SSRN PREPRINT — PRELIMINARY DRAFT

Climate Transition Risk Mitigation: Introducing the CLoCo Bond

Chris Cormack[1 2] & Andrea Macrina[3 *]

[1] *Quant Foundry Limited, New London House, 6 London Street, London EC3R 7LP, United Kingdom*
[2] *UK Centre for Greening Finance and Investment, Smith School of Enterprise and the Environment, University of Oxford South Parks Road, Oxford OX1 3QY, United Kingdom*
[3] *Department of Mathematics, University College London, Gower Street, London WC1E 6BT, United Kingdom*
[*] *Corresponding authors emails: chris.cormack@quantfoundry.com, a.macrina@ucl.ac.uk*

3 June 2024

Executive summary

Recent events regarding governmental climate transition policy (e.g., UK announcement on electric vehicle roll-out, statements on climate change by political parties in the United States) and uncertainties linked to the ability for industry sectors and consumers to manufacture and purchase low carbon technologies, respectively, have led to a wider need to embed a richer framework for uncertainty in climate transition outcomes. This uncertainty creates a number of financial risks for firms, their investors, the banking sector, potentially also including sovereign risks. With the current academic literature (for a review see Cormack & Shrimali) and documentation by professional bodies and institutions (e.g., ISDA, CFRF, NGFS, ECB, BoE) modelling has been focussed on building frameworks that can transmit climate change external risk factors from physical or transition pathways to financial impacts. Furthermore, there has been an increased interest in embedding the variability and uncertainty of climate change risks, leading to a need to develop a probabilistic framework (e.g., Rebonato & Kainth, and Kenyon, Macrina & Berrahoui). In this article, we build on these concepts and propose a probability space that supports climate transition risk. The main objective is to develop novel applications to develop financial instruments for firms to reduce the risk of climate transition policy changes and adverse economic environments. In particular, we propose greenhouse gas (GHG) emission trajectories on a probability space for firms within a specified industry sector for regions worldwide. The GHG emissions trajectories are specifically linked to defined emissions policies. Here, we endeavour to develop a tangible probabilistic approach with measurable quantities which are clearly linked to policy objectives. An associated goal is to build tools that can assist firms, their stakeholders, and governments in reducing risks exacerbated by climate change. As an example of a risk-sharing instrument, we propose a novel financial product, termed climate-contingent convertible (CLoCo) bond, whose financial structure permits firms to reduce the risk of default due to adverse climate transition policies over the product's lifetime. We utilise the transition probability space and detailed firm-level models to develop the pricing theory for such an instrument. The implications of the proposed financial instrument are such that it can lead to not only reduced risk of default for firms, thereby increasing the expected firm value, but it also reduces the dependency of firm failures on the banking sector and potential bail-out costs incurred by sovereign nations.

1 Introduction

The drive by international governments to reach net-zero greenhouse gas (GHG) emissions by 2050 has initiated a significant change in corporate business strategies while driving increased capital expenditure into new technologies and business processes. This move to a lower emissions economy has created a change in business models that may impact energy security and prices, strain supply chains and have the potential to impact the wider macroeconomy significantly. The ability or otherwise for firms to affect a change in their business models to address decarbonisation policies creates an economic uncertainty termed transition risk. These risks manifest themselves through a number of mechanisms, for example, reduced revenues from restrictions to carbon-intensive products, impacts on pricing through taxation, supply and demand adjustments, and direct policy-driven impacts.

These risks, alongside weather-driven physical damage to economic assets and infrastructure, reduced food yields, and the significant number of anticipated second-order effects (Cormack and Shrimali, 2023), have led to the desire for governments and their central banks to embed financial climate risk assessments for both, the firms and commercial banks. Within these assessment tests, commercial banks have been mandated to test the financial viability for loans and derivatives with counterparties [1] under several potential economic and climate scenarios.

These scenarios consist of several government-determined economic drivers that comprise of a combination of incentives such as subsidies from the large scale, such as the United States Inflation Reduction Act (Goverment, 2022b), to smaller scale, such as the UK (fossil fuel) boiler replacement programme (Goverment, 2022a). Alongside economic penalties such as carbon taxation and emissions or production caps (Government, 2023) on high GHG emitting technologies, firms are subject to several pressures to decarbonise their production. Firm interventions on the supply side, such as the US IRA, can considerably reduce the risks for firms and incentivise production within firms that are incorporated in the US, and at the same time, create pressures on non-US firms to decarbonise, thus creating further risks. Mechanisms such as production caps and production fines, e.g., car production in the UK, were implemented alongside consumer subsidies to reduce the purchase cost of an electric vehicle (EV) in the UK. However, as the size of the consumer subsidy was reduced faster than the speed of cost reduction for EV cars, the demand for EVs fell below the target number of the mandated proportion of sales. This resulted in a change in the mandate for production targets in the UK, creating concern for manufacturers, who had already embarked on planned capital expenditure in anticipation of demand.

This is one specific example of policy-driven transition risks affecting firms where they have committed to a strategy utilising a specific technology and its associated capital expenditure, which may lead to an adverse outcome for firms if the forecast future business cash-flows do not cover their future liabilities.

Recent events regarding changes in governmental climate transition policy, ranging from the recent announcement in the UK (Government, 2024) for vehicle manufacturers to phase out internal combustion engine (ICE) cars, political uncertainty on climate change policies by the major parties in the US, rapid cost deflation for solar PV and other technologies (Reuters, 2023), and uncertainties linked to the ability for industrial sectors and consumers to manufacture and purchase low carbon technologies, respectively, to impacts to the macro-economy from inflation driven interest rate increase that curtail capital investment, have led to a wider need to embed a richer framework for uncertainty in climate transition outcomes. This set of uncertainties creates challenges for all economic agents subject to the transition.

This uncertainty creates many financial risks for firms, their investors, and the banking sector and could impact sovereign states adversely. For a review of the current academic literature in this context, see Cormack and Shrimali, 2023. Moreover, industry and governmental organisations from the ECB, BoE, NGFS, ISDA (Europen Central Bank, 2023; England Prudential Regulation Authority, April, 2019; UK Department for Energy Security and Net Zero, 2023; ISDA, 2024) have focused on building frameworks that can transmit external risk factors induced by climate change from physical or transition pathways to financial impacts. Furthermore, there has been an increased need to embed (a) the variability and uncertainty of climate (change) risks, requiring the development of a probabilistic approach to assess the possibility of a firm failure (i.e., in financial terms, its probability of default), and (b) a view on the impact that such a failure within the economy may have on policy choices and hence the overall atmospheric greenhouse gas concentration over time.

In this paper, we build on these concepts and put forward a probability space that underpins climate transition risk, specifically to develop novel applications and support the design of financial instruments which enable firms to reduce the risk arising from the variability of climate transition policies or adverse economic environments. We note that a probability space designed for the modelling of climate change policy risk is also proposed in (Kenyon, Macrina, and Berrahoui, 2023b), where the authors discuss the implications for firm defaults. In this paper, this space is used directly to develop financial instruments that are explicitly linked to the probability of climate transition trajectories. This paradigm is then used in (Kenyon, Macrina, and Berrahoui, 2023a) to calculate the so-called CO2eVA charges based on a weighted average of carbon price scenarios.

Building on previous work (D. Kainth and Rebonato, 2024 and F. Venmans, 2022), we propose conditional probabilities for greenhouse gas emissions (GHG emissions) trajectories for firms within a specified industry sector for regions around the world. The GHG emissions trajectories are specifically linked to emissions policies stated by regional governments that would impact a specific commercial sector.

The objective of a probabilistic approach is twofold: first, to develop a tangible probability space that supports and links to policy objectives, and second, to develop a means to help firms, their stakeholders, and governments reduce their risks. Furthermore, we seek to develop a market-implied view of these transition probabilities to enable a more effective mechanism for financial markets to mitigate these risks.

To facilitate the development of such a market, we propose a class of financial instruments that are directly sensitive to transition risks and price in transition risk probabilities. As an example, we propose the *Climate-Contingent Convertible Bond*, abbrev. as CLoCo , whose financial structure permits firms to reduce the risk of default due to adverse climate transition policy trajectories over the product's lifetime. In developing the pricing theory for such an instrument, we utilise the bespoke probability space on transition trajectories, which underpin detailed firm-level models.

[1] As well as other assets and liabilities in their portfolio.

1.1 Financial Instrument Objectives

The primary objective of instruments such as the CLoCo is to reduce the risk of diminished returns or even default for firms, thereby contingently increasing the expected firm value. Whilst such instruments are designed to improve the robustness of firms and hence the wider economy to climate transition risks, introducing such instruments has wider implications in providing improved market transparency of transition risks through pricing. This can enable improved regulatory oversight for climate risks across issuing firms and their instrument pricing agents. Such instruments would provide further means to hedge climate risks in financial portfolios. With increased transparency of transition risks on firms, such instruments would provide a direct means for policymakers to assess the impact of current and future policy choices on firm valuations and capital flows.

