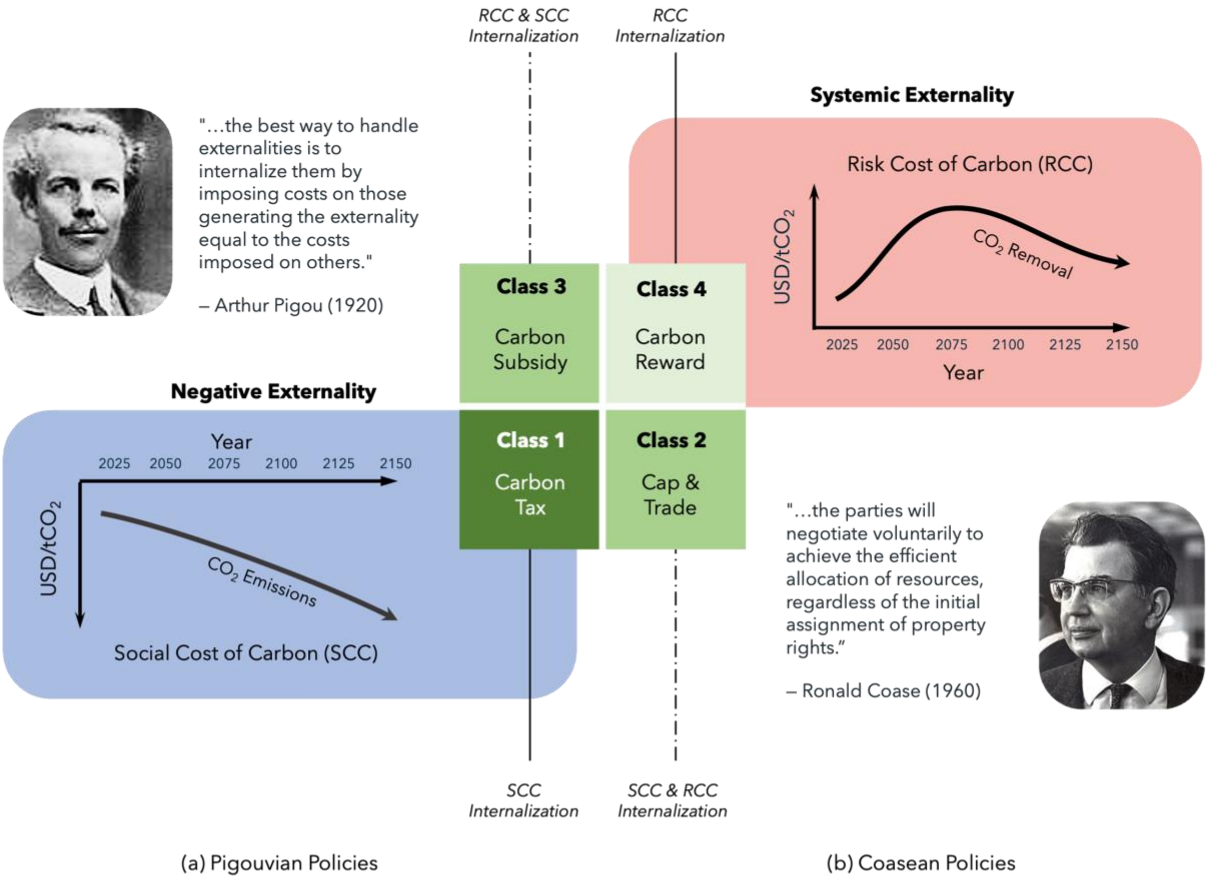


Figure 16. A market-and-system failure in carbon emissions: policy matrix for carbon (shown green), and the dual-externality thesis (see Table 9 for details).

Table 9. Policy Matrix for Carbon: Objectives, Externalities & Geopolitical Scales

Class	Policy	Objective	Primary Externality	Secondary Externality	Geopolitical Scale
1	Carbon Tax (Stick)	Social Efficiency	SCC	—	Local-National
2	Cap-and-Trade (Stick)	Mixed	SCC	RCC	Local-Regional
3	Carbon Subsidy (Carrot)	Mixed	RCC	SCC	Local-Regional
4	Carbon Reward (Carrot)	Systemic Safety	RCC	—	Multilateral-Global

Footnotes: (a) The market-and-system failure does not include a positive externality.

(b) A technical guide for the SCC and RCC is provided in Appendix B.

The XCR market will target private investors through both wholesale and retail channels (see Section 8.2.1): the wholesale segment aims to crowd-out traditional investments such as bonds, stocks, and precious metals, while the retail segment seeks to increase household savings and reduce household consumption. The intention is to use these XCR markets to reach a Pareto optimal redistribution of private finance to help cover the cost of GHG mitigation, regardless of the initial distribution of this finance. When private finance is insufficient, central banks provide the remainder through CQE (Definition Box 10). Beyond this Coasean interpretation, the anticipated utility of these XCR markets is to overcome political barriers and promote broad economic cooperation.

Policies with secondary objectives are said to have 'mixed objectives' (see Table 9). More specifically, the current interpretation is that policy Classes 1 & 2 can partially internalise the SCC as a primary objective, while Class 3 can partially internalise the SCC as a secondary objective. Conversely, the current interpretation is that policy Classes 3 & 4 can partially internalise the RCC as a primary objective, while Class 2 can partially internalise the RCC as a secondary objective. These interpretations follow the logic of the 2×2 outcome matrix, as outlined in Section 2.5 and Figure 2. Another important point, is that Pigou's positive externality is not included in the policy matrix because it is considered redundant in this context.

The policy matrix in Figure 16 addresses both externality types—RCC and SCC—without contradicting Pigou's original theory. The policy matrix is also consistent with the following nuanced observations regarding the real-world utility of market-based policies:

- It recognises that a mix of market-based policies can internalise a mix of costs and risks as an emergent outcome.

- It recognises the narrow Overton window for carbon taxes (Class 1). This challenge faced by carbon taxes appears logical when viewed through the policy matrix, because the matrix regards the carbon tax as being vulnerable to political obstruction, unsuitable for internalising the RCC, and only a partial solution to the market failure.

- It recognises that carbon subsidies (Class 3) are typically used to address specific economic barriers instead of following Pigou's externality model that seeks to achieve a socially efficient outcome. For example, carbon subsidies are often used to support R&D, new technologies, green jobs, and to provide financial certainty and attract private investment in nascent industries (e.g., IEA, 2023). These applications of carbon subsidies appear logical when viewed through the policy matrix, because the matrix regards the carbon subsidy as being useful for internalising a portion of the RCC (primarily) and SCC (secondarily) because it can overcome economic barriers to nascent industries and help finance a reduction in GHG emissions. However, the matrix also views the carbon subsidy as a partial solution because it is constrained by fiscal budgets and thus lacks scalability.

8.2.5 Addressing the Nordhaus-Weitzman Debate

The Nordhaus-Weitzman debate focuses on the risk of catastrophic climate damages in relation to 'fat tails' in the probability distributions for climate damages and the SCC (Nordhaus, 2017; Weitzman, 2011, 2014). Nordhaus, using his DICE model, argued for a relatively low SCC and a corresponding low carbon tax. In contrast, Weitzman warned that fat-tailed distributions could result in extreme, catastrophic outcomes, and he subsequently advocated for more stringent climate policies based on a 'precautionary principle.'

Recent studies, such as those by Keen (2021), Bilal & Känzig (2024), Moore et al. (2024) and others, indicate that Nordhaus's (2017) DICE model significantly underestimated climate damages and the SCC. These findings lend support to Weitzman's concerns about fat tails. However, even if the accuracy of integrated assessment models (IAMs) improves, the original debate remains unresolved because higher SCC estimates do not automatically translate into proportionally higher carbon taxes because of political resistance to rising taxes. Thus, real-world constraints limit the effectiveness of Pigou's tax and Weitzman's precautionary principle, when applied to GHG emissions.

It is claimed here that the Nordhaus-Weitzman debate was previously unresolved because Nordhaus and Weitzman did not address a dynamic coupling between the mean and the spread of the probability distributions for the climate damages and SCC. It is argued here that such a mean-spread coupling actually exists because of the systemic risks mentioned in Section 3.2, including persistent political and social resistance to strong mitigation policies, and the unpredictable, non-linear nature of climate dynamics. In other words, when improved IAMs suggest a higher mean SCC, this would logically require a higher carbon tax. However, a higher tax typically faces greater political opposition, creating a self-reinforcing cycle of inaction (Figure 1) and resulting in relatively high GHG emissions, stronger climate feedbacks, and a fatter tail (i.e. a larger spread) for the SCC. This mean-spread coupling and associated feedback loop increases the probability of severe damages.

This paper offers a potential resolution to the Nordhaus-Weitzman debate by acknowledging the mean-spread coupling and introducing the (Class 4) carbon reward for internalizing the RCC into the economy, as indicated in Figure 16. The carbon reward is specifically designed to address the catastrophic risk highlighted by Weitzman. The potential resolution includes all four policies of the policy matrix in Figure 16, including the (Class 1) carbon tax for internalizing the SCC into the economy. This potential resolution reclassifies the market failure as a market-and-system failure (Definition Box 5) and introduces carrots-and-sticks as a policy combination for breaking the mean-spread coupling problem. It also introduces a new social principle, called the 'preventive insurance principle,' as explained in Section 8.3.2.

8.2.6 Addressing the Nordhaus-Stern Debate

The Nordhaus-Stern debate centres on the social discount rate (SDR) used in economic assessments of the SCC (Heal & Millner, 2014; Nordhaus, 2007; Stern, 2014). Nordhaus advocated for a relatively high SDR (3-4%) as a key input into his DICE model, which led to a relatively low carbon tax and an 'optimal' warming trajectory of 3-4°C by 2100. In contrast, Stern argued for a low or near-zero SDR, resulting in a higher SCC and correspondingly higher carbon tax, with the aim of limiting warming to about 1.5°C. Nordhaus's relatively high SDR prioritises present welfare, whereas Stern's relatively low SDR emphasises long-term welfare and intergenerational equity. The political gridlock associated with carbon taxes is closely linked to this debate (refer Sections 8.2.1-8.2.5).

The policy matrix for carbon represents a structural resolution to the impasse between Nordhaus and Stern. The solution is to introduce the systemic externality, quantified by the RCC, and to contextualise the SCC and RCC by explaining why these costs exist (refer to Appendix B). The SCC, defined by Pigou's method (see System A in Figures 13 & 14), reflects a potential loss in social welfare. The RCC, on the other hand, is a cost that associates with managing societal and earth systems, and is therefore considered an institutional cost (see C in Figures 13 & 14).

The SDR is needed to estimate the SCC because people and businesses naturally time-discount. In contrast, the RCC is the cost of managing systems, and so the SDR is not needed in the estimation of the RCC (Definition Box 7). Instead, the RCC is based on a planning horizon for pricing CDR at the global level (Figure 10). The ideal planning horizon should (a) be long enough to encompass most of the global warming potential associated with GHG emissions, and (b) be forward-looking to communicate the long-term financial opportunities for markets, and the technological challenges for inventors. A planning horizon of 100 years rolling-forward is recommended in this working paper (Section 5.5).

Based on the above ideas, it is inferred that the Nordhaus–Stern debate over the preferred SDR is unresolvable if the economic framework is limited by Pigou's single objective of social welfare maximisation (i.e., internalising the SCC). The resolution offered here is to expand the economic framework by introducing the RCC and reclassifying the market failure as a market-and-system failure (Definition Box 5). With this reframing, the carbon reward policy introduces a 100-year planning horizon that does not involve time-discounting and thus resolves the SDR dilemma.

8.3 Addressing Key Knowledge Gaps

8.3.1 Overlooked Instrument: 'Carbon Reward'

Terms like carbon tax, cap-and-trade, subsidy, and carbon credit, are widely recognized, but the term 'carbon reward' is currently absent from economics textbooks and is rarely used in climate policy circles (see Appendix C for a detailed comparison of cap-and-trade with the carbon reward policy). This omission reflects a semantic void in the contemporary economics narrative. To help fill this semantic void, it is recommended here that a 'reward' be recognised as a specific type of market instrument that associates with mitigate-and-trade (Figure 6). To help bring the reward instrument into the mainstream policy lexicon, a concise definition of a carbon reward is provided in Definition Box 14. Scholars and policymakers are encouraged to consider whether the reward instrument may be suitable for addressing other market failures. For example, for addressing the market failures in nitrogen (Pannell, 2017) and phosphorus (Chatterjee, 2009).