Such instruments also provide a mechanism to reduce the private sector's reliance on public sector funding, allowing public capital to address critical sectors of the global economy, such as agriculture, that may not have easy access to financial markets.

Achieving such objectives requires a number of factors from clear policy communication, emissions measurement and viable risk frameworks; these concepts are described in detail in Sections 2 and 3, with the definition of the CLoCo bond described in Section 4.

2 Probability for climate policies

Within climate finance, there exist several means for investors to engage in accelerating the transition to a net-zero economy and society. Typical instruments such as loans, bonds, and primary equity serve as direct funding to enable firms to improve and add to improved lower emissions productions or processes.

Alongside investor activities, commercial banks are developing frameworks to assess climate-linked financial risk related to all counterparties, whether these seek to fund climate transition programs or just their susceptibility to weather events or wider economic pressures.

As such the financial system that seeks, provides and manages investment of these risks has taken an implied view of the wider externalities that emerge with climate risk. On inspection of an asset manager's portfolio or a bank's risk capital allocation (as far as risk capital is currently calculated) to transition-related finance, there is an implied (market) view of both risk and returns, where one might infer relative to other investment or capital allocations the risk preferences. As a consequence, investors have a view about the set of risks that may manifest themselves. Expressed in mathematical terms, a collective view is considered on probability distortions in financial performance measures due to the impinging impact of climate (change) events (e.g., a firm achieving its returns targets and estimating and managing their associated uncertainties). A firm's use of productive assets is a function of its risk appetite that faces uncertainties from input costs, taxation, consumer demand, policy restrictions and market factors. Future investment is defined by a firm's forward-looking view of its expected returns distribution.

With the introduction of frameworks such as TCFD, TPT, and SEC disclosure rules and the direct introduction of governmental net-zero pledges such as the Paris Accord, firms and their investors impose constraints on firms' capital deployment. Such disclosures and policies have driven concepts such as carbon taxation, carbon trading (carbon credits) and cross-border trade tariffs linked to emissions (CBAM) in the EU (Europen Commission, 2023). Investors are operating in a world where policymakers and regulators are applying a set of constraints on activities that can decrease GHG emissions. Risk to firms is manifested in a number of ways: (i) enforced restrictions on emissions leading to prosecution or direct economic/legal penalties, (ii) economic disincentives such as carbon taxes, and (iii) the impact of competition from firms with lower emission profiles. These constraints exist alongside policy incentives to reduce GHG emissions, such as consumer subsidies for new products. Furthermore, national-level penalties may be imposed within the EU on nation-states or further increased taxation on profits for firms with high GHG emissions.

Investors in firms subject to such regional policies consider the likely impact of such policies over the horizon they wish to engage with. These views are formed alongside questions about the specific nature of firms they engage with; these factors include current knowledge of their financial position, capital structure controls, business strategy and associated plans, and competition. In addition, investors need to understand what a firm produces, its impact on its business processes on key metrics such as GHG emissions, and its by-products from designated pollutants to disposal costs.

2.1 Manifestation of transition risks

For firms subject to climate change policies, variation in future policies may pose a material impact on their current and future business performance and, hence, their market-traded instruments. Within the EU, for example, the *directive on corporate sustainability due diligence* (Commision, 2022) puts forward the mandate that firms reduce their emissions in their business process or else be subject to compliance orders, legislated fines, as well as civil liabilities. Such a mandate provides a clear vector for firms' non-compliance. Whilst the magnitude of the impact is uncertain, it is conceivable that regulators would assess the feasibility of the speed of transition across a wide number of firms and assess whether a firm has taken actions that are in line with other firms within an industry. For example, the speed and cost of decarbonisation may be economically prohibitive, so much so that consumers do not engage with a new product, as has been seen with the current uptake of electric vehicles and the challenge put forward by manufacturers in the UK (Guardian, 2024) and the purchase of heat pumps in the UK (National Audit Office UK, 2024). In the case of electric vehicle sales, UK firms face a direct penalty for each vehicle produced that does not meet the zero emissions criteria as part of the governmental transition plan.

Alongside policy mandates, firms in different jurisdictions are also subject to direct taxation on emissions (within their legal jurisdiction), and are also subject to emissions-based tariffs on exports to other regions, e.g., mechanisms such as the EU CBAM emission tariff scheme Europen Commission, 2023. Such taxation policies incur direct costs over time and are designed to bring the cost of high-emitting processes closer to the expected current and future costs of low-emission technologies.

Typically, a policy choice for a firm will impose constraints on its capital allocation. For firms to adapt to a specific policy, they need to deploy capital, whether from their funds or investment. Either decision may impact a firm's ability to manage its debt or returns on equity. However, unlike an investor's capital, for a firm to exit (or abandon) an asset investment for a potentially lower emissions technology inevitably comes with considerable economic frictions (losses)—options for hedging such capital risk are very limited. Consequently, firms that allocate capital to new renewable technologies that may not have reached a long-term and stable capital cost per unit face several challenges, including reduced margins and potential losses to maintain demand position with firms that are later investors in cheaper technologies. This could lead to increased default risk if firms cannot cover their liabilities. This is significant for firms and their customers that adopt transition technologies early, where it is conceivable that such low-emission technologies may become unprofitable compared to later emerging lower-cost technologies. There are many ways to manage such risks, from subsidies (requiring taxation) and investments from equity investors prepared to subsidise early-stage firms to achieve a break-even price to improved regulatory price-setting that ensures that forward-looking prices reflect the needs to cover early-stage investments across an industry. The use of regulatory price setting is commonplace for UK and EU electricity generators (UK Department for Energy Security and Net Zero, 2017) where electricity prices are effectively fixed via contracts for difference (CFD) to enable capital investments by utilities to proceed.

Aside from emissions, firms are considering the cost of adapting to a changed climate, whereby further investment provisions are made (or allocation of own funds) to reduce the level of potential damage from weather-linked events. This emerges as a cost driven by the need to insure, repair, retrofit, redesign and absorb losses from production outages.

In summary, the financial impact to a firm can include the cost per unit emission $C_{Tax/GHG}(t)$ and the cost $C_{r,i,a,o}$ incurred from damage repairs, insurance, adaptation and outage, and losses due to a demand reduction.

2.2 On corporate hedging

Firms are subject to a number of uncertain factors and engage in a number of strategies to reduce risk, thus taking financial positions in interest rates, foreign exchange and commodity markets to hedge. They also manage their supply chain risks through diversification and make assessments on operational risks. Alongside these factors, firms engage in the assessment of product investment and assess project-specific risks and uncertainty. Project investments are decided by expected returns on capital and their associated uncertainties. For firms, each project choice can be based on real options models of returns subject to uncertainty.

Adding climate policy uncertainty to the set of risk factors will increase the uncertainty of future returns. The volatility of the returns, conditional on available information, is expected to be higher.

For example, one might construct a probabilistic graphical model of the uncertainty set of policies to infer the potential outcomes for firm project (capital investment) returns and infer the range of impacts to a firm over the horizon for decarbonisation. Firms undergoing a transition of their business models from a set of high-emissions business processes/products to low emissions should asses their robustness to the set of uncertainty factors that will influence their profitability. This uncertainty will cover input prices (costs) in financial metrics and market factors, such as interest rates, foreign exchange rates, and credit and commodity prices. Most large firms engage in some form of hedging or strategies to reduce risk in financial markets. However, the impact of policy change creates a significant shift in demand and supply factors alongside potential impacts on taxation/subsidy/production factors for a firm.

2.3 On the dynamics of policy choice

For firms, a high level of confidence in policy mandates (or choice) is required to reduce risk. A recent example in the UK regarding EV production has highlighted the challenges firms face when policy changes and their tenure becomes uncertain. Understanding and being able to model the uncertainty attached to policies that may change before their specified expiry date is of great importance to firms seeking to mitigate the risk policy change brings forth. To address such a challenge successfully, one must consider current policies and the impact that may result from their modification. Across the literature, there is a set of well-documented causal factors that drive the trajectory of decarbonisation amongst climate-linked policies; these fall into the following categories:

Enablers and technological factors

- Technological innovation: The creation and refinement of new technologies and solutions to change and improve business processes—this is the primary enabler of mitigation and adaptation.
- Technological learning: This is the fundamental process whereby the cost of deploying technology reduces in value for each defined production unit over time. This process comes about through improved processes such as automation and the application of other new technologies or reduced material/capital/labour costs. Such cost curves have dominated the switch to renewable power with considerable reductions is deployment costs. In behavioural models, when presented with a choice of goods of equal choice, economic agents would choose either equally. However, the utility of a technology that has reduced emissions is more likely to be chosen, especially if the alternative solution may increase future risk (i.e., cost).

Drivers from direct policy factors

- Fiscal policy and subsidies: These are designed to switch customer preferences from high-emissions technologies/energy sources to lower a firm's overall costs, ideally leading to improved technological learning.
- Restrictive policies on firms leading to reduced economic activity or legal liabilities for high emission firms.
- Removal of decarbonisation policies: This may have a similar adverse impact on firms that have committed to reducing emissions and adapted their investment strategy to reflect their future demand forecasts. This could include the removal of subsidies/tax breaks or consumer incentives.

With the fundamental enablers/drivers from the list above, once the set of technologies and their costs (and a view of their likely future costs) are established, the ability to affect a transition is driven by the rate of capital formation. For each economic agent, there are operating constraints on the capital formation process. These constraints are driven by, e.g., firm or government credit quality management to reduce the risk of default and maintain a target cost of funding to ensure its continued function.

Any combination of the aforementioned policies will give rise to uncertainty in the target decarbonisation trajectory and, hence, the associated risks to a firm. Taking each set of risks in turn, technological learning impacts firms directly because as new technologies become more affordable, firms that have invested in more expensive technologies face increased competition from lower-cost products. Reallocating capital investment to new technologies, if commercially available, will enable firms to adapt their costs. However, firms would be likely to provide services that seek to maintain overall profit margins. Radical price changes to consumers may be unlikely if an industry sector has already invested in long-term higher capital cost assets. Hence, the risk of significant price shocks would be a function of the fraction of new technology versus the fraction of legacy low-emissions technology and its operational lifetime. Alternatively, most large market capitalisation firms may have taken similar investments with similar costs (provide evidence on margin, credit ratings, etc.). Hence, price competition may be marginal if a smaller firm enters with a newer technology. Another typical behaviour that exists is that new technologies arise from smaller firms that are typically funded by private equity (i.e., potentially subsidised by investors at diminished capital costs); due to the potential impact on larger firms' business models, they become subject to acquisitions, thereby mitigating the overall capital cost pressure of the set of larger firms.

Further to the point of accelerated technological learning, informed policymakers would be reasonably expected to be knowledgeable about projected cost changes and utilise this (e.g. through learning from frameworks such as IAMs) to define decarbonisation policy rates to enable or accelerate projects. Consequently, it is feasible that an informed policymaker might choose to enhance the decarbonisation policy in light of future reduced costs. This choice may be made more likely in the event of increased emissions concentration or increased physical damage from adverse weather events. Ultimately, the collective set of factors above, coupled with the ability to deploy capital to affect the implementation of a technology/process, is the economic observation and measure determining the likelihood of such a transition policy. However, with the emergence of viable financial instruments to help mitigate firm transition risk [2]

Building a probabilistic view of climate policy constraints In looking at the constraints of climate policy choice, it is natural to look for a set of metrics that would define an optimal transition—or an optimal policy switch. Such factors could include prices, impacts on inflation, employment, capital growth, asset values, population health, GDP growth, etc. It makes sense to define what could or should drive rational policy change. It is worth exploring factors that set limits to the current expected tolerance for a severe rapid decarbonisation and the concept of no new technological changes to drive down emissions at the other end of the decarbonisation scale.

Considering the case for no further action results in increasing GHG emissions and a considerable increase in physical damage to economic assets, and human and natural habitats. The associated temperature increases are anticipated to produce considerably larger second-order effects, such as increased migration, political unrest and conflict. Under such a scenario, choices are made regarding future values. Clearly, in the policy space, many nations/firms have expressed a vanishingly small desire for this to occur, and many nations are on a path to decarbonise.

At the other end of the set of decarbonisation rates are the policy choices to rapidly decarbonise. We may ask: Can we decarbonise the system within the space of a few years, and what would that take? To assess such a statement, one must look at the factors limiting such a rapid transition. These factors would include impacts on growth targets, GDP, capital investment rates, and capital costs. Current commonly used IAMs such as those used by the NGFS (NGFS, 2022; UK Department for Energy Security and Net Zero, 2023) have usually used fixed GDP (or with calibrations that reproduce the input GDP) growth trajectories such as those from the SSPs (Riahi et al., 2017). Consequently, the models do not fully propagate the impacts of externalities from climate-linked damages or constraints imposed from restrictive emissions policies. Due to impacts on growth and supply and demand volatility, prices will face increased uncertainty.

Such model-dependent scenarios may be used to estimate regional decarbonisation rates to the extent that the model can capture actual regional policies and, hence, a probability distribution derived from required decarbonisation. This is explored in the next Section 3.

3 Uncertain decarbonisation policies

Building on work by (Kenyon, Macrina, and Berrahoui, 2023b), Rebonato et al. (D. Kainth and Rebonato, 2024), and Venmans & Carr (F. Venmans, 2022), we propose a probability space that supports the probabilistic modelling of decarbonisation policies. The aim is to lay the foundations to

[2] Regulators and investors must be wary of higher emitting firms that may wish to issue such instruments without viable (e.g., commonly accepted) decarbonisation strategies.

build an approach that enables the adoption of likelihoods for decarbonisation trajectories at each point on a timeline.

3.1 Probabilistic policy scenarios for decarbonisation

We introduce a practical application of a probability space designed to enable firms to reduce or improve their resilience to climate transition risks. We investigate the concept of policy decarbonisation trajectories (used here synonymously to scenarios) that give rise to a tangible risk for firms actively required to reduce their carbon emissions as part of their business practice. This concept is explored in more detail in Section 2 and, in summary, would cover policies that mandate a reduction in Scope 1 and 2 grenhouse gas emissions (e.g., for electricity production and fuel transportation), see (Krach et al., 2023), and firms whose products give rise to indirect emissions, the so-called Scope 3 downstream emissions, such as the automotive industry, where there are clearly defined mandates to reduce overall emissions by a specified amount and by a given date else face an economic penalty such as a fine, restriction in economic activity, etc.

Roughly speaking, policy scenarios $\mu_{[T_i,T_{i+1}]}$, $i = 0, 2, \ldots, n \in \mathbb{N}$, are defined as a planned decarbonisation trajectory over a time period $[T_i, T_{i+1}]$. The instantaneous emissions $g(t)dt$ in any one period are accumulated over the infinitesimal interval dt from cumulative economic activity (production) $P(t)dt$ in a region r for a given industrial sector s. The region can be defined at a geo-spatial scale, i.e., from the size of a city, a country, or all the way to global scale. The cumulative emissions over $[0, T_i]$ are given by

$$G(0, T_i) = \int_0^{T_i} g(t)dt, \tag{1}$$

so that the emissions generated over any interval $[T_i, T_{i+1}]$ can be written as

$$G(T_i, T_{i+1}) = G(T_{i+1}) - G(T_i) = \int_{T_i}^{T_{i+1}} g(t)dt. \tag{2}$$

A useful quantity is the change in emissions per period of time given by

$$\mu_G^s(T_i, T_{i+1}) = \frac{G^s(T_{i+1}) - G^s(T_i)}{\Delta T_{i,i+1}}, \tag{3}$$

where $\Delta T_{i,i+1} = T_{i+1} - T_i$, and the superscript s denotes a specific economic sector. Thus, μ_G^s is the emission policy rate for sector s. For firm k, the policy-dependent decarbonisation rate 3 can be written in the form:

$$\mu_G^s(t, T_i, T_{i+1}) = -\beta^s_{[T_i,T_{i+1}]} \times G^s(T_i)/\Delta T_{i,i+1} \tag{4}$$

where for $G^s(T_i) > 0$ [3] we have

$$\begin{aligned} \beta^s_{[T_i,T_{i+1}]} &= (G^s(T_i) - G^s(T_{i+1}))/G^s(T_i) \\ &= -\mu_G^s(t, T_i, T_{i+1})\Delta T_{i,i+1}/G^s(T_i). \end{aligned} \tag{5}$$

[3]Not necessarily firms have overall negative emissions. However, this can be incorporated as an additional requirement.

Hence $\beta^s_{[T_i,T_{i+1}]}$ can be used as the policy standard measure of proportional decarbonisation for any firm k in sector s to remain on target with the policy for sector s, ie.$\beta^s_{[T_i,T_{i+1}]} = \beta^k_{[T_i,T_{i+1}]}$. This enables each firm to assess whether they are aligned or otherwise with a policy μ_G^s specified for the period $[T_i, T_{i+1}]$.

To build an effective view of the decarbonisation rate across a sector, the measure requires a reliable measurement and audit of the values of associated emissions from firms and the resulting sector (or product). A firm k in region r and sector s may wish to express the rate $\mu_G^k(T_i, T_{i+1})$ of decarbonization for each reporting period $[T_i, T_{i+1}]$ or a relative amount $\mu_G^k(T_i, T_{i+1})/G(T_i)$ compared to the beginning of the monitoring period. As we intend to use μ_G as a measure to define policy trajectories, firms can also choose to indicate their robustness to default (or Impact to earnings) to different decarbonisation trajectories. Such an investigation will be explored in Section 3.4.