The carbon reward may be communicated to stakeholders using the carbon market matrix in Figure 8 and the background information presented in Appendix A. A useful feature of Figure 8 is that it shows that the carbon reward does not support carbon offsetting. Offsetting is far from ideal for global decarbonization because it has a major limitation: it employs zero-sum arithmetic, where one entity's emissions reductions justify another entity's continued pollution. Related challenges include questionable additionality, uncertain long-term accountability, leakage risks, and temporal mismatches (Baras, 2024; Brander & Broekhoff, 2023). By contrast, the carbon reward creates a positive-sum framework by directly financing absolute GHG reductions, avoidance, and removals. It avoids offsetting and ensures long-term accountability with rolling 100-year contracts (Sections 5.5 & 5.6).

Definition Box 14. Carbon Reward Instrument

The carbon reward instrument, XCR, is a market instrument that can be used to incentivise GHG mitigation for remaining within a relatively 'safe' carbon budget. The XCR is supplied as conditional grants for carbon dioxide removal (CDR) and conventional GHG mitigation, and under long-term contracts. Thus, the XCR is:

- a market incentive, and
- a carbon-linked financial asset.

The XCR will have policy-driven economic value, but it will not be used to buy goods or services. Thus, the XCR is:

- not a medium-of-exchange, and
- not a currency.

The XCR will not transfer the ownership of mitigated carbon and will not be available for carbon offsetting. Thus, the XCR is:

- not a carbon credit.

The XCR will have a policy-driven price floor that is to be guaranteed by central banks via open market operations and supported by international agreements. Thus, the XCR instrument is:

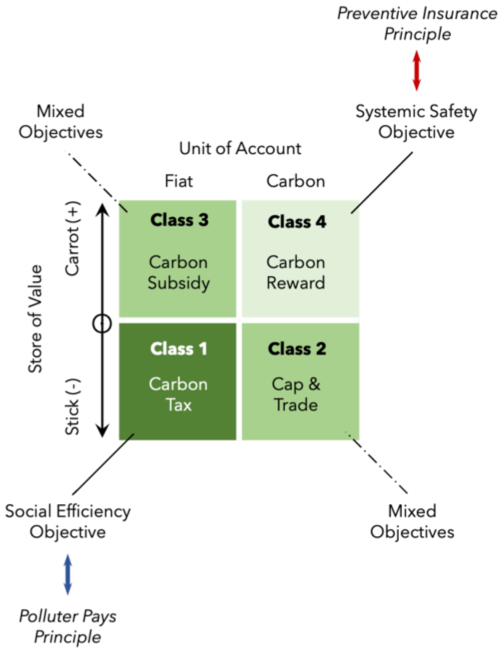
- a sovereign-backed asset.

With this guaranteed price floor, the XCR instrument will provide a predictable price signal for GHG mitigation in a primary market for XCR issuance, called the 'carbon reward market.' The same price floor will also attract private demand in a secondary market for XCR investing. This secondary market for XCR is anticipated to operate in foreign exchange (FX) markets where the XCR will be traded by private investors and central banks. Thus, the XCR instrument is:

- a limited-risk financial asset.

8.3.2 Overlooked Principle: 'Preventive Insurance'

The policy matrix's practical value depends on the feasibility of implementing a carbon reward market and the XCR price floor (Figures 10 & 15). Ideally, the XCR price floor would be guaranteed by central banks under a monetary-carbon alliance. Each central bank in this alliance would need a mandate to undertake carbon quantitative easing (CQE), as explained in Section 5.7.2. For convenience, this mandate is called a 'carbon mandate,' as shown in Figure 17.



(a) Policy Matrix for Carbon

Table. Inferred Mandates for Central Banks

Common Mandates:	Systemic Financial Stability, Price Stability & Economic Growth
New Mandate:	Systemic Safety in Carbon
Mandate Name:	'Carbon Mandate'
New Social Principle:	Preventive Insurance Principle
New Remit:	Monetary-Carbon Alliance
New Program:	Carbon Quantitative Easing (CQE)

(b) Inferred Mandates for Central Banks

Figure 17. The policy matrix for carbon and inferred mandate for central banks.

Social principles for contextualizing the carbon mandate were sought, and the following principles were considered as part of this study:

- Common but Differentiated Responsibilities (Stone, 2004)
- Intergenerational Equity (Asheim, 2010)
- UNESCO's Precautionary Principle (UNESCO, 2005)
- Biosphere Principles for Sustainable Development (e.g., Nerland et al., 2023).

Each of the above principles appears consistent with the notion of a carbon mandate however none of them contextualizes the carbon mandate in a manner that could be directly applied to central banks and financial regulators. This suggests that central banks and financial regulators may be missing an important social principle for responding to the climate crisis. For example, the 'polluter pays principle' (OECD, 2008) is used to give the carbon tax its ethical and legal context as a fiscal policy (Class 1 in Figure 16). To help contextualize the ethical and legal context of the carbon reward (Class 4 in Figure 16) a new social principle, called the 'preventive insurance principle,' is proposed in Definition Box 15 and Figure 17.

Definition Box 15. Preventive Insurance Principle

> The preventive insurance principle is defined as a social principle and legal assertion that governments, central banks, and financial regulators be required to (a) acknowledge that systemic risks to the carbon cycle are caused by societal systems and earth systems, and (b) accept responsibility for managing these systemic risks through appropriate policies, laws, mandates, alliances, remits, and programs. For additional clarity:
>
> - The word 'preventive' denotes that proactive financial support should be provided for leveraging mitigation solutions and addressing root causes.
> - The word 'insurance' denotes that systemic risks should be managed with a focus on hedging, with the financial hedging being undertaken by central banks.
> - The term 'preventive insurance' conveys that physical safeguards are needed to stabilise the climate and protect essential systems from cascading failures, including ecosystems, agriculture, insurance, finance, water supplies, etc.

The preventive insurance principle (Definition Box 15) has implications for the Network for Greening the Financial System (NGFS) because it aims to expand the mandates of central banks beyond that which is customary. For example, the NGFS (2024, p.6) advises that:

"Central banks take as given climate science, government policy, and their respective mandates. Central banks are not the experts on climate science. Instead, they are focused on how climate change affects the economy and the financial system, and therefore the achievement of their statutory objectives. On the policies needed to mitigate climate change, it is governments, not central banks, that are in the driving seat…"

The NGFS (2024, p.6) go on to say that:

"…While central bank mandates across the NGFS membership vary, one key aspect that unites all central banks is that as the impact of climate change and of the policies enacted to address it increases, it becomes an increasingly relevant consideration for monetary policy."

The NGFS (2024b) advises that central banks have a role to play in managing climate-related systemic risks of a financial nature, including transitional risk and physical risk (see Figure A4). In the expanded economic framework, these transitional risks and physical risks are considered Class 3 risks, as shown in Figure 4. Furthermore, with the preventive insurance principle, as defined in Definition Box 15, it is explicitly stated that that governments should mandate their central banks to support the carbon reward policy with financial hedging.

8.3.3 Overlooked Thermoeconomics: 'Carbon-Balanced Agnostic-Growth'

Garrett (2011, 2012) developed a thermoeconomic 'heat-engine' model of civilisation that links primary energy consumption to cumulative, inflation-adjusted world GDP, implying a tight coupling among economic production, energy demand, and CO_2 emissions at the aggregate level. In this heat engine model of Garrett (2011, 2012), civilisation is treated as a single open system. According to Garrett (2011, 2012), observed energy efficiency gains correlate with growth in aggregate energy consumption, thus a narrow strategy of improving efficiency is unlikely to yield absolute reductions in global CO_2 emissions: a conclusion that is even stronger than Jevons paradox, which is traditionally applied at the sectoral level (Jevons, 1866; Polimeni, 2008).

Garrett et al. (2020) estimate that holding global CO_2 emissions steady while allowing energy use to grow at recent rates would require adding roughly 480 GW/year of zero-carbon power (~1.3 GW/day). The IEA (2025) reports that around 700 GW of renewable capacity was added in 2024 (~1.9 GW/day of capacity). While the IEA's (2025) data reflect significant progress in global decarbonization, energy-related CO_2 emissions still rose in 2024 by about +0.8%, and so it is unclear when anthropogenic CO_2 emissions will peak. Moreover, Garrett et al. (2020) infer that atmospheric CO_2 is already committed to levels above 500 ppm and, without rapid decarbonization, passing 650 ppm by about 2040 is plausible based on current economic trends. These forecasts suggest that the PA goal of pursuing +1.5°C is effectively unachievable and that remaining well below +2°C becomes doubtful without an immediate acceleration of decarbonization and CDR.

The expanded economic framework presented in this working paper goes beyond the single heat-engine model of Garrett (2011, 2012) by proposing a meta-system that is comprised of four 'engines,' as shown in Figures 13 & 14, namely: (A) heat engine (conventional markets that burn fossil fuels), (B) negentropy engine (CDR markets), (C) negentropy engine (agricultural photosynthesis), and (D) carbon-neutral engine (clean electrified markets). The carbon reward, as described in Sections 5-7, was developed to establish the pairing of the (A) heat engine with the (B) negentropy engine and (D) carbon-neutral engine, resulting in a meta-system solution that provides 'carbon-balance agnostic-growth,' as defined in Definition Box 16. This 'pairing of engines' is based on:

- carbon reward finance for CDR via Reward Channel 1, as indicated in Figures 9 & 13, to address residual GHG emissions and emissions overshoot; and

● carbon reward finance for conventional decarbonisation via Reward Channel 2, as indicated in Figures 9 & 14, to rapidly reduce reliance on fossil fuels and carbon intensive technologies;

Definition Box 16. Carbon-Balanced Agnostic-Growth

Carbon-balanced agnostic-growth is a style of economic development that aims to remain within a relatively safe greenhouse gas (GHG) budget and avoid dangerous amplification of climate damages, as an overarching objective, rather than employ explicit GDP growth or degrowth strategies. The term 'agnostic-growth' (a-growth) was first coined by Van Den Bergh (2011, 2017). The term 'carbon-balanced' refers to managing GHG emissions and removals through layered carrot-and-stick incentives and associated laws, regulations, and standards. The layered incentives of carbon-balance agnostic-growth embed an explicit trade-off that favours long-term systemic safety over short-term social efficiency when these objectives are in conflict. It is important to note that carbon-balanced agnostic-growth does not purport to resolve all concerns related to planetary boundaries and social sustainability.

From a thermoeconomic perspective, carbon-balanced agnostic-growth pairs markets that behave as a 'heat engine' with markets that behave as a 'negentropy engine' or a 'carbon-neutral engine.' This pairing directs financial capital and tangible resources away from fossil-energy-consuming markets (heat engine) and towards CDR markets (negentropy engine) and electrified markets (carbon-neutral engine), thereby reducing GHG emissions in absolute terms. In this framework, carbon-balance agnostic-growth offers an alternative to the green-growth versus degrowth dichotomy by focusing on a meta-system that aims to balance GHG emitting markets with CDR markets and electrified markets. This meta-system is governed as a closed-loop control system that seeks a dynamic equilibrium in atmospheric GHGs while subject to physical constraints.

From a thermoeconomic perspective, the carbon-balance agnostic-growth (Definition Box 16) would require the transfer of natural and human resources from the (A) heat engine to the (B) negentropy engine and (D) carbon-neutral engine (Figures 13 & 14). This transfer of resources between open systems is inspired by biological symbiosis in green plants, corals, lichens, etc. For example, plants pair mitochondrial respiration in mesophyll cells, acting as sub-cellular heat engines, with chloroplast photosynthesis that captures solar energy and stores it in chemical bonds, acting as sub-cellular negentropy engines. Here, the concept of 'negentropy' follows the ideas presented by Schrödinger (1944). This biological symbiosis is an example of paired engines, with each engine performing complementary roles to sustain a dynamic equilibrium in carbon.

The meta-system solution in Figures 13 and 14, based on paired engines, presents a distinct approach. It differs from mainstream green-growth proposals that largely preserve current economic structures (OECD, 2015), and from degrowth strategies that primarily seek sustainability through planned reductions in material and energy throughput via a suite of socio-economic reforms (Kongshøj, 2023).

Carbon-balanced agnostic-growth contributes to the GDP debate by proposing a formal control architecture to manage the global carbon balance. Drawing on established control theory in engineering (Frank, 2018; Gao, 2014) and cybernetics (Wiener, 2019), this architecture specifies sensors to monitor outputs (e.g., atmospheric CO_2), a governor to compare outputs to set-points (e.g., preferred CO_2 concentrations), and actuators to adjust inputs (e.g., financial incentives), thereby aiming for dynamic, system-level regulation rather than unbounded or poorly managed economic development.