3.2 Subjectivity of probability spaces for decarbonisation

We introduce a probability space $(\Omega, \mathcal{F}, \mathbb{P})$, where the probability space $\mathbb{P}$ is a subjective probability measure. Along with this probability space, we also introduce a filtration $(\mathcal{F}_t)_{t\geq 0}$ (the information available up to time t), which will be necessary to evaluate expectations about random variables. Before we deal with the detailed construction of a filtered probability space in the context of climate change, mathematical climate finance, and the decarbonisation of economies, in general, we shall first discuss the subjectivity of the probability measure $\mathbb{P}$ and the approach to constructing the probability space.

The envisaged probability space shall be designed to allow the modelling of future scenarios on a probabilistic basis. The question one would like to answer is: What is the probability that a specific future scenario will be realised among all the possible ones? The answer might be 43% if given by one entity but might be 77% if provided by another. So, we consider the situation where the selection of a probability measure employed to answer the above question depends on who responds. This gives rise to the subjectivity of the probability measure. One sees that the subjective probability measure $\mathbb{P}_i$, where $i \in \mathbb{N}$ is the i-th entity answering the question, may have little to do with climate science (physics, chemistry, etc.), but rather with the perceived subjective probability attributed by an entity to how likely a specific future scenario will occur. One then may ask what lies at the basis of the subjectivity of the selected probability measure, in other words, what influences the subjectively perceived probabilities attributed to future scenarios. Here, we can think of experiences that an entity deems relevant, subjective beliefs (climate change proponent versus climate change denier), but perhaps most importantly, the information an entity considers that impacts the perceived probabilities of scenario outcome. If information is regarded as having a significant influence on the subjective probability measure, then the role of the filtration $(\mathcal{F}_t)$ moves to the foreground. One would consider indexing the filtration, analogous to the probability measure $\mathbb{P}_i$, to obtain a subjective filtration $(\mathcal{F}_t^i)$ associated with the

i-th entity. The result would be a subjective filtered probability space $(\Omega, \mathcal{F}^i, (\mathcal{F}^i_t), \mathbb{P})$ linked to each entity $i \in \mathbb{N}$. The sample space Ω would be shared in common by all entities and the filtrations could be ordered to obtain a sequence of subfiltrations $(\mathcal{F}^1_t) \subseteq (\mathcal{F}^2_t) \subseteq \ldots (\mathcal{F}^i_t) \subseteq \ldots (\mathcal{F}^n_t)$.

Where does the role of subjective filtration matter in pinning down a subjective probability measure? Consider the evolution of a probability distribution over time; that is, we consider a time-inhomogeneous distribution function. In the next Section 3.3 we discuss how views on probabilities for transition policies can be informed by improved modelling so that one can price instruments such as CLoCos in Section 4. Their pricing would reveal a direct view of implied transition risks.

3.3 Construction of transition policy probability spaces for firms

To build a viable climate transition space, it is essential to understand the likelihood of required policy decisions at any given point in time. It is helpful to build an understanding of the primary enablers for the transition, the factors that determine the uncertainty in outcomes and a set of constraints that may be regarded as uncertain in their own right. This system will effectively constitute the space for asset allocation strategies to address the need to evolve current production. The asset allocation agents can be split into public expenditures funded through taxation and private investors. The set of asset allocation strategies is naturally large; however, it is worth exploring several choices made in allocating capital and ensuring returns on assets. Asset allocation choices are primarily split in standard private investment models across sectors for debt and equity investment; here, it is natural to expect that investors in firms would demand returns comparable to current expectations across their portfolio. Alongside this, private investors will invest in sovereign and municipal bonds/projects, usually providing lower yields but improved credit loss protection.

Policymakers that choose to impose carbon taxation or financial restrictions/penalties for firms with high emissions will create a mechanism that will define a pathway that can be modelled to permit an estimation of the economic impact of each level of taxation. Other policies that impact firms by 'fining' them for excess emissions will play a similar role. The economic impact of such fiscal policies can vary significantly depending on how the proceeds of taxation are redistributed; for example, the tax funds can be made available to consumers to purchase low emissions solutions from the same company, reducing the overall financial impact on the sector. As such, the ability to capture such taxation effects will be required to be included in the modelling.

In Rebonato et al. (D. Kainth and Rebonato, 2024), the authors put forward a set of concepts that aim to set realistic expectations in setting the set of future decarbonisation trajectories; their set of limits defines a conditional probability space based on the carbon taxation level. This is based on the least cost hypothesis built into many IAM model paths. Within the text (D. Kainth and Rebonato, 2024), the authors explore reasonable bounds for decarbonisation trajectories based on abatement expenditures as a fraction of GDP and the required capital expenditure to install renewable energy generation. Specifically, they estimate the SSP2-19 within the DICE model (Nordhaus, 1992; Riahi et al., 2017) would require approximately USD 6 trillion in 2030 alone for wind turbine installation, which at the cost of around USD 2 - 4 million per turbine implies 1 million turbines. According to the authors, this number contrasts with the current installation of 341,000 turbines. Furthermore, they use evidence of typical expenditure/tax take as a fraction of GDP for other social programs such as healthcare and use this to set likely upper bounds on the tolerated level of carbon tax and propose that the total increased tax take would be of order 3% to 8% of GDP based on the distribution of taxation to GDP for other social programs. Within this study, they conclude that some of the SSP pathways imply an unrealistic level of emissions taxation > 8% of GDP on top of already committed taxation. The paper is focused mainly on carbon taxation policies as the mechanism that defines the transition; this paper intends to expand on this concept to explore other factors, whether from the probability space implied from other models as proposed by (F. Venmans, 2022) and future work proposed by ourselves on improving firm-level modelling that will influence decarbonisation rates.

In general, capital formation will consist of investment from both public and private sectors, with an indication from several studies citing a requirement to deploy USD 9 trillion (McKinsey and Company, 2022) per annum to affect the transition. This is decomposed into current spending requirements of USD 5.7 trillion and a future required spending of USD 3.5 trillion.

Questions on the speed of capital expenditure, whether for consumers or at the firm level, tax take and the ability of supply chains to meet the required demand for renewable energy technologies also set bounds on the set of decarbonisation trajectories that can be realistically implemented to define the rate of decarbonisation over any period. Furthermore, increasing disruption to current infrastructure, food production, and company assets from rising adverse weather events over time will impact firm earnings levels and volatility. Clearly, anticipated capital expenditure is a function of anticipated revenue growth for each of a firm's business units that will be invested in. This will naturally be a function of the uncertainty in these processes, which may have an adverse impact on expectations for decarbonisation rates.

From the perspective of a bank's risk management function, any policy choice may be feasible. However, it is important to develop a richer understanding of the drivers of policy choice to assign more informed likelihoods to expected and tail risk events. A probability measure built on the capital formation process conditional on economic activity provides a general means to assess the likelihood of the rate of decarbonisation. The capital formation process includes both public and private corporate debt. Hence, an understanding of the capital formation process and its associated drivers for private firms, the allocation of private investment into government debt (whether sovereign or municipal), and the cost of decarbonisation (abatement costs) allow all economic stakeholders to build a view on the likelihood of transition speeds for each industry, conditional on a growth target.

3.3.1 Measuring market-implied climate transition probabilities

In assessing climate transition probabilities, the capital formation measure permits an observable estimate of the expectations of market implied returns and for a given risk or, equivalently, a view on risk for a given expected return. The use of reverse optimisation as outlined in Section 3.3.1 can provide an implicit view on climate change transition probabilities based on the allocation of debt across firms in a sector allocated to decarbonisation projects. More conventional studies look at the potential impact on firms' defaults as part of a stress testing analysis much along the lines of recent studies performed, for example, by the ECB and the BoE (Europen Central Bank, 2023; Bank of England, 2022). Studies of climate-linked probabilities of default (PD) through bond or credit spreads may provide an indication of transition risk exposure. As firms will look to adjust their business models to control for such risks (and investors and financial firms may be oblivious to them), the market may not be able to express directly the implied transition risk. For example, for firms that actively control their capital structure to mitigate default risks (or, more generally, to be in line with their internal growth and risk appetite), new factors such as climate transition policies (or other climate-driven costs) will likely be observed in impacts to firms revenue/earnings hence their equity values. Assessing such impacts is explored in the section below.