The carbon reward policy is designed to operationalise the above-mentioned control system principles: scientific and financial outcomes are continually monitored, the CEA interprets data against climate targets, the CEA adjusts the reward rules and prices (via Reward Channels 1–3), and central banks implement the price floor. This closed-loop governance is intended to ensure operational flexibility and persistent alignment with climate objectives. In summary, the key thermoeconomic concepts arising from carbon-balance agnostic-growth include:

- **Heat Engine:** Conventional markets that combust fossil fuels function as a global heat engine, and with tight coupling between GDP and fossil energy use.
- **Paired Engines:** The framework creates a coordinated pathway by linking the heat engine (refer above) with a negentropy engine (CDR markets) and a carbon-neutral engine (electrified markets).
- **Symbiosis:** The reciprocal exchange in systems like green plants, corals, lichens, etc.—between respiration and photosynthesis—exemplifies a biological analogue for achieving a dynamic equilibrium in carbon.
- **Control Systems:** The carbon reward policy is designed to act as a closed-loop control system, using dynamic information feedbacks to adjust market incentives.

Closed-loop control systems can outperform their open-loop counterparts because they are more adaptive when moving towards their stated objectives.

The above concepts are not explored further in this working paper for reasons of brevity, but they deserve more attention in the pursuit of a complete economic theory for managing carbon emissions and responding to climate change.

8.4 Recommendations for Policy Advancement

8.4.1 Business Planning & Scoping

To further advance the carbon reward policy, a business plan[4] and scoping study are recommended to identify opportunities to secure funding, partnerships, and good governance for developing, testing, and implementing a carbon reward (XCR) market. This may include:

● **Business Planning:** Invite governments, institutions, and private-sector firms to help develop and implement a business plan and governance strategy covering policy development, feasibility studies, pilots, digital platform development, and associated fundraising through philanthropic grants, donations, sponsorship[5], and revenue generation[6]. This business development may include training, certification, accreditation, RCC publication, copyright strategies, and digital platform licensing.

● **Scoping of Digital Platforms:** Define the required digital stack for the Carbon Exchange Authority (CEA) and market participants, including: XCR trading and settlement; XCR FinTech rails and FX connectivity; MRV with sensor integration and tamper-evident data; automated reward issuance; auditable ledgers and registries; long-term data archiving (100-year durability); standardized long-term contracts (time-split, milestone, pro-rata, clawback); governance and dispute-resolution tools; policing and fraud analytics; subcontractor onboarding

[4] Business planning and development will require expert tax and legal guidance to ensure compliance with applicable IRS regulations. For example, a 501(c)(3) nonprofit may facilitate the creation of a new for-profit entity provided the transaction is conducted at arm's length, the arrangement advances the mission of the charity, the nonprofit receives fair market value, and there is no private inurement or impermissible private benefit. This can be done without violating IRS rules or jeopardizing the nonprofit's tax-exempt status, provided all IRS requirements regarding legal separation, governance, and public benefit are met.

[5] U.S. 501(c)(3) organizations may accept corporate sponsorships, provided the arrangement does not constitute an "exchange of value" that primarily benefits the corporation. Sponsorships must be structured to comply with IRS rules on qualified sponsorship payments.

[6] References to "revenue generation" or other investment strategies is illustrative only of possible funding and scaling models for independent institutions or entities. A 501(c)(3) nonprofit is legally restricted from holding or managing investments for private return.

and training; and RCC estimation, publication, and versioning linked to the XCR price floor.

8.4.2 Research Activities

This policy paper provides a general introduction to the carbon reward policy and expanded economic framework; however, certain related topics were only covered superficially or may have been omitted. To complete the policy's development, documentation, and validation, the following research activities are recommended:

- **Economic Theory:** Develop an economists' guidebook to define the market-and-system failure (Definition Boxes 4-5), explain the expanded economic framework (Sections 3-4), and propose a policy taxonomy.

- **Policy Design:** Prepare a policymakers' guidebook outlining the policy's reward channels, reward rules, and strategies for decarbonizing each economic sector and industry of importance. The guidebook should describe the mandates of required institutions and governance systems, technical procedures for establishing the mitigation roadmap and XCR price floor, the design of an equitable CQE program (Sections 5-6), and the vulnerabilities of existing carbon markets.

- **Thermoeconomic Study:** Develop an analytical thermoeconomic model of the carbon reward policy, beginning with the framework shown in Figures 13 & 14. Related topics include the control system theory, Kaya identity, Jevons paradox, earth's energy imbalance, solar radiation management (SRM), circular economy, planetary boundaries, and climate tipping points.

To help validate the carbon reward policy, the following applied research is recommended:

- **Economic Assessment:** Develop a suitable integrated assessment model (IAM) to estimate the likely impact of CQE on the money supply and monetary inflation, as well as forecasting the future energy supplies, carbon emissions, CDR, climate damages, and climate-related inflation. Related topics include capital flows, world GDP, savings rate, employment, and resource limits.

- **Stakeholder Consultations:** Conduct stakeholder consultations to evaluate the policy's likely impact on decision-making in sectors and industries that contribute significantly to GHG emissions. Stakeholder may include business leaders, climate scientists, industry representatives, ecologists, diplomats, citizens, etc.

- **Expert Interviews:** Interview subject-matter experts to collect their views on the policy's political and technological feasibility; and the policy's compatibility with existing legal and financial frameworks, including the Paris Agreement and regulations that govern central banks, foreign exchange markets (FX), and international trade.

For testing the policy's effectiveness, it is recommended that governments and financial institutions design and initiate pilot programs based on the ideas presented in Sections 5.8 and 8.1.

9. Concluding Remarks

9.1 Key Insights

9.1.1 Potential Resolution

This working paper offers a potential resolution to the market failure in greenhouse gas (GHG) emissions. This resolution builds on Arthur C. Pigou's (1920) theory with new concepts (Section 2), describes the market failure in greater fidelity (Section 3), explains why it has been intractable (Sections 2-3), and offers a policy-driven resolution (Sections 4-7).

This resolution differs markedly from the mainstream narrative on climate change. While climate change has worsened in recent decades, the mainstream narrative has oscillated between pessimism and optimism. On the pessimistic side, the crisis is typically blamed on fossil fuel dependence, political inaction, and corporate profit-seeking. On the optimistic side, the solution is typically viewed as inexpensive renewable energy, electrification, electric vehicles, and impact finance. These popular narratives are ad hoc, however, because they mostly ignore Pigou's (1920) theory that the negative externality should be corrected with a tax or similar. Evidently, Pigou's theory has failed to attract broad international support or capture the public's imagination. The introduction of the expanded economic framework represents an opportunity to bring Pigou's foundational theory back into the public spotlight by complementing it with the policy matrix and the carbon reward.

9.1.2 Expanded Economic Framework

This working paper presents an expanded economic framework for the market failure in GHG emissions (Figure 7). This framework includes a damage matrix (Figure 3), a risk matrix (Figure 4), and a policy matrix (Figures 8 & 15–16). If found to be reliable, this framework should have far-reaching implications for climate policy and climate leadership because of its capacity to respond to climate damages, systemic risks, and the main goals of the Paris Agreement.

Key to this expanded framework is the reclassification of the market failure as a 'market-and-system failure' (Definition Box 5). This reclassification, with its emphasis on systems, results from the introduction of a second externality. The first externality is the negative externality, already familiar to economists and referring to unpriced damages imposed on society. The second, new externality is called a 'systemic externality' (Definition Box 4). This second externality refers to unpriced systemic risks caused by societal systems (e.g., political gridlock) and earth systems (e.g., climatic feedbacks). These are systemic risks that threaten the stability of the carbon cycle and amplify the negative externality (Definition Box 3). For reasons of brevity, the topics of co-benefits, climate adaptation, SRM, and governance are not explicitly addressed in this paper.

9.1.3 Matrix Approach

This working paper presents three 2×2 matrices for classifying climate damages, systemic risks, and policies (Figures 3, 4, & 6, respectively). Each matrix is comprised of four clearly defined outcomes: Class 1, Class 2, Class 3 and Class 4. These matrices are memorable, convenient, and potent, because they can be used to contextualize nuanced information and expedite communication between people working in different fields. Ultimately, these matrices could be used to establish new taxonomies in climate change, including in policymaking, climate science, finance, carbon markets, and politics. These three matrices are recommended as the 'signature diagrams' for communicating the expanded framework to economists, policymakers, and scientists.

The carbon market matrix (Figure 8) is a 3x4 matrix that expands on the policy matrix by including voluntary carbon markets, carbon credits, and offsetting. This larger matrix is recommended as the 'signature diagram' for communicating the expanded framework to private actors working in carbon markets.

9.1.4 Cooperation Deficit & Policy Matrix

A key feature of the expanded framework is the interpretation (and forecast) that a rising social cost of carbon (SCC) will provoke ever greater political resistance, which in turn will amplify the fat tail risk for the SCC. This interpretation is called the 'self-reinforcing cycle of inaction' (Figure 1) and it constitutes a cooperation deficit and possible 'blind spot' in economic philosophy. The expanded framework offers a resolution by positing that the strategic layering of carrot-and-stick policies can bypass the self-reinforcing cycle of inaction, and fill the cooperation deficit for responding proportionally to the climate crisis.

9.2 Carbon Reward Policy

9.2.1 Overview

The policy matrix introduces the carbon reward—a novel policy highlighted in the title of this paper. The carbon reward policy may be more recognizable to economists through its alternative name, mitigate-and-trade. The policy establishes in a financial carrot intended for international use. A key measure of the policy's success will be its ability to fill the annual climate finance gap of about US$4-5 trillion dollars per year until about 2050 (see Appendix D2.6)—without direct costs for stakeholders—and catalyse global action for remaining within a relatively safe carbon budget. It would be used to decarbonise each economic sector and industry, as described in Sections 5.8, 6.2-6.5 and 8.1.

Correcting the market-and-system failure with carbon rewards will require trade-offs that may attract concern from economists and pundits who believe that the only economic objective is the maximisation of social welfare. In this working paper, it is argued that this objective is inadequate when facing the climate crisis, and that the international discourse on human development should consider an economic trade-off for systemic safety.

9.2.2 Reward Instrument (XCR)

The market instrument of the carbon reward policy is a carbon-linked sovereign-backed asset, also called a 'carbon reward' and denoted 'XCR' (Table 2). Operationally, the policy should manage the XCR supply and demand, and this will involve guaranteeing the XCR price floor. The XCR has these important features and functions:

- it will incentivise carbon dioxide removal (CDR) at scale,
- it will incentivise conventional GHG mitigation at scale,
- it will valorise otherwise stranded fossil energy assets to improve cooperation,
- it will avoid carbon offsetting,
- it will be a limited-risk financial asset for trading in open markets, and
- it will not impose fiscal costs on governments or market actors.

9.2.3 Central Bank Mandates & Monetary Inflation

The proposed carbon mandate for central banks (Section 8.3.2; Figure 17) is likely to be the most provocative aspect of the carbon reward policy. This is because the new mandate is designed to give central banks the ability to guarantee the XCR price floor with carbon quantitative easing (CQE) (Definition Box 10). This mandate may appear provocative to those who believe that:

- the mandates of central banks should not change, or
- monetary inflation resulting from CQE is too risky.

Supporting the carbon mandate is the fact that central bank responsibilities have evolved significantly since the 17th century, when the first central banks were established to address the financial needs of national governments. For example, the Bank of England, founded in 1694, was created to raise war funds for their government (Goodhart, 2018). According to Goodhart (2011), central bank mandates have evolved across three stable epochs: Victorian gold-standard central banking, the mid-century era of government control, and the late-twentieth-century triumph of markets. It appears that central banks have always pursued price and financial stability, but the mix of instruments and institutional relationships has shifted after crises that reset their mandates. Today, central bank mandates are characterized by inflation targeting, last-resort lending, liquidity management, and interest-rate setting. With this historical perspective, the proposed carbon mandate (Section 8.3.2; Figure 17) may be seen as the inspiration for a fourth epoch in central banking to address the global climate crisis and associated systemic risks.

Supporting the carbon mandate is a preliminary estimate of monetary inflation induced by CQE (see Appendix D for the method and Section 6.6 for results). The estimated inflation is low-to-moderate and appears manageable (see Table 7 and Figures 11–12). This finding strengthens the case for CQE, the carbon mandate, and the carbon reward policy.

9.2.4 Why CQE is Not MMT

The proposed carbon mandate for central banks and associated CQE program (for supporting the XCR price floor; Section 5.7.2) is distinct from policies advocated under modern monetary theory (MMT). Some MMT proponents seek to consolidate the roles of government and central banks, based on the premise that a sovereign state issuing its own currency cannot run out of money (Lavoie, 2019). By contrast, the CQE entails no reduction of central bank independence at the national level, and it does not interfere with their existing mandates. CQE is an international monetary program that instructs all participating central banks to purchase specific volumes XCR at specific times. CQE seeks international cooperation between central banks because climate change is a global challenge that needs a global solution. This contrasts with MMT's national orientation, which provides tools for domestic investment (such as in renewable energy or green technology) but offers little guidance for managing the global carbon budget.

9.3 Resolving Debates

9.3.1 Dual-Externality Thesis

The expanded economic framework (Figures 7 & 16) is applied to three longstanding debates in climate change economics: (1) Nordhaus–Weitzman debate on catastrophic climate risks (Section 8.2.5), (2) Nordhaus–Stern debate on the social discount rate (SDR) (Section 8.2.6), and (3) the green growth versus degrowth debate (Section 9.3.4). These debates may be resolved by the dual-externality thesis, which claims that the negative externality (captured by the SCC) is complemented by a second externality, called the systemic externality (captured by the RCC) (refer to Figures 5, 7 & 16; Table 9). This implies that two externalities should be addressed in concert, requiring a trade-off. It is recommended here that this trade-off be managed through the policy matrix in Figure 16 and Table 9.

9.3.2 Nordhaus–Weitzman Debate on Catastrophic Risk

First, the expanded framework addresses the Nordhaus-Weitzman debate, discussed in Section 8.2.5, by proposing that the fat-tailed risks of climate damages should be attributed to unpriced systemic risks to the carbon cycle (RCC). Instead of relying on upward revisions to the climate damages (SCC) and associated carbon tax—an approach stymied by political resistance—the expanded framework introduces the carbon reward to internalise the RCC and avoid potentially catastrophic damages. The carbon reward internalizes the RCC via a price floor underpinned by central banks, thereby requiring central banks to hedge against the systemic risk using bank reserves (M0). In this framework, the 'preventive insurance principle' is advocated (Definition Box 15), rather than Weitzman's more general 'precautionary principle' (Weitzman, 2009a).

9.3.3 Nordhaus–Stern Debate on Social Time Discounting

Second, the Nordhaus-Stern debate, discussed in Section 8.2.6, is centred on the magnitude of the social discount rate (SDR) for discounting future climate damages and the SCC. Introducing the RCC—as the cost of managing systemic risk—reduces reliance on unusually low SDR values and relatively high carbon taxes. The SCC remains relevant for social welfare optimization and depends on the SDR, however the RCC is governed from the perspective of systems management and a rolling 100-year planning horizon (Section 8.2.6). This long-term planning horizon does not involve a SDR because internalising the RCC does not aim to optimise for social welfare. Complementing the SCC with the RCC moves beyond the original discounting controversy.

9.3.4 Green Growth versus Degrowth Debate

A third key consideration is the unresolved dichotomy between green growth and degrowth (as discussed in Section 8.3.3). This debate presents two contrasting approaches to economic development for environmental sustainability:

- Green-growth strategies mostly aim to decouple economic activity from environmental impacts while expanding GDP through green investment, efficiency gains, and resource reallocation (OECD, 2015).
- Degrowth strategies mostly aim to directly reduce production, consumption, and natural resource use to lower environmental impacts (Kongshøj, 2023).

Section 8.3.3 proposes an alternative pathway to manage the anthropogenic carbon balance, termed 'carbon-balanced agnostic-growth.' While the concept of agnostic-growth (or a-growth) for climate action was introduced by Van Den Bergh (2011, 2017), this new formulation is more specific. It explicitly adopts the meta-system solution (see Figures 13 & 14)—enabled by the carbon reward policy—as a complement to traditional policies and carbon markets (see Figure 8). This meta-system is designed to balance GHG sources and sinks across four specialized markets, which function as 'thermoeconomic engines' (refer to Definition Boxes 11–13):

(A) conventional markets reliant on fossil energy and biofuels,

(B) carbon dioxide removal (CDR) markets powered by clean energy,

(C) photosynthesis markets producing biofuels and biomass, and

(D) electrified markets powered by clean energy.

Carbon-balanced agnostic-growth offers a potential resolution to the green-growth vs. degrowth dichotomy within the carbon-energy nexus. It achieves this by reallocating resources from conventional markets (A) to CDR markets (B) via Reward Channel 1 (Section 5.3) and to electrified markets (D) via Reward Channel 2 (Section 5.3). Under this framework, aggregate GDP may rise or fall with no assumed target.

Structured by the carbon reward policy, carbon-balanced agnostic-growth is inclusive of other policies, including those in the carbon market matrix (Figure 8). It is important to note, however, that this development pathway does not purport to resolve all material resource constraints, planetary boundaries, or social provisioning issues. The policy does offer flexible opportunities to support communities, ecosystems, and industries via Reward Channel 3 (Section

5.3), which is introduced only briefly in this paper. The proposal for a Robin Hood-style reward redistribution system under Reward Channel 3 deserves further attention in future studies.

From a scholarly perspective, the benefits of carbon-balanced agnostic-growth may be understood through two key analogues (Sections 7.4 & 8.3.3):

- through the biological processes of respiration, photosynthesis, and symbiosis in ecosystems and associated homeostasis, and
- through engineered control systems that serve humanity.

These analogues provide a scientifically-grounded vision for sustainability in the carbon and energy domains. A more comprehensive analysis of this agnostic-growth model is warranted to fully assess its potential impacts on GHG emissions, GDP, primary energy, capital flows, employment, inflation, communities, ecosystems, and industries.

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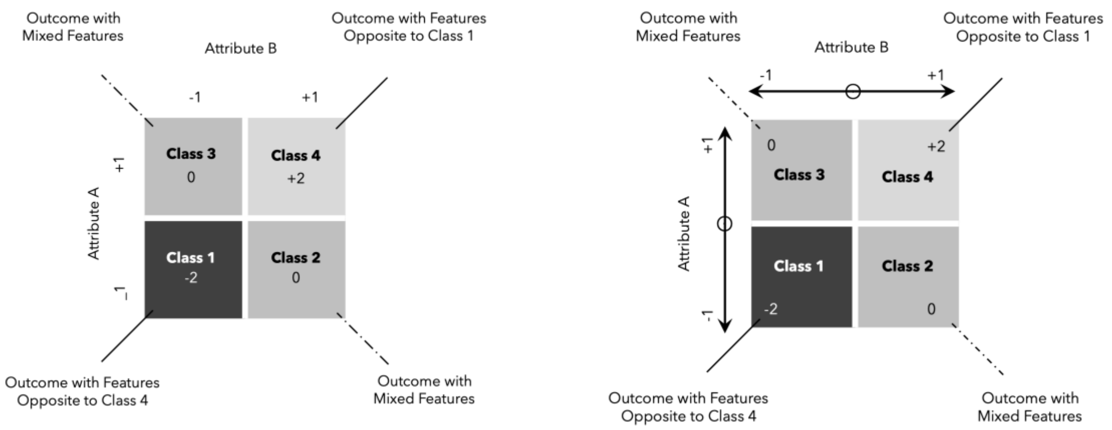
Appendix A. Two-by-Two Outcome Matrix & Examples

Appendix A provides additional clarification on the pattern recognition tool that underpins much of the expanded economic framework presented in this paper: the two-by-two (2×2) outcome matrix. As explained in Section 2.5, the 2×2 matrix was used to explore the market failure in carbon. It was chosen because it allows complex systems to be simplified into four outcome classes according to just two defining attributes. While deceptively simple, this matrix structure is powerful, because the compounding interaction of its two attributes yields emergent outcomes that can have recognisable opposing or mixed features. To help demonstrate its utility, four examples—taken from economics, decision making, risk management, and science—are presented in Figures A2-A5. Together, these examples demonstrate that the 2×2 outcome matrix can be a useful tool for understanding the emergent outcomes of certain complex systems.



(a) Attributes A and B are divisible into binary options.

(b). Attributes A and B are divisible into opposing value categories.

Figure A 1. The 2×2 outcome matrix for systems with attributes A and B that have compounding effects on outcomes.

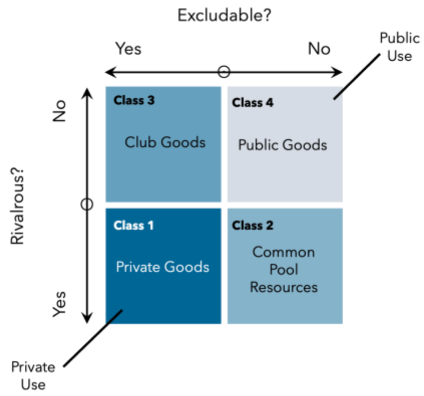


Figure A 2. Fourfold model of goods matrix (adapted from Mankiw, 2012).

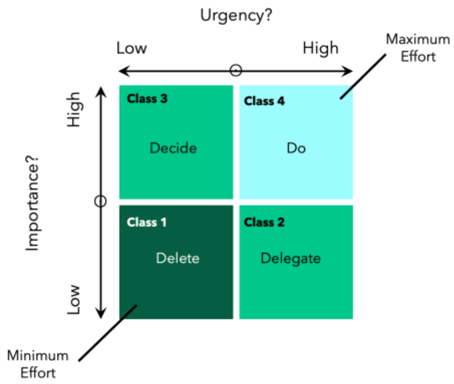


Figure A 3. Eisenhower decision matrix (adapted from Covey et al., 2003).

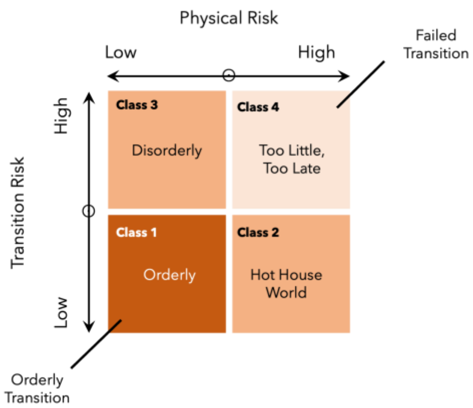


Figure A 4. NGFS systemic risk scenario matrix (adapted from Richters et al., 2022).

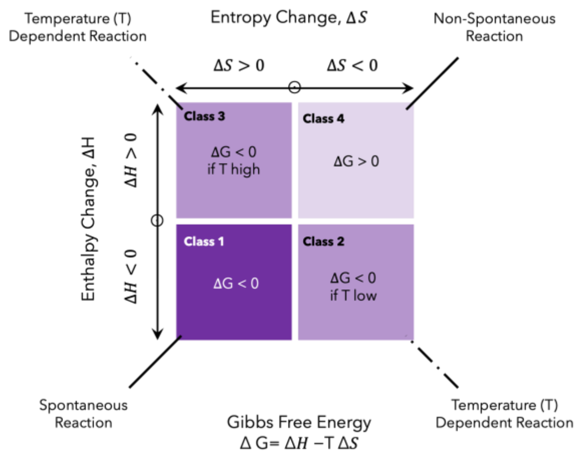


Figure A 5. Gibbs free energy matrix for the spontaneity of chemical reactions (see Atkins & De Paula, 2006 for a definition of Gibbs energy).

Appendix B. Technical Guide for the SCC & RCC

B1. Introduction

Appendix B provides a technical guide for the two externalities underpinning the policy toolkit presented in this paper: the social cost of carbon (SCC) and the risk cost of carbon (RCC). The aim is to clarify how the RCC complements the SCC, and why the carbon reward policy is needed to account for the profound uncertainty inherent in SCC estimates. By integrating the RCC alongside the SCC, the expanded framework enables policymakers to target not only immediate social costs (via the SCC) but also systemic and catastrophic climate risks (via the RCC). In this dual structure, the carbon reward is used to finance both conventional mitigation and carbon dioxide removal (CDR) at the scale and pace necessary to achieve long-term climate stability, even as profound uncertainty in the SCC persists.

To begin, consider that Pigouvian economics (after Pigou, 1920) requires that the ideal carbon tax for correcting the market failure in GHG emissions be determined using SCC estimates based on cost–benefit analysis (CBA), as illustrated in Figures B1 & B2. Whilst Pigou's approach may appear logical, it is argued in Section 2 and here that the SCC is undermined by high levels of uncertainty attributed to societal and earth system influences—including political gridlock over policies that involve rising taxes and other penalties, and potential climate feedbacks and tipping points. This uncertainty in the SCC limits the reliability of Pigou's method and it undermines the possibility of effectively managing risks through the SCC concept.

The RCC addresses the policy gap for risk management by providing an economic measure of systemic risk resulting from the dynamics of societal systems (e.g. political gridlock) and earth systems (e.g. amplifying climate feedbacks). The RCC is derived procedurally from the marginal cost of additional CDR that is sufficient to remain within a relatively safe carbon budget, as indicated in Figures B4-B5. It is essential to note that the additional CDR, denoted as ΔQ_{CDR}, requires the acceptance of a risk tolerance defined by the X^{th} percentile for ΔQ_{CDR} and denoted ΔQ^*_{CDR} (refer to Figure B4). It is also essential to note that ΔQ^*_{CDR} is itself coupled to an additional rate of conventional mitigation (ΔQ^*_{CONV}) that corresponds to a 'safe' carbon budget (see Eq. B1). This coupling between ΔQ^*_{CDR} and ΔQ^*_{CONV} is operationalised through the reward multiplier, R, which allows flexible and cost-effective pricing of conventional mitigation at the project level (see Figure B6).