Measuring investor-implied climate risk from reverse optimisation One other approach that can be applied to assess returns distributions for any investment is the so-called *Reverse Optimisation*, see e.g., (Dimitris Bertsimas, 2011). The implications are that investors are (and likely will) be engaged in either equity or, notably, bond investments with firms. Consequently, the set of all asset allocations for firms in a sector or across sectors reflects views of risk and returns over the holding period of the investment. Whether this investment asset is a bond or equity, its valuation typically reflects an implicit cashflow (e.g., coupon) or earnings expectation of that asset for a period that may be longer than the investment holding period [4]. Two Sigma (TwoSigma, 2020), for example, have performed a study looking at implied investor returns; in this study, they used a study on a global market portfolio consisting of exchange-traded equities, private equity, bonds and loans, real estate, and commodities, with the portfolio weights as given in Figure 1 based on the work of Doeswijk, Lam, and Swinkels (2019) (TwoSigma, 2020).

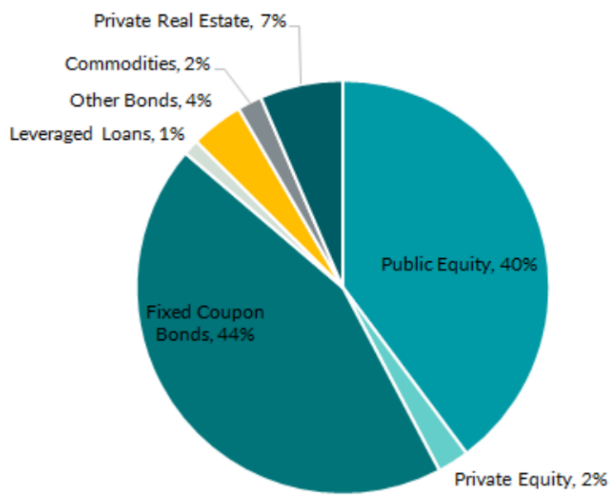

Figure 1: *Global investor asset allocation as determined by (TwoSigma, 2020).*

3.3.2 Bayesian views of transition-linked risk

Within a model framework such as (Cormack et al., 2020) and other scenario modelling frameworks it is possible to ask 'What-If' scenario questions on potential outcomes for firms under different policy decarbonisation trajectories. Of particular interest here is the question of how default probabilities may be affected by adopted or imposed decarbonisation policies given the other usual constraints, such as prevailing market conditions and available balance sheet information. Assessing the specific market-implied transition-dependent probability of default for a firm based on the relevant credit spread curve over a period $[T_i, T_{i+1}]$ and determining the model-implied view of default for the same period is central to any firm performance scrutiny. Aside from assessing default risks, it is also possible for firms to assess the potential impact on revenues and earnings and to explore the requirements of pricing or cost reduction to maintain target business margins. Such analysis can be used to form a discrete set of outcomes and hence test a firm's resilience (robustness) to potential decarbonisation policies. Extending such probabilistic analysis requires a richer dynamic probability space that is considered in Section 3.4.

3.4 Construction of the decarbonisation measure

We propose that the capital expenditure rate for low emissions technologies probability measure that defines the outcome is based on the likelihood that this capital formation is split between investment in corporate securities (debt or equity) and government expenditure driven by sovereign and/or municipal debt issuance or from direct taxation. The framework below will outline allocation strategies by governments and private investors and highlight how we can derive a probabilistic distribution for likely decarbonisation.

3.4.1 Company capital formation process — Mathematical Formulation

Company capital investment is expected to be the most significant driver of decarbonisation. Furthermore, this rate is likely to inform policymakers about the likely achievable emissions reduction rate, informing government investment strategies to reduce emissions in hard (expensive) industry sectors. For the firm-level capital formation process, let $F_{k,s}$ correspond to

[4]This is clear for most bonds and for equity valuation models that account for future net earnings or dividend growth in valuation which has been demonstrated through empirical observation.

a firm k in industry sector s. Each firm will currently or in the future have an investment in a production or service where the annual production output is defined as $P_{k,j}(T_i, T_{i+1})$, where j is the index over the list of technologies, i is the annual time index. For each production unit, we introduce the concept of a capacity unit to produce $\Gamma_j(T_i, T_{i+1})$ units over the interval $[T_i, T_{i+1}]$, each unit P_j of production gives rise to an amount of emissions g_j. Each capacity unit Γ_j is utilised at a rate $U_j(t) \in (0, 1)$ with efficiency $E_j(t) \in (0, 1)$, and has a production rate of $P(t)$ per unit time; hence the amount of production is given by:

$$P^{TOT}_{k,j}(T_i, T_{i+1}) = \Gamma_j(T_i, T_{i+1}) * U_j(T_i, T_{i+1}) * E_j(T_i, T_{i+1}) * P(T_i, T_{i+1}) \quad (6)$$

this production gives rise to a total emissions G_j given by

$$G_j(T_i, T_{i+1}) = P_{k,j}(T_i, T_{i+1}) \times g_j. \quad (7)$$

The capital cost to develop a unit of capacity for technology j at time t is $\kappa_j(t)$. For a firm operating in a given business segment, it may expect future demand for its product at time t to be $D_{k,j}(t)\Delta t$ the demand over an interval denoted as $D_{k,j}(T_i, T_{i+1}) = \int_{T_i}^{T_{i+1}} D(t)dt$ such that $P^{TOT}_{k,j} = D_{k,j}(T_i, T_{i+1})$. For each unit of production, the firm sells this product at a price $p_{k,j}(t)$ giving rise to total revenue for that product of:

$$R_j(T_i, T_{i+1}) = P^{TOT}_{k,j}(T_i, T_{i+1}) \times \langle p_{k,j} \rangle \quad (8)$$

where $\langle p_{k,j} \rangle$ is the average price of the product sold over the period. Further, a firm may expect specific changes in revenue from the sale of its products based on the demand functions $D_{k,j}(t)$; this expected demand will inform its capital expenditure commitments to each product j. Alongside the revenue generated, each unit produced incurs a cost $c_j(t)$ with a total cost:

$$C_j(T_i, T_{i+1}) = P^{TOT}_{k,j}(T_i, T_{i+1}) \times \langle c_{k,j} \rangle \quad (9)$$

the total earnings from the sale are given by:

$$EBITDA_j(T_i, T_{i+1}) = R_j(T_i, T_{i+1}) - C_j(T_i, T_{i+1}) \quad (10)$$

Firms are also subject to uncertainty in demand, price and costs denoting $P_R(\Omega, \mathcal{F}, \mathbb{P})$, $P_p(\Omega, \mathcal{F}, \mathbb{P})$, $P_c(\Omega, \mathcal{F}, \mathbb{P})$, $P_{EBITDA}(\Omega, \mathcal{F}, \mathbb{P})$, the set of probability spaces for revenue, prices, costs and earnings for the firm at time t. Within this proposal, we will investigate likely stochastic processes that describe these probability spaces to enable the development ultimately of a viable probability space for climate transitions.

Denoting the set $j \in \tilde{\Lambda}$ as the set of all high emissions solutions and the set $j \in \hat{\Lambda}$ such that the product (e.g. Energy) from the set $\tilde{\Lambda}$ has at least one replacement from the set $\hat{\Lambda}$, the set $\hat{\Lambda}$ may contain the null replacement i.e. a firm may choose not to replace its high emissions production. The Implication is that the firm will be required to substitute its production or, equivalently, find alternative sources of revenue by investing in new capabilities.

If the value of a capital asset is denoted as $K_{k,j}$, where k is the index over firms deploying technology j. Denoting the rate of depreciation for an asset as $(K_{k,j}/T_{k,j})\Delta T$ over a period of time $\Delta T_{i,i+1} = T_{i+1} - T_i$ as $\Delta K_{k,j}(T_i, T_{i+1})$, this function may be the commonly used straightline depreciation function $\Delta K(T_i, T_{i+1}) = \kappa_j(t) \times \Gamma_j \times (\Delta T_i)/T_{TOT}$ where $\kappa_{k,j}(t)$ is cost of capital per unit of capacity production for product j or can be substituted with other depreciation functions that reflect the future value of production assets on a firms balance sheet.

A firm subject to a regional policy requiring it to reduce its overall emissions at a policy rate of μ^s_G will require that the firm reduce its overall level of production of its high emissions products $j \in \tilde{\Lambda}$, this results in an effective reduction in utilisation of the high emissions capacity units. Whilst a firm may have an optimal strategy to retire certain high emissions production over others, under a decarbonisation mandate, the set of firms must decarbonise the ensemble of technologies at the required sectoral rate. As an approximation, an expectation across the set of firms reducing output from emissions can be taken such that a reduction in emissions corresponds to a decrease in production for high emissions technologies:

$$\Delta P_{k,j}(T_i, T_{i+1}) = \frac{G(T_{i+1}) - G(T_i)}{g_j}, \quad (11)$$

where $g_j > 0$. For a firm investing to achieve an anticipated demand $D_{k,j}(t)$ for its production or, more specifically, revenue and earnings targets, the change in high emissions production may need to be replaced by low emissions solutions, hence requiring a portion of the investment to replace the equivalent output with a lower emission product $\hat{j}$ by an amount:

$$P_{k,\hat{j}}(T_{i+1}, T_{i+2}) = \Gamma_{\hat{j}}(T_{i+1}, T_{i+2}) \times U_{\hat{j}}(T_{i+1}, T_{i+2}) \times E_j(T_{i+1}, T_{i+2}) \times \rho_{\hat{j}} \quad (12)$$

This would incur an emissions reduction-driven capital expenditure of:

$$\Gamma^g_{\hat{j}}(T_{i+1}, T_{i+2}) \times \kappa_{\hat{j}} \quad (13)$$

Alongside this sum is a potential required investment for replacing current high—and low-emission technology and new investment in anticipation of future demand growth.

$$(\Gamma^r_{\hat{j}}(T_{i+1}, T_{i+2}) + \Gamma^d_{\hat{j}}(T_{i+1}, T_{i+2})) \times \kappa_{\hat{j}} \quad (14)$$

Factors that impact firm capital growth Firm lending and equity issuance are driven by the anticipation of returns, as a consequence each firm engages in financial forecasting, design of business plans and strategy and the management of the associated risks whether related to business operations, trading environment and financial risks. Consequently, firms manage their debt and equity levels (capital structure) to maintain a desired risk profile. This can be measured as a set of operating bounds Θ_{u,b_k} where u, b correspond to a set of upper and lower bounds that may be regarded as absolute or fuzzy boundaries with defined probabilistic support for the boundary condition. These operating bounds are generally a function of the current firm's financials, market variables such as interest rates and the firm's views of its future financials and market conditions. Such rules are ultimately linked to the firm's projections of its profitability, its ability to service its liabilities and maintain its targets for its asset utilisation.

Hence, the rate of capital formation for a given set of firms in a sector can be defined by

$$K^s(t; T_i, T_{i+1}) = \sum_k \sum_j K^s_{k,j}(t|\Theta_{u,b}). \qquad (15)$$

In Section 3.5, we investigate the distributions over time for a commonly used set of financial operating bounds for firms to develop a process in a later paper for pricing securities introduced in Section 4.

Impact of climate policies on firm growth Policies that require strict adherence to emissions levels and a decarbonisation policy will force a direct reduction (shutdown) of high-emitting production in firms. Consequently, a firm's decarbonisation policy has a strict upper bound, which is the policy-mandated trajectory. Firms with a sufficiently strong balance sheet and access to technologies to decarbonise their production can narrow the uncertainty about achieving a set decarbonisation goal.

3.5 Empirical observation of capital formation process

One can analyse several company operating ratios for capital formation to assess the rate of capital formation. Forecasting anticipated future revenue and earnings is at the core of any well-managed capital formation process. Ultimately, a firm's earnings define its ability to service its debt, and hence, firms typically monitor the total amount of debt to earnings (usually EBITDA); further management ratios can be deployed to build a richer set to define the complete set of operating bounds Θ_{u,b_k}. However, it is informative to look at the process that is implied from monitoring the ratio Net-Debt-to-EBITDA ratio θ^{ebitda}_k across each sector k:

$$\theta^{ebitda}_{u,k} = \frac{NetDebt}{EBITDA} \qquad (16)$$

Within each sector, each firm's earnings are contingent on several factors as highlighted in Section 3.4.1, which will result in an emergent set of uncertainties that will define the process volatilities of the values of θ^{ebitda}_k. The observed time-series of $P(\theta^{ebitda}_k), t|\theta^{ebitda}_{k,0}, t_0)$ are given below for the S&P 500 in Figure 2.

3.5.1 Firm revenues and earnings ratios

Knowledge of a firm's likely earnings is required to understand a sector's ability to raise debt. Rich agent-based model frameworks allow one to assess the impact of several scenarios on a firm's revenue and earnings at any given time. Knowing how a sector (at the product level) would perform is essential for policymakers; hence, knowledge of likely earnings for a given demand forecast is informative. In figure 3, we plot the EBITDA margins defined as $EBITDA/Revenue$ for the set of US firms in our sample as an illustration. The ratios demonstrate that industrials and utilities typically actively manage business margins within the sector. The margin and inventory management process in an industry sector provides the set of rules for an ABM to manage future prices and impacts on

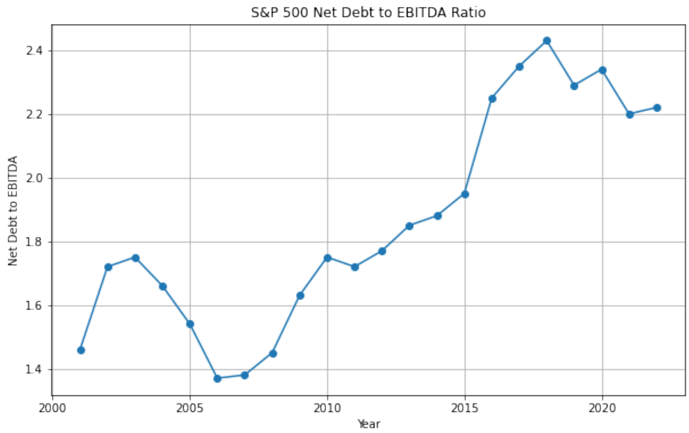

Figure 2: *Examples of annual NETDEBT/EBITDA ratios for the S&P 500.*

supply. Firms in each sector will have planned their business strategies on forecasts for demand and prices for their products within this competitive environment, hence with a view on the distribution of revenue defined by the probability space $P^k_R(\Omega, \mathcal{F}, \mathbb{P})$, the earnings margin $P^k_M(\Omega, \mathcal{F}, \mathbb{P})$ and the set of rules defining capital formation $\Theta^k_{u,b}$.

As a consequence to complete the picture of a firms ability to deploy capital to decarbonise, we utilise a process for future revenues based on a set of firm-level processes $P^k_R(\Omega, \mathcal{F}, \mathbb{P})$, that gives rise to the sectoral revenue $P^s_R(\Omega, \mathcal{F}, \mathbb{P})$.

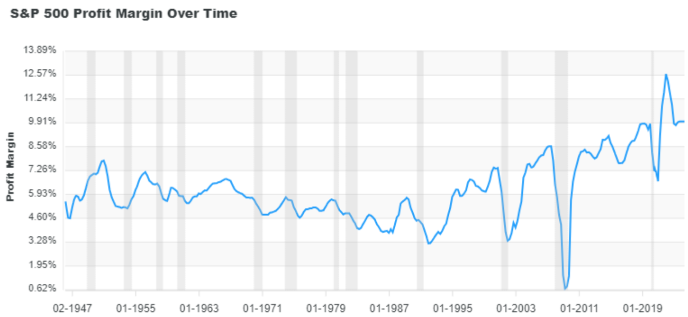

Figure 3: *Example of quarterly median profit margin for the S&P 500 index.*

3.6 Modelling Process: Agent-based models

Building a process that captures the set of constraints on a firm and the effect of climate externalities from policy to the impacts of climate-linked losses requires detailed model frameworks. Model frameworks such as agent-based models (ABM) offer a powerful means to explore such impacts.

A firm-level Agent-Based Model (Firm-ABM) consists of a number of rules that effectively govern investment decisions, dividends, cash-flow management, capital structure, risk appetite, and hedges and ultimately give rise to the firms' emergent state. Within the academic literature, the firm agent-based model from (Cormack et al., 2020) has an interface to a wider scale technology and macro-economic scenario set from integrated assessment models such as those used by the NGFS (the model used in the paper is based on the partial equilibrium model framework GEM-E3 POLES). The IAM in this model architecture provides a temperature pathway due to the energy production and utilization models. These demand and supply pathways are used to drive expected demand predictions for the modelled firms. The firms that are modeled are subject to a set of agent rules that define the management of their capital structure and profitability targets based on known data of the firms. Such data on the firm involves knowledge of specific costs covering operational, variable and funding and information on its credit quality metrics and investor engagement communications covering, for example, dividend payments. Furthermore, the firms engage in micro-competition based on price and capacity to supply. The model framework integrates macroeconomic factors such as government yields and inflation and detailed specific economic supply and demand drivers. The output of such a model consists of financial data on the firm's performance (eg. Balance sheet, income statement and cash flow statements) and information on its non-financial performance, such as emissions, physical production and capacity. Also, specific data on firm-level physical damage. In terms of financial performance, the model produces a value for the firm's equity and returns, its probability of default, losses given default, credit rating and funding costs. Such frameworks provide a means to assess a firm to a set of policy choices, changes in demand, and funding costs as part of a full stochastic analysis. Such micro models can be used in conjunction with macroeconomic ABMs (Macro-ABM) such as that from (Poledna et al., 2023) to inform the overall potential emerging impact from decarbonisation policies [5].