B2. Conventional Risk Management with the SCC

The ideal carbon tax, based on Pigou's (1920) approach, is set where the marginal abatement cost (MAC) equals the social cost of carbon (SCC) (see Figure B1). Pigou's approach is framed by cost-benefit analysis (CBA) because it seeks a socially efficient market—but underestimating the SCC is a risk. This risk is conventionally addressed by adding a margin of safety to the SCC based on a shape of the SCC probability distribution and the policymaker's risk appetite (see Figure B2).

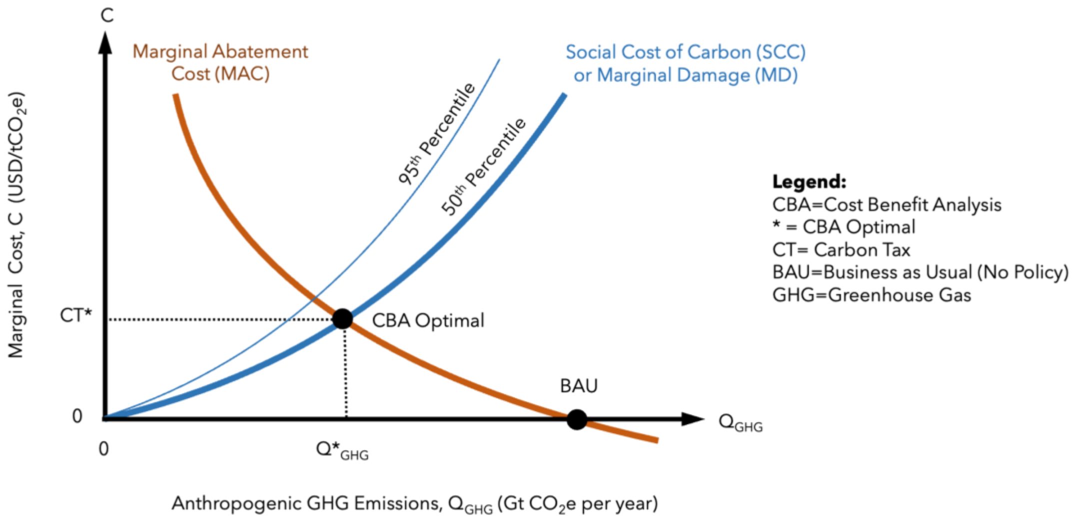


Figure B 1. Cost-benefit analysis (CBA) for determining the carbon tax (hypothetical).

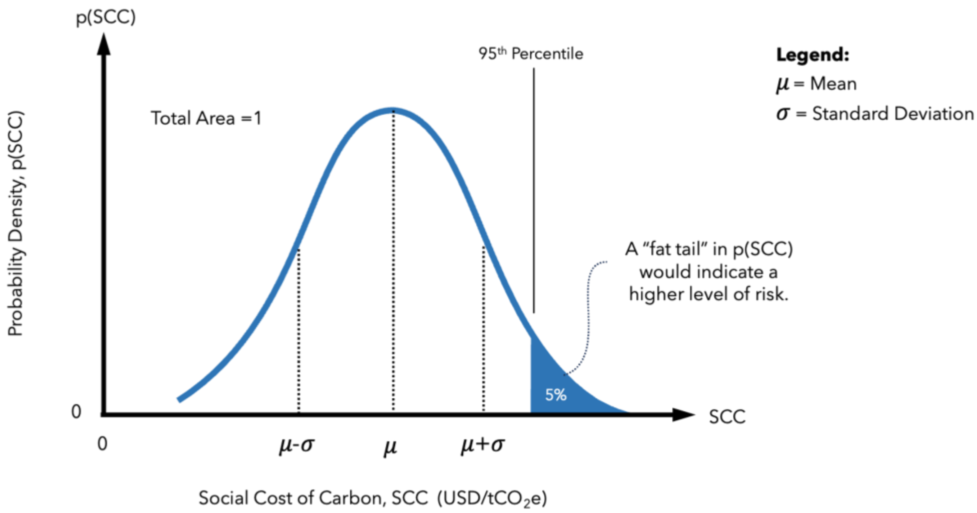


Figure B 2. Probability distribution for the SCC (hypothetical).

B3. Systemic Risk Management with the RCC

In this section the RCC is introduced and explained from a procedural standpoint. To begin, consider Figure B3, which illustrates three hypothetical probability distributions for the SCC. The first (distribution No. 1) represents a conventional SCC probability distribution based on the results of an integrated assessment model (IAM). The second (distribution No. 2) incorporates the increased likelihood of high-emission scenarios due to political resistance to the carbon tax and other punitive policies, reflecting how real-world politics can inflate the mean and spread of the SCC distribution. The third (distribution No. 3) factors in the potential acceleration of climate change driven by amplifying climate feedbacks and tipping points. Important is that distribution No. 2 could be indeterminate if political resistance is correlated to the SCC, because this would result in a political feedback loop, such that the SCC would need to be updated periodically to account for evolving politics. Also important is that distribution No. 3 could be indeterminate if the climate system passes thresholds that are too dynamic to be understood or forecast using available climate models. Distribution No. 3 could also be unbounded if catastrophic levels of climate change were to occur due to the passing of a climate tipping point, such as the collapse of the Atlantic Meridional Ocean Circulation (AMOC) (Drijfhout et al., 2025b; Laybourn et al., 2023; Van Westen et al., 2025).

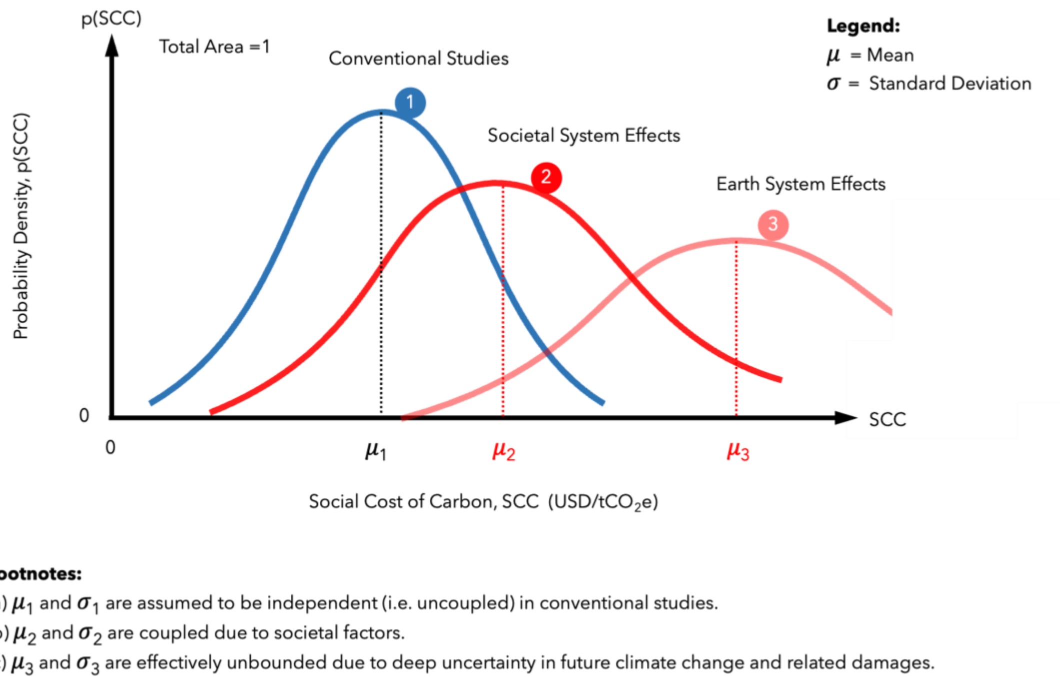


Figure B 3. Three hypothetical probability distributions for the SCC: (1) conventional, (2) with political resistance to standard policies included, and (3) with climate feedbacks and tipping points included.

While conventional risk management relies on adding a safety factor to the SCC estimate (refer to Figure B2), the actual value of the SCC could be indeterminate (i.e. unresolvable) or even unbounded (i.e. catastrophic) when real-world political constraints and earth system dynamics are taken into account. In such cases, the SCC becomes deeply uncertain or even unknowable. To resolve this problem, the required rate of carbon dioxide removal (CDR) is estimated, as in Figure B4, for remaining within a relatively safe carbon budget. A probabilistic approach to CDR is needed because there is uncertainty over future emission trajectories, system dynamics, and mitigation technologies (see Figure B4). This includes a tolerance for systemic risk, denoted as the X^{th} percentile for CDR, to account for different possible scenarios (such as delayed action or a higher system climate sensitivity) that would require more CDR.

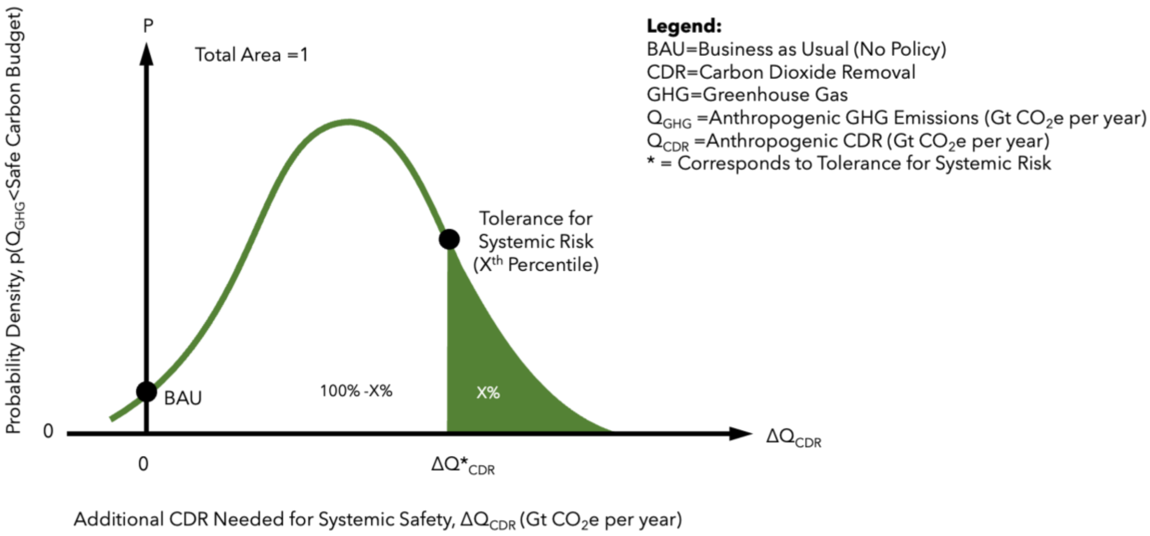


Figure B 4. Probability distribution for the CDR requirement (hypothetical).

The marginal supply curve in Figure B5 suggests an increasing cost of deploying higher levels of CDR, while the marginal demand curve suggests weak voluntary (endogenous) demand for CDR. The RCC is the cost difference between the marginal supply and demand for CDR, at the point where the additional rate of CDR is sufficient to meet the risk tolerance (ΔQ^*_{CDR}).

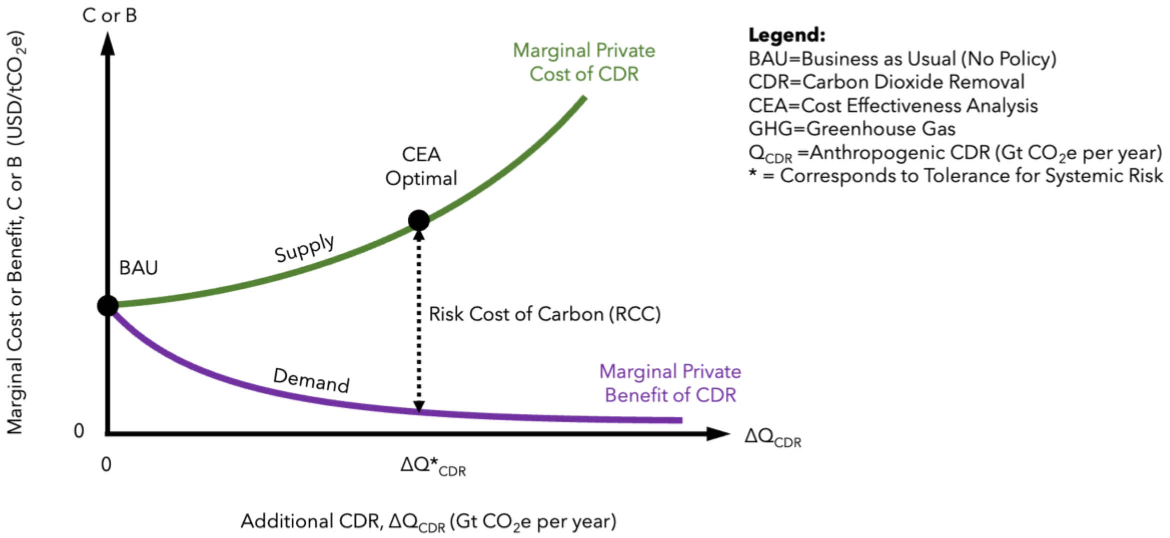


Figure B 5. Supply and demand curves for additional CDR (hypothetical).