3.6.1 Macro-Economic, Micro-Economic, Industrial Sector- and firm-level revenue process

Central to determining the rate of decarbonisation is an understanding of expected economic activity (growth or otherwise) over the firm's forecast horizon. Within this framework, we use concepts such as firm-based forecasts (that do not have perfect foresight) that is based on to use a forecast of firms' revenues based on predictions of GDP/sectoral demand, for example. In general, as part of the proposed ABM for the firm, these predictions would be based on the model's internal forecast period on period. For illustrative purposes for this paper, the forecast for GDP from the IIASA SSP forecasts (Rogelj et al., 2018; Riahi et al., 2017; Gidden et al., 2018), the latest set of SSP pathways are shown in figure 4.

A further publication will fully construct the processes outlined above, expanding on concepts such as a firm-level ABM and exploring alternative modelling frameworks.

3.7 Summary of the Implications for sectoral and firm level climate decarbonisation probability distributions

In this section, we propose the set of microeconomic factors to be considered for each firm when assessing its ability to achieve a target decarbonisation rate alongside its views on potential growth. With a view on a firm's revenue, margin and set of capital constraints with a risk modelling framework of

[5]This study is reserved to a future analysis

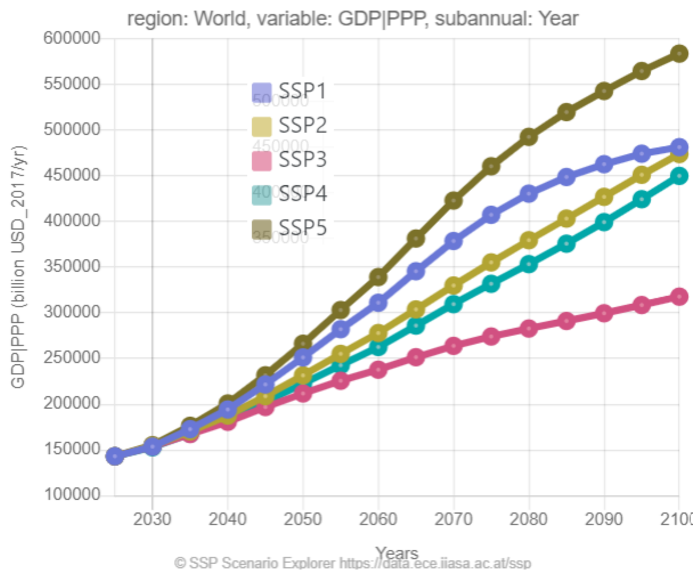

Figure 4: *SSP pathways for global GDP (Source IIASA SSPs 2023 update).*

a firm and its sector, it is possible to perform forward-looking stress analysis and determine the set of policy-mandated decarbonisation trajectories $\tilde{\mu}_G(t)$ that could lead to either default or a significant reduction in financial performance for said firm. More generally, the ABM permits us to investigate the set of decarbonisation rates amongst firms in a sector and the implications for firm revenues and earnings growth. Consequently, this allows us to assess the expected rates of decarbonisation for a sector given a revenue/earnings growth target and, hence, the distribution of decarbonisation across the firms in a sector.

For a firm, understanding the lower bound on the decarbonisation rate (the decarbonisation trajectory is negative) conditional on a growth target [6] is critical for firm-level transition risk management. Furthermore, this concept can be extended to explore the likely speed at which capital formation can take place to effect a transition and, hence, sectoral emissions trajectories. With a hypothesis for the process $P^k_R(\Omega, \mathcal{F}, \mathbb{P})$, the earnings margin $P^k_M(\Omega, \mathcal{F}, \mathbb{P})$ and the set of rules defining capital formation $\Theta^k_{u,b}$ and a defined set of decarbonisation solutions with their associated costs it is possible to build a set of conditional decarbonisation likelihoods, i.e. $P(\mu^s_G(t)|G(t_0, \{k\}))$, this can be extended to build a process for $\mu_G(t)^s$, $P^s_{\mu_G}(\Omega, \mathcal{F}, \mathbb{P})$.

For policymakers, such insights enable the assessment of growth rates given a sectoral decarbonisation rate, permitting a deeper understanding of how a policy change may affect risks in a sector. Its our intention with the proposal of the CLoCo (described in detail in Section 4)to permit policymakers to understand the potential impact in firm *market* valuations across the firms within a sector as an equivalence of the potential value of required governmental funding that would have been required to ensure no erosion of firm *market* values.

[6]The growth target will be defined to link to firm fundamentals eg. revenue/earnings not to its stock price, for example,, to avoid further uncertainty.

4 Climate contingent convertible bonds (CLoCos)

A **CL**imate c**o**ntingent **Co**nvertible bond CLoCo is a convertible bond designed to be issued by firms engaged in funding a clearly defined transition to lower GHG emission processes. Specifically, they permit the issuer of the bond to convert it to Equity at a defined put price S_{CP} or an alternative bond where a reduced notional N_{CP} (the so-called trigger event) is returned to bondholders should a government introduce an adverse climate policy for an industry sector over the lifetime of the bond. In a standard contingent convertible, the trigger event may be motivated by a firm's capital requirements based on capital ratios and firm or market value. However, for a CLoCo, the trigger event is defined by a policy-driven decarbonisation trajectory $\mu_G(t)$, or the evolution of sectoral emissions. For example, an increase in emissions in a sector over time would effectively increase the magnitude of the decarbonisation policy trajectory, triggering the bond.

The implications for a firm that issues such a security would be to improve the firm's default or financial risk robustness under policy uncertainty with the objective. This allows the firm to issue Equity in the event of an adverse policy to reduce debt levels and may result in a significant risk reduction for both bond and equity holders.

In addition to a firm being able to reduce its own risk, the broader issuance of CLoCo bonds at potentially different decarbonisation trigger rates $\mu_G(t)$ or otherwise would permit the development of an implied view of transition risks and decarbonisation rates across a regional sector, offering investors a means to engage with or hedge this risk.

4.1 CLoCo bond features

The principal risk management feature of the CLoCo bond is that it is designed to reduce a firm's liabilities, specifically in the event of an adverse subsequent policy choice for decarbonisation companies in a given sector and regional jurisdiction. The ability of the firm to convert the bond in such an event provides a means for the firm to reduce its probability of default and reduce the potential need for governments to bail out firms as a consequence of adverse policy choices. This last feature may be desirable for all stakeholders in regions where a transition firm may play a significant role in that economy.

4.1.1 What Constitutes an Adverse Policy Choice and how would firms and markets engage with CLoCos

The characteristics of an adverse policy impact on a firm must be clearly defined by each firm issuing the security. Clearly, the region the firm operates in needs clarity in its policy communication, with well-defined decarbonisation rates μ_G^s, for example. Defining an adverse policy can be communicated to investors using, for example, scenario analysis of increasing decarbonisation rates and how this may impact a firm's revenue or earnings or potentially even lead to default. Firms would likely wish to benchmark their potential performance relative to other firms in their sector if seeking to maintain their relative competitive position. The use of an instrument such as the CLoCo would be best used to strengthen the balance sheet of those firms who find they are less robust to changes in policy before default rather than as an alternative to default. As part of the analysis of choosing to issue a CLoCo a firm would assess the impact of likely credit ratings downgrades or the cost equity is given that at the time of a policy announcement, markets in a sector may be suffering from increased volatility and investor risk aversion and hence find it difficult and/or expensive to raise further funding(In equity or debt) in likely adverse market conditions.

Conversely, it is unlikely that firms in jurisdictions that have poorly communicated or have uncertainty in policies and their enforcement would be able to engage investors. This lack of certainty relative to jurisdictions with improved certainty with access to a CLoCo market would likely attract more investment due to its ability to reduce risk

4.2 Climate trigger: the conversion to equity

The trigger event specifies the exact circumstances where the bond will be converted into shares or where a write-down of the bond notional will occur. Setting aside market-based triggers such as share price levels, which have been well studied (Martynova and Perotti, 2018), trigger events based on defined

The principal feature of the CLoCo bond is an option to convert to equity contingent on an adverse climate policy introduced by governments. The issuance of the bond should be linked to funding a well-defined decarbonisation project[7], it is in the firm and investors' interests to be able to limit the subsequent risks related to such a project, specifically those linked to policy changes away from government commitments at the time of issuance. The manifestation of these risks could occur in several different scenarios. For example a firm that has made a clear strategy statement to engage in decarbonising its production in line with a government-mandated average decarbonisation rate $\mu_G^s(t, T_0, T_n)$ where T_0 is the time of issuance, T_n is the time stated policy target time for GHG emissions such that emissions at T_n are specified as $G(T_n)$ and $\mu_G^s(t, T_0, T_n)$ is defined in equation 3. Evidently, observing the trigger threshold requires well-defined, transparent reporting and measurements of firm-level emissions in their respective legal jurisdictions. This measurement and reporting process may happen rapidly for individual firms; it is already conceivable that this data will become available annually (Carbon Data Project, 2024) and potentially at higher frequencies in the future. Hence, it would be possible for investors and governments to obtain a realised measurement of sectoral emissions and determine if a firm may choose to trigger the bond if it is not a policy adjustment. For the case where policymakers explicitly change policy, CLoCo's would provide investors with a view on such likelihoods. Furthermore, policymakers could assess the economic impact of the policy shift implied by a change in decarbonisation policy, providing an improved insight into financial risks.