To conclude this technical guide for the SCC and RCC, one more step is needed, which is to link ΔQ^*_{CDR} to the required rate of additional conventional mitigation, ΔQ^*_{CONV}. This link is expressed in terms of the total (i.e. global) rate of additional mitigation, ΔQ^*_{TOTAL}, as follows:

$$\begin{aligned} \Delta Q^*_{TOTAL} &= \Delta Q^*_{CONV} + \Delta Q^*_{CDR} \\ &= \sum \Delta q_{CONV} + \Delta Q^*_{CDR} \end{aligned}$$

(Eq. B1)

where, Δq_{CONV} represents the conventional GHG mitigation outcome of a particular industry, technology, or project that participates in the carbon reward market.

Important to note is that the carbon reward policy aims to provide each mitigation project a cost-effective amount of reward finance. This would be achieved through the adaptive use of a reward multiplier, R, when determining reward payouts at the project level (see Section 5.5 and Definition Boxes 8-9). The aim is to cover the marginal abatement cost of carbon (MACC), as indicated in Figure B6. Note that R=1 is equivalent to the RCC, which is illustrated in Figure B5 and Figure 10. By pricing the RCC into the market, the carbon reward policy is able to address the systemic risks that Pigou's approach overlooks. These systemic risks are reflected in the indeterminate and unbounded nature of the SCC, illustrated in Figure B3.

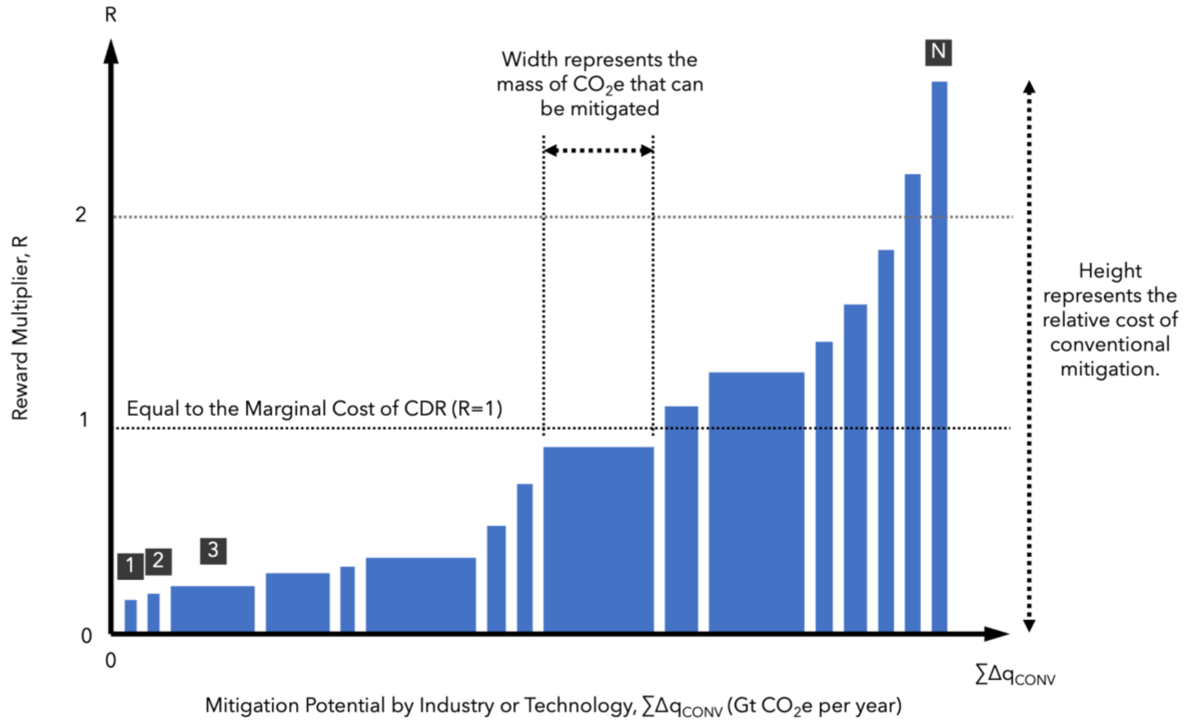


Figure B 6. Marginal abatement cost of carbon curve (MACC curve) for conventional mitigation (hypothetical). The reward multiplier, R, is a dimensionless factor for price comparison.

Appendix C. Comparison of Cap-and-Trade & Mitigate-and-Trade

Appendix C provides a comparison of cap-and-trade and mitigate-and-trade (aka carbon reward) based on the expanded economic framework presented in Section 4.2. Note that this comparison is not intended to set one policy in competition with another. On the contrary, all four policy classes in the policy matrix for carbon (see Figures 7-8) are recommended with the aim of establishing carrot-and-stick incentives in a layered approach that would eventually cover all economics sectors and geopolitical scales.

Table B 1. Comparison of Cap-and-Trade and Mitigate-and-Trade

Policy Features	Cap-and-Trade	Mitigate-and-Trade (aka Carbon Reward)
Policy Class	Class 2	Class 4
Incentive Type	Stick	Carrot
Policy Type	Market and fiscal approach	Market and monetary approach
Social Principle	Polluter Pays Principle	Preventive Insurance Principle
Social Agreement	The authority will reduce GHGs in certain economic sectors by reducing the volume of emissions permits over time, and allowing polluters to trade their permits to soften the financial impact.	The authority will offer carbon rewards (XCR) for additional mitigation outcomes, and central banks will guarantee a price floor for the XCR. Private XCR trading and central bank XCR purchases will finance enough conventional mitigation and CDR to remain within a relatively safe carbon budget. There will be no direct costs for stakeholders.
Geopolitical Scale	Local to regional.	Multilateral to global.

Table B1 (continued)

Policy Feature	Cap-and-Trade	Mitigate-and-Trade (Carbon Reward)
Jurisdiction	State or national legislatures, or a multi-country agreement.	International agreement, including a monetary-carbon alliance for central banks.
Primary Externality	Negative externality	Systemic externality
Primary Externality Metric	Social cost of carbon (SCC)	Risk cost of carbon (RCC)
Secondary Externality Metric	Risk cost of carbon (RCC)	Not applicable
Market Instrument	Tradable CO_2e emission permit with time constraints.	Tradable carbon-linked financial asset, called a carbon reward (XCR), supplied by the authority to projects with long-term mitigation contracts.
Increasing Stringency	The volume of emission permits is reduced over time based on choices informed by the SCC and political and scientific advice.	A price floor is set for the XCR in open markets. This is the minimum required marginal price for atmospheric CO_2e removal and storage to remain within a relatively safe carbon budget. The reward rules increase in scope over time by including more sectors, industries, and technologies.
Policy Authority (Controls the Ledger)	State or national government	International institution under agreements or treaty

Table B1 (continued)

Policy Feature	Cap-and-Trade	Mitigate-and-Trade (Carbon Reward)
What is Priced?	CO_2e emissions are not explicitly priced. Caps are set, and the price is discovered through private trading.	CO_2e removal from the atmosphere and storage is explicitly priced for global markets. CO_2e mitigation (reduction and avoidance) is adaptively priced for local markets.
Co-Benefits	None specified	Co-benefits are adaptively incentivised, including for communities, ecosystems and industries.
Economic Objective	Improve market efficiency by setting caps and inviting the trade of emissions permits via Coasean bargaining (for the Pareto optimal distribution of costs).	Ensure systemic safety by offering rewards (adaptively) and inviting the trade of carbon rewards via Coasean bargaining (for the Pareto optimal distribution of the cost). Monetary inflation is used to distribute some of the cost, when needed.
Operational Aims	Reduce CO_2e emissions by setting a declining cap on the mass emitted with emissions permits, and allowing the trade of these permits.	Stay within a relatively safe carbon budget by offering XCR for CDR and conventional mitigation. Also invite decentralized incentives to maximize co-benefits.
Co-Benefits?	None specified	Co-benefits potentially include community wellbeing, ecosystem health, and industrial reliability.

Table B1 (continued)

Policy Feature	Cap-and-Trade	Mitigate-and-Trade (Carbon Reward)
Unit of Account	1 metric ton CO_2e emitted to the atmosphere within a certain period.	1 metric ton of CO_2e removed from the atmosphere and durably stored for 100 years or more. It also represents a 1/R metric ton of CO_2e mitigated (avoided or reduced) using cost-effective methods, where R is the reward multiplier for each mitigation project.
Store of Value	Negative. GHG emission permits impart an average negative value on CO_2e emitted, but permits may have a positive value for firms with surplus permits.	Positive. XCR has a positive value for projects that mitigate CO_2e emitted, for all holders of XCR. For central banks, XCR is registered as an asset on their balance sheets.
Medium of Exchange	Not applicable because emission permits do not function as money.	Not applicable because XCR does not function as money.
Strengths	Some room for political negotiation over the cap on CO_2e emissions. Supported by standard economic theory and successful examples in the European Union and elsewhere.	Complements other market policies. Funds global CDR, swaps fossil fuels with renewables to overcome political gridlock, avoids stranded assets and mobilizes private finance at scale. Also reduces debt levels, invites voluntary participation, provides economic stimulus, creates green jobs, attracts green R&D, and provides predictable long-term prices for CO_2-e mitigation.

Table B1 (continued)

Policy Feature	Cap-and-Trade	Mitigate-and-Trade (Carbon Reward)
Vulnerabilities	May face political opposition to rising costs. Has national or regional limited jurisdiction and therefore cannot coordinate the global economy for resolving the market failure in GHG emissions. Requires border adjustments for addressing the carbon embodied in imported goods and services.	Requires gradual international implementation through a club of nations, and extensive administration. Requires an extension of central bank mandates. Informed by new economic theory. A focus on public relations is needed to explain the induced monetary inflation and to attract private investment in the XCR asset.

Appendix D. Preliminary Estimate of Monetary Inflation

D1. Background & Objective

There is no change in the aggregate money supply (M0, M1 or M2) when XCR is initially created and issued to mitigation projects as a reward. This is because XCR is not a currency (it is a financial asset). By issuing newly created XCR to mitigation projects, these projects enjoy the seigniorage value of their earned XCR. This system of reward payment will be reliable as long as the market value of XCR is sufficient and stable while the supply of XCR increases with time.

An annual increase in M0, M1 and M2 (denoted ΔM0, ΔM1 and ΔM2) and associated monetary inflation (π) are expected when carbon quantitative easing (CQE) is implemented by central banks to support the market value of XCR. CQE is a monetary program that is designed to coordinate the efforts of central banks to ensure that the XCR spot price remains above its prescribed price floor. When CQE is applied, participating central banks will create M0 to purchase a sufficient amount of XCR in open markets to defend the price floor. The additional M0 enters the checking accounts of XCR brokers, resulting in a direct increase in M1 and a subsequent increase in M2 through the banking system, with corresponding monetary inflation (π).

The anticipated π was estimated for a scenario in which the carbon reward policy is initiated in 2025 and deployed on a global scale to target +1.75°C by 2100, which is the mid-point of the PA climate goals. The magnitude of π (as an annual %) was estimated using an analytical approach based on the quantity theory for money. Initially, the following two equations were considered for estimating π:

$$\boldsymbol{\pi} = \frac{\Delta \text{M1}}{\text{M1}} \tag{D1a}$$

$$= \frac{\Delta \text{M0}}{\text{M1}} \tag{D1b}$$

and

$$\boldsymbol{\pi} = \frac{\Delta \text{M2}}{\text{M2}} \tag{D2}$$

where changes in the money supply are assessed annually (Δt = 1 year), and

- M0 is the global supply of currency (banknotes and coins) in circulation, plus the global sum of reserve balances at central banks (held by other banks and depository institutions);

● M1 is the global supply of currency (banknotes and coins) held by the public, plus transaction deposits (checking accounts and other very liquid deposits) at depository institutions; and

● M2 is M1 plus the global sum of near-money assets that can be quickly converted to cash (but less liquid than M1), including savings accounts, time deposits, and money market funds.

The annual volume of new bank reserves (ΔM0) that would be created between 2025-2100 through CQE was constrained by published estimates of (a) the climate finance gap for the Paris goals, and (b) the required rates of CDR for the same Paris goals. The future aggregate money supply between 2025-2100 was constrained by World GDP forecasts and M1-to-GDP and M2-to-GDP ratios from recent decades. Most of this appendix is dedicated to explaining how ΔM0, the aggregate money supply, and π were estimated for the 75-year scenario, ceteris paribus. The resulting π estimate, shown in Section 6.6, is preliminary because its accuracy has yet to be evaluated.

D2. Methodology

D2.1. Money Supply vs. Nominal GDP (2025-2100)

An estimate of global M1 and M2 supplies is needed when using Equations D1 and D2, respectively. Rather than directly estimating M1 or M2, the ratio of M1-to-GDP and M2-to-GDP over the past 65 years were considered, as shown in Table D1. Benati et al. (2021) examined 38 countries between the early-20th and early 21st centuries, and found strong evidence for a long-run relationship between the M1-to-GDP ratio and short-term interest rates. Their analysis is not global, but it points to a global M1-to-GDP ratio of 20-25% (see Table D1). The World Bank (2025c) provides a record of the M2-to-GDP ratio between 1960-2024, as shown in Table D1.

Table D 1. Money Supply as a Percentage of World GDP

Ratio	1960's to 1980's	1990's to 2000's	2010's to 2020's	2024
World M1/GDP	~15-25%	~15-25%	~20-30%	~20-25%
World M2/GDP	~50-90%	~85-110%	~110-140%	~130-140%

Source: Benati et al. (2021); World Bank (2025a)

The money supply ratios in Table D1 could be used to infer M1 and M2 from projected World GDP for the 75-year policy scenario (spanning 2025-2100). This method simplifies the analysis because World GDP is a standard output of most climate policy assessments, whereas future global M1 and M2 estimates are rarely reported. The adopted method of estimating π is based on an intermediate measure of the global money supply (M^*), as follows:

$$\boldsymbol{\pi} \approx \frac{\Delta M1}{M^*} \tag{D3a}$$

$$\approx \frac{\Delta M0}{M^*} \tag{D3b}$$

where

$$M1 < M^* < M2 \tag{D4}$$

and

$$M^* = \theta \times \text{World GDP} \tag{D5a}$$

$$\theta = 0.50 \tag{D5b}$$

Equations 3–5 were adopted in the current estimation of the aggregate money supply and π for the following reasons:

- **Intermediate Money Supply:** The intermediate money supply (M^*) was adopted because it was unclear if M2 is the appropriate metric for π forecasting in this case.
- **Conservative Approach:** The fixed M^*-to-GDP ratio (θ = 0.50) was adopted to be conservative, meaning that the resulting π is likely to be higher than actual. This conservatism may be needed because certain other monetary factors, such as financial leveraging and financial volatility, were not considered in the estimation of π.
- **Simplified Calculations:** The fixed M^*-to-GDP ratio (θ = 0.50) was adopted to simplify the calculations for estimating π.

Future studies may review the suitability of Equations 3–5, and may adopted other methods that can more accurately capture the monetary expansion from CQE.

D2.2. GDP (Nominal) vs. GDP (PPP)

World GDP can be expressed in units of Purchasing Power Parity (PPP) by year. PPP units equalise the prices of an identical basket of goods across countries. For example, PPP (2010) removes both inflation after 2010 and cross-country price-level differences. When undertaking assessments of inflation, the usual practice is to work with nominal data (not inflation adjusted data) to assess inflation effects. However, when deploying CQE (i.e. as the financial guarantee of the carbon reward policy) monetary inflation is imposed on the financial system by directly expanding M0 and M1. For this reason, we can estimate monetary inflation (π) from records of World GDP that have been adjusted to PPP 2005, which are the units of GDP that are used in IPCC AR6. In this study, GDP and all other values are converted to 2005 USD to maintain consistency in terms of comparing value.

Converting between different GDP units requires national/global GDP deflators for specific years, and adjustments for living standards. Rather than undertaking such complex calculations, the following linear regression formulas were developed from 2010-2014 GDP data, as follows ($R^2 = 0.99$):

$$\text{World GDP (PPP 2005)} = 1.6417 \times \text{Nominal World GDP} \tag{D6a}$$

$$\text{World GDP (PPP 2010)} = 1.4398 \times \text{Nominal World GDP} \tag{D6b}$$

$$\text{World GDP (PPP 2010)} = 0.877 \times \text{World GDP (PPP 2005)} \tag{D6c}$$

The conversion factor 0.877 is the GDP deflator obtained from the World Bank's World Development Indicators (WDI) database, when aggregated for the world.

D2.3. World GDP in 2024

World GDP in 2024 (nominal) was obtained from the World Bank (2025):

$$\text{World GDP (2024)} = \$111\text{T (2024 USD)} \tag{D7}$$

The above GDP estimate was inflation adjusted via Equation D6a to provide:

$$\text{World GDP (PPP 2005)} = 1.6417 \times \$111\text{T (2024 USD)} \tag{D8a}$$

$$\text{World GDP (PPP 2005)} = \$182\text{T USD} \tag{D8b}$$

D2.4. World GDP for +2.6°C (2025-2100)

A business-as-usual (no policy) scenario is not needed to undertake the calculations for estimating π however BAU is of interest for making comparisons. Riahi et al. (2017) examined the Shared Socioeconomic Pathway SSP2-4.5 ('Middle of the Road'). This scenario reaches +2.6°C of global warming by 2100, and this was adopted as the BAU scenario. Riahi et al. (2017) estimate that:

$$\text{World GDP (PPP 2005)} = \$540\text{T USD} \tag{D9}$$

The above World GDP for +2.6°C by 2100 approximates future economic development as a result of continuing with current levels of climate ambition and existing policies. This scenario of +2.6°C by 2100 does not take into account recent developments in climate science that might result in a worse BAU scenario.

D2.5. World GDP for +1.75°C (2025-2100)

The IPCC's Sixth Assessment Report (AR6, 2021-2023) includes GWP (PPP 2005) forecasts for Shared Socioeconomic Pathways (SSP) that correspond to +1.5ºC and +2.0ºC by 2100. The following information was obtained from these reports:

$$\text{World GDP for } +1.5°\text{C at } 2100 = \$450\text{-}500\text{T (PPP 2005 USD)} \tag{D10}$$

$$\text{World GDP for } +2.0°\text{C at } 2100 = \$400\text{-}450\text{T (PPP 2005 USD)} \tag{D11}$$

The average of the above two values was used in this study to estimate World GDP at 2100 for the +1.75°C by 2100 scenario (the Policy Scenario):

$$\text{World GDP for } +1.75°\text{C at } 2100 = \$450\text{T (PPP 2005 USD)} \tag{D12}$$

World GDP values between 2025 and 2100 were interpolated from Equations D8b and D12 based on a power function with fixed compounding. This approach smoothed-out minor fluctuations in GDP during the 75-year scenario and allowed us to focus our attention on the theoretical impact of the carbon reward policy on M0, M1, M2 and M^* (Equations D1–D5).

Important to note is that the IPCC's AR6 indicates that scenarios projecting +2.6°C warming by 2100 (e.g., SSP2-4.5) typically result in slightly higher World GDP compared with +1.5°C (SSP1-1.9) or +2°C (SSP1-2.6). This outcome arises because achieving lower warming requires more aggressive, near-term mitigation, which imposes economic costs that modestly slow GDP growth. Beyond ~3°C, damages appear to dominate, flipping this relationship.

D2.6. Finance Gap for Conventional Mitigation (2025-2100)

The climate finance gap refers to the difference between current annual climate finance flows and that needed to limit global warming to specific targets. These estimates are derived from the Climate Policy Initiative's (CPI) 2024 report, *Global landscape of climate finance 2024: Insights for COP29*. The CPI report is summarised in terms of the following mean estimates (2022 USD):

$$\text{Climate Finance Gap (2023-30) for } +1.5°\text{C} = \$7.2\text{T USD/yr} \tag{D13a}$$

$$\text{Climate Finance Gap (2031-50) for } +1.5°\text{C} = \$9.4\text{T USD/yr} \tag{D13b}$$

$$\text{Climate Finance Gap (2023-30) for } +2°\text{C} = \$5.5\text{T USD/yr} \tag{D13c}$$

$$\text{Climate Finance Gap (2031-50) for } +2°\text{C} = \$8.0\text{T USD/yr} \tag{D13d}$$

The approximate climate finance gap for the Policy Scenario (+1.75°C) was interpolated from the above mean estimates, providing (2022 USD):

Climate Finance Gap (2023-30) for +1.75°C = \$6.4T USD/yr (D14a)

Climate Finance Gap (2031-50) for +1.75°C = \$8.7T USD/yr (D14b)

CPI (2024) data are quoted in units of 2022 USD to reflect real purchasing power. Given that the current analysis is based on 2005 USD, a conversion factor of 0.666, from the U.S. Bureau of Labor Statistics (2025), was applied to provide the following (2005 USD):

Climate Finance Gap (2023-30) for +1.75°C = \$4.2T 2005 USD/yr (D14a)

Climate Finance Gap (2031-50) for +1.75°C = \$5.8T 2005 USD/yr (D14b)

The climate finance gaps presented above include some costs for CDR and adaptation. Given that the carbon reward policy manages the reward finance (XCR) through three channels— (Reward Channel 1) CDR, (Reward Channel 2) conventional mitigation, and (Reward Channel 3) co-benefits (refer to Figure 9)—the climate finance gap was sub-divided based on the first two reward channels. Reward Channel 3 is ignored in this analysis because it employs a Robin Hood system to incentivise co-benefits (incl. adaptation) and thus it does not create new XCR. Subsequently, only Reward Channels 1 and 2 are relevant to this analysis.

CPI's (2024) estimate of the climate finance gap includes about 5-15% for CDR and adaptation. Thus, a factor of 87.5% was used to estimate the finance gap for Reward Channel 2, as follows (2005 USD):

Reward Channel 2 (2023-30) for +1.75°C = \$3.7T 2005 USD/yr (D15a)

Reward Channel 2 (2031-50) for +1.75°C = \$5.0T 2005 USD/yr (D15b)

The climate finance gap for CDR (Reward Channel 1) was estimated using an independent method (see Section D2.7).

CPI (2024) did not provide estimates of the climate finance gap beyond 2050. To simplify the analysis, it is assumed that Channel 2 finance will fall smoothly to zero by 2100 because the world should have decarbonised by 2100—except for the residual and historical emissions that are unable to be abated and will be addressed with CDR. This assumption is formulated as follows:

Channel 2 Finance (2100) for +1.75°C = \$0T 2005 USD/yr (D15c)

A fitted polynomial was used to interpolate the climate finance gap for conventional mitigation, giving the following result for Reward Channel 2 (r^2=0.94, 2005 USD):

$$\text{Channel 2 Finance (2025-2100) for } +1.75°\text{C} = a\ t^3 + b\ t^2 + c\ t + d \tag{D16}$$

where,

t = year (2025-2100)
a= 0.00004682026
b= - 0.29112
c=603.2498
d=- 416587.8

The above polynomial was used to estimate the annual rate of XCR issuance for Reward Channel 2 (T 2005 USD/yr).

Comment Box D1. Background to the polynomial for Reward Channel 2 finance (Equation D16)

Important to note is that the polynomial in Equation D16 provides a smooth-curve for XCR issuance via Reward Channel 2 (Trillions 2005 USD). This implies that the estimated XCR issuance is amenable to the estimation of incremental changes in M0, M1, and π over the 75-year policy scenario. This smooth-curve approach does not imply that the resulting π estimates are accurate, but the approach is consistent with the economics of decarbonisation because the results are constrained by CPI's (2024) climate finance gap estimates in terms of annuals and totals for 2025-2050.

D2.7. CDR Requirement (2025-2100)

It should be noted that the financial mechanism of the carbon reward policy is framed by the XCR price floor, which is defined as the marginal price for CDR that aligns with the declared mitigation roadmap (see Figures 9-10). In this policy scenario, the mitigation roadmap targets +1.75C by 2100. The required CDR for +1.75C by 2100 were estimated from IPCC AR6 reports.

It is noted that CDR cannot substitute for immediate and deep emissions reductions. If overshoot does occur, then CDR rates need to rise significantly. The feasibility or sustainability of CDR rates, whether high for overshoot or low for undershoot, is not considered in this preliminary analysis that is focused on monetary inflation.

The IPCC AR6 (WGIII) reports highlight that CDR is essential in nearly all scenarios for +1.5°C and +2°C by 2100 as a means of counterbalancing residual emissions and achieving net-zero or net-negative CO_2 emissions. Exact totals for CDR between 2025-2100 are not explicitly provided in these IPCC reports but CDR estimates are provided for key decades, as shown below. IPCC AR6 estimates of total CDR for limiting warming to 1.5°C by 2100 are:

$$\text{Total CDR \& No Overshoot (2020-2100) for } +1.5°\text{C} = 328 \text{ GtCO}_2 \quad \text{(D17a)}$$

$$\text{Total CDR \& Overshoot (2020-2100) for } +1.5°\text{C} = 100\text{-}1000 \text{ GtCO}_2 \quad \text{(D17b)}$$

$$\text{Total CDR \& Overshoot (2050-2100) for } +1.5°\text{C} = 360 \text{ GtCO}_2 \quad \text{(D17c)}$$

IPCC AR6 estimates of CDR rates for scenarios that limit warming to +1.5°C by 2100 and require net-negative emissions, are:

$$\text{CDR Rate \& Overshoot (2030s) for } +1.5°\text{C} = <1 \text{ GtCO}_2 \text{ / yr} \quad \text{(D18a)}$$

$$\text{CDR Rate \& Overshoot (2040s) for } +1.5°\text{C} = 2\text{-}5 \text{ GtCO}_2 \text{ / yr} \quad \text{(D18b)}$$

$$\text{CDR Rate \& Overshoot (2050s) for } +1.5°\text{C} = 6 \text{ GtCO}_2 \text{ / yr} \quad \text{(D18c)}$$

$$\text{CDR Rate \& Overshoot (2060-2090) for } +1.5°\text{C} = 7\text{-}14 \text{ GtCO}_2 \text{ / yr} \quad \text{(D18d)}$$

$$\text{CDR Rate \& Overshoot (2100) for } +1.5°\text{C} = 14 \text{ GtCO}_2 \text{ / yr} \quad \text{(D18e)}$$

CDR requirements for 2°C are approximately half those of 1.5°C pathways in median cases. IPCC AR6 estimates of total CDR for scenarios that limit warming to +2°C by 2100 are:

$$\text{Total CDR \& No Overshoot (2020-2100) for } +2°\text{C} = 252 \text{ GtCO}_2 \quad \text{(D19a)}$$

IPCC AR6 estimates of CDR rates for scenarios that limit warming to +2°C by 2100 are:

$$\text{CDR Rate (2030s) for } +2°\text{C} = <1 \text{ GtCO}_2 \text{ / yr} \quad \text{(D20a)}$$

$$\text{CDR Rate (2040-2060) for } +2°\text{C} = 1\text{-}3 \text{ GtCO}_2 \text{ / yr} \quad \text{(D20b)}$$

$$\text{CDR Rate (2061-2090) for } +2°\text{C} = 3\text{-}7 \text{ GtCO}_2 \text{ / yr} \quad \text{(D20c)}$$

$$\text{CDR Rate (2100) for } +2°\text{C} = 5\text{-}10 \text{ GtCO}_2 \text{ / yr} \quad \text{(D20d)}$$

A polynomial formula was fitted to the above data points in such a way that the CDR requirement is about mid-way between the CDR needed for +1.5°C and +2°C in terms of both cumulative mass and annual rates (2025-2100). The fitted polynomial is as follows (r^2=0.99):

$$Q_{CDR} = 0.80 \times (a\, t^3 + b\, t^2 + c\, t + 0.5) \quad \text{(D21)}$$

where,

Q_{CDR} = CDR Rate (Gt CO_2/yr) for +1.75°C

t = year (2025-2100)

a= 0.00000012366702

b= 0.00043193712

c=0.36780208

The above polynomial was used to estimate the CDR requirement for Reward Channel 1 of the Policy Scenario for +1.75°C by 2100. This polynomial results in a total CDR of 417 $GtCO_2$ over the 75-year period and peak CDR rate of 10.65 $GtCO_2$ /yr at 2100. This CDR total is slightly above the mean total CDR for the +1.5°C and +2°C scenarios.

Comment Box D2. Background to the polynomial for CDR requirements (Equation D21)

Important to note is that the polynomial in Equation D21 provides a smooth-curve for estimating annual CDR requirements that could earn XCR via Reward Channel 1. This smooth-curve is amenable to the estimation of incremental changes in M0, M1, and π over the 75-year policy scenario. This smooth-curve approach does not imply that the resulting π estimates are accurate, but it is consistent with the economics of CDR because the results are constrained by the IPCC's AR6 estimates of CDR in terms of annual rates and totals between 2025-2100.

D2.8. XCR Price Floor (2025-2100)

Lutz (2022) provides an estimate the XCR price floor—also called the risk cost of carbon (RCC)—for achieving +1.5ºC by 2100 (see Figure D1). Lutz's price floor estimate does not include information on inflation adjustments, and so it is assumed here that it is priced in 2015 USD given that most CDR research is recent. A polynomial was fitted to Lutz's price floor to arrive at the following formula:

$$\text{XCR Price Floor for +1.5ºC (T 2015 USD)} = a\ t^3 + b\ t^2 + c\ t + d \qquad \text{(D22a)}$$

$$\text{XCR Price Floor for +1.5ºC (T 2005 USD)} = (a\ t^3 + b\ t^2 + c\ t + d)\ e \qquad \text{(D22b)}$$

where,

XCR Price Floor (trillions 2015 USD/Gt CO_2/yr)

t = year (2025-2100)

a= 0.00000186667

b= -0.01164

c=24.1916

d=-16757.1

e= 0.8241 (Bureau of Labor Statistics)

The above formula was adopted without adjusting for the less ambitious climate objective of +1.75°C, thus introducing a conservative bias for CDR costs and π. Equation D22 is, in any case, only approximate because the raw data for determining the XCR price floor is rather limited.

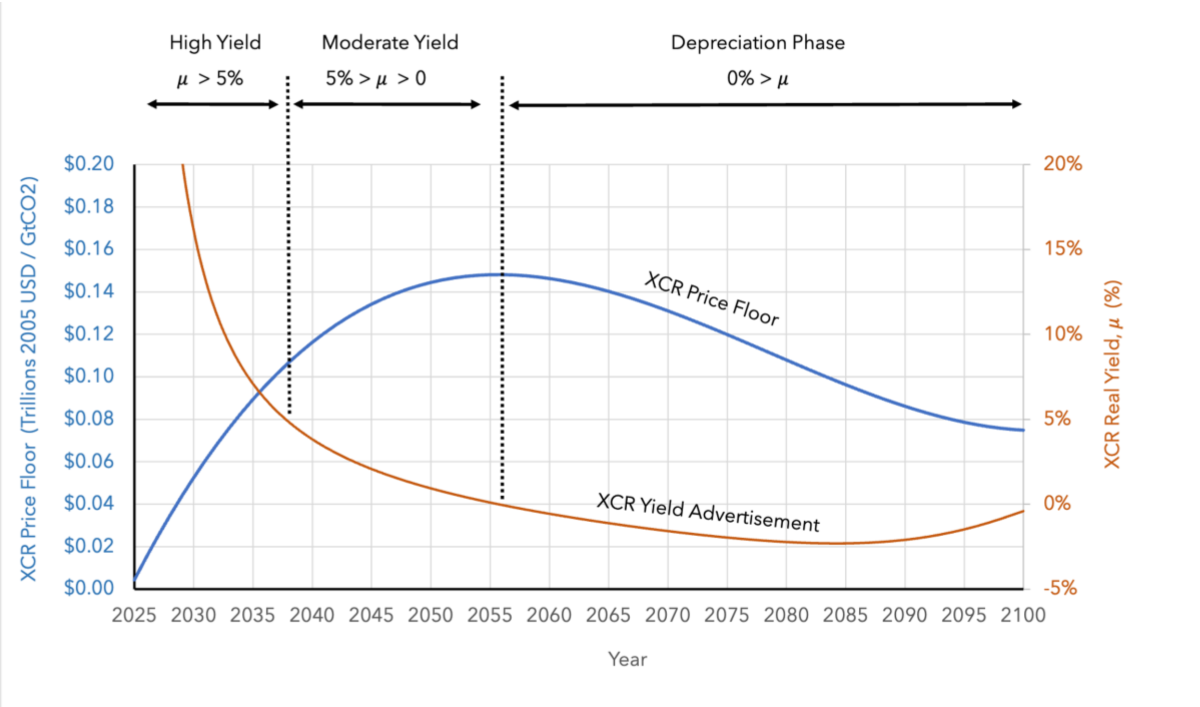


Figure D 1. Estimate of the XCR price floor for +1.75°C by 2100 (adapted from Lutz, 2022).

A simple check on the Equations D21 and D22 is provided below by comparing the annual cost of CDR in 2030 with the CPI (2024) estimate of \$0.05-0.3T USD/yr (2022 USD) by 2030. CPI's (2024) estimate was multiplied by 0.6671 to convert to 2005 USD:

CDR Cost in 2030 = <u>\$0.033-\$0.20T USD /yr (2005 USD)</u> (D23a)

Equations D21 and D22 provide the following CDR cost for 2030, which falls within CPI's (2024) estimated range:

CDR Requirement in 2030 = 1.36 Gt CO_2 /yr (D23b)

XCR Price Floor in 20230 = \$0.052T USD per Gt CO_2 (2005 USD) (D23c)

CDR Cost in 2030 = <u>\$0.071T USD /yr (2005 USD)</u> (D23d)

D2.9. XCR Yield Advertisement (2025-2100)

The XCR price floor and real yield are practical metrics because they correspond to the CDR requirement of the declared mitigation roadmap (in this case +1.75°C by 2100; see in Figure D1). The price floor is not just a price signal for GHG mitigation. It is also a yield advertisement for XCR investing, and is calculated as the annual rate change of the XCR price floor.

The three phases of real yield in Figure D1 are relevant to the level of private demand for XCR and forecasting when CQE is most likely to be needed to defend the price floor. In other words, a low or negative yield is likely to result more CQE, an expansion of M1, and a positive π. CQE activity is likely to be most intense during the depreciation phase that occurs after 2050. The uncertainty associated with the level of private XCR ownership is managed in the next section by introducing an assumed level of private XCR ownership.

D2.10. Private vs. Central Bank XCR Ownership (2025-2100)

The fraction of the total XCR supply that is held by the private sector (α) at any point in time is vitally important, because it reveals the level of central bank buying (via CQE) that was needed to defend the XCR price floor leading up to that moment in time. In this analysis, α is a variable that is assumed, as follows:

$$\alpha_{\text{max}} \geq \alpha \geq \alpha_{\text{min}} \text{ and } \alpha \text{ is linearly interpolated between } t_1 \text{ and } t_2 \tag{D24a}$$

$$\alpha_{\text{max}}\ (\mu > 5\%) = 1.0 \text{ and } t_1 = \sim 2037 \tag{D24b}$$

$$\alpha_{\text{min}} = 0.80,\ 0.60,\ 0.40, \text{ or } 0.20 \text{ and } t_2 = 2100 \tag{D24c}$$

Four different financial pathways were assumed based on a α_{min} (t=2100) as shown in Equation D24. Between the years 2025-2100 the value of α was interpolated, beginning with an assumed α=1 when the real yield (μ) is greater than 5% (Equation D24b) and then declining (linearly) until α reached its assumed minimum value at 2100 (Equation D24c).

Comment Box D3. Background to the linear interpolation of private sector ownership (Equation D24)

Important to note is that α maximum, α minimum, and the time-linear interpolation scheme for α (Equation D24) were assumed. Other interpolation schemes that provide a more rapid decline in α would result in relatively higher ΔM0, ΔM1, and π, but no other interpolation schemes were considered for reasons of brevity.

D2.11. Spreadsheet Calculations

The estimation of π between the years 2025-2100 was carried out within MS Excel based on the following logical steps:

Step 1. Calculate World GDP (Trillions PPP 2005 USD) for the Policy Scenario for each year using Equations D8b and D12 and a simple power function with fixed compounding (i.e. exponential interpolation).

Step 2. Calculate M* (Trillions 2005 USD) using the results from Step 1 and Equation D5.

Step 3. Calculate the XCR price floor (Trillions 2005 USD/GtCO_2-e/yr) using Equation D22b.

Step 4. Calculate the CDR requirement (GtCO_2-e/yr) using Equation D21.

Step 5. Calculate the Reward Channel 1 finance (Trillions 2005 USD/yr) as the multiple of results from Steps 3 & 4.

Step 6. Calculate the Reward Channel 2 finance (Trillions 2005 USD/yr) using Equation D16.

Step 7. Calculate the total annual reward payments (Trillions 2005 USD/yr) as the sum of Steps 5 & 6.

Step 8. Calculate the cumulative XCR payments (Trillions 2005 USD) in each year using the results of Step 7.

Step 9. Calculate the yield advertisement (%) of the XCR price floor using the results of Step 3.

Step 10. Calculate the private ownership ratio (α) based on the results of Step 9 and the linear interpolation model of Equation D24.

Step 11. Calculate the cumulative private ownership of XCR (Trillions 2005 USD) in each year as the multiple of the results from Steps 8 & 10.

Step 12. Calculate the cumulative central bank ownership of XCR (Trillions 2005 USD) for each year as the difference between the results of Steps 8 & 11.

Step 13. Calculate the annual increase in M0 and M1 (Trillions 2005 USD/yr) as the yearly incremental change in central bank XCR ownership (related to CQE) based on the results of Step 12.

Step 14. Calculate the monetary inflation (π) by the dividing the results of Step 13 by the results of Step 2, as required by Equation D5.

D3. Data Sources

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