In the event of a decarbonisation policy rate set below the trigger, the firm would then have the right to convert the

[7] This is to avoid arbitrary use of the bond for general funding and to provide clear incentives for investors to invest in the firm.

CLoCo . The firm may or may not exercise this right depending on several factors, such as its strength of balance sheet and equity value relative to the cost of debt. The structuring of the bond trigger will define the relevant pricing factors.

- $N_{\mathbf{CLoCo}}$ corresponds to the notional of the CLoCo bonds issued by the firm
- c_j corresponds to the coupon payment for the standard corporate bond.
- m the number of coupons paid by the CLoCo up to time T_n
- α is the fraction of the bond notional that may be returned to the investor upon conversion $\alpha \in (0, 1)$
- Conversion Price is set to the price on the trigger. The conversion price is set to $C_p = S^*$, the share price observed at the trigger time T^*. Unlike COCOs issued by banks due to reduced capital ratios, the impact on a climate transition firm's share price may be somewhat lower as the firm may still have a strong balance sheet. Bond investors would likely prefer this trigger conversion price mechanism and set an expectation of the impact on shareholders from the dilution of equity upon conversion. Hence, the conversion ratio $C_r = 1$
- $\{T_o, T_{o+p}\}$ corresponds to the period where a firm may observe decarbonisation policies relevant to the bond.
- $\{T_l, T_{l+q}\}$ corresponds to a time interval where the firm may hold the right to convert the bond, contingent on the change in decarbonisation policy. The time $T_{o+p} \leq T_{l+q} < T_n$ and $T_o \leq T_l$

The features of the CLoCo are highlighted in figure 5.

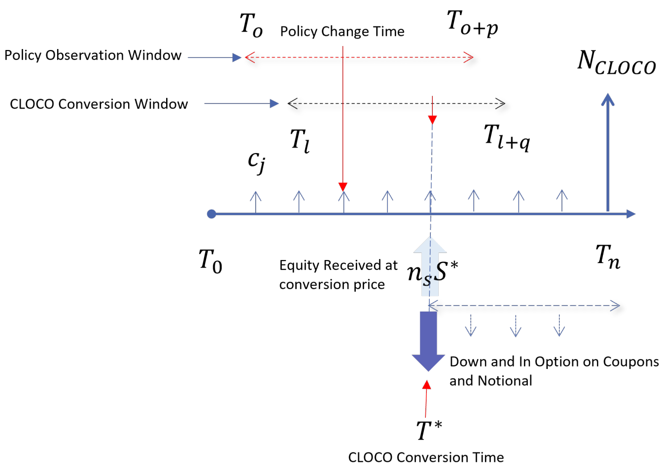

Figure 5: *Diagram highlighting the features for the CLoCo .*

4.3 Potential opportunities arising from CLoCo bond issuance

The opportunity for firms issuing CLoCo provides a clear means to reduce default risks and improve longer-term capital structure, reassuring current investors and financial stakeholders in the event of an adverse policy choice that the firm can deploy further capital when general market conditions may be adverse for investors.

4.3.1 Shareholder and bondholder engagement in firms issuing CLoCos

Firms issuing a CLoCo would naturally wish to engage their current investor base before issuing such a security. It is likely that whilst firms may wish to issue CLoCo s to hedge implicit policy risks, those firms most likely to benefit are those with an elevated exposure to policy uncertainty. This exposure may manifest specifically in a given sector or from worldwide uncertainty in regional policy choices. For example, a firm may wish to improve its growth plans' robustness and anticipate adverse policy impacts across its global markets. Hence, by engaging with current investors, other finance stakeholders, such as banks/governments, may find the contingent ability of the firm to convert debt to Equity attractive. The implication is that the firm would be provided with an option to further increase its investment in decarbonisation solutions rather than suffering a default with all the disruption that may cause. As highlighted in section 4.2, designing the bond's trigger features such that the bond's total notional value is converted to shares at the trigger price S^* improves the loss profile for both bond and equity holders.

4.4 CLoCo valuation models

In this section, we address the pricing of a coupon paying CLoCo that converts to shares on the realisation of a policy trigger event at time T^*. We consider a bond that pays m coupons with notional value c_j, paid at times $\{T_j\}$, in the event of conversion, the coupon value, in general, is reduced to αc_j. As a consequence, the value of each coupon is transformed into a set of binary down-and-in options. Upon exercise of the trigger, the bondholder will receive equity in the firm at the conversion strike price S^* at time T^*. The price of the CLoCo can be defined in the simple case where the observation window and the trigger window exist for the lifetime of the bond as:

$$P_{\mathbf{CLoCo}}(T_0, T_n) = \begin{cases} P_B(t, T_0, T_n), & \text{if } T^* \geq T_n \\ \\ P_B(t, T_0, T_n) + & \\ F(t; S^*, T_0, T^*, T_n, N_{\mathbf{CLoCo}}) & T^* < T_n \\ -\sum_{j=1}^{m} \alpha c_j DCF(r(T^*, T_i)) & \end{cases} \tag{17}$$

where

- $P_B(t, T_0, T_n)$ is a standard fixed coupon bond paying a periodic coupon of c_j at times T_j;
- $DCF(T_a, T_b) = DCF(T_0, T_b)/DCF(T_0, T_a)$ is the forward discount factor for a cash flow at time T_b discounted to time T_a whee $T_b \geq T_a$;
- $F(S^*, T_0, T^*, T_n, N_{\mathbf{CLoCo}})$ is the value of the forward on the firm's stock received at the conversation time T^*. This is explicitly defined below.

The total value of the stock received $S^* = n_s S_{T^*}$ at the time of the trigger T^* in this bond is taken to be equal to the value of the bond notional $N_{\mathbf{CLoCo}}$ at time T^*:

$$F(S^*, T_0, T^*, T_n, N_{\mathbf{CLoCo}}) \quad (18)$$
$$= C_r \times \left(n_s S_T - \frac{\alpha DCF(T^*, T_n) N_{\mathbf{CLoCo}}}{C_r} \right) \mathbb{1}_{\{T^* \leq T_n\}}$$

where $C_r = 1$, $\alpha = 1$ and $n_s * \times S_{T^*} = N_{\mathbf{CLoCo}} \, \forall t$, where n_s is the number of shares issued at the so-called floating strike S^*. Consequently, the expected forward value upon conversion is identically zero for all time. For the case where the observation and conversion period covers the whole lifetime of the bond, the valuation formula for the CLoCo at time t is given by

$$\begin{aligned} P_{\mathbf{CLoCo}}(t, T_0, T_n) &= \sum_{j=1}^{m} \mathbb{E}_t^{\mathbb{Q}} \left[c_j e^{-\int_t^{T_j} r_u du} \mathbb{1}_{\{T^* > T_j\}} | \mathcal{F}_t \right] \\ &+ N_{CloCo} \times \mathbb{E}_t^{\mathbb{Q}} \left[e^{-\int_t^{T_n} r_u du} \mathbb{1}_{\{T^* > T_n\}} | \mathcal{F}_t \right] \\ &+ N_{CloCo} \times \mathbb{E}_t^{\mathbb{Q}} \left[e^{-\int_t^{T_n} r_u du} \mathbb{1}_{\{T^* < T_n\}} | \mathcal{F}_t \right] \\ &+ \mathbb{E}_t^{\mathbb{Q}} \left[n_{s^*} S_{T^*} e^{-\int_t^{T^*} r_u du} \mathbb{1}_{\{T^* < T_n\}} | \mathcal{F}_t \right] \\ &- N_{CloCo} \times \mathbb{E}_t^{\mathbb{Q}} \left[e^{-\int_t^{T_n} r_u du} \mathbb{1}_{\{T^* < T_n\}} | \mathcal{F}_t \right] \end{aligned} \quad (19)$$

where r_u is the relevant zero coupon yield used to discount the firm's cash flows. It can be seen that a holder of the convertible bond does not have direct valuation exposure to the equity during the lifetime of the bond, only interest rate, default and climate transition policy risks.

This can be rewritten as:

$$\begin{aligned} P_{\mathbf{CLoCo}}(t, T_0, T_n) &= \sum_{j=1}^{m} \mathbb{E}_t^{\mathbb{Q}} \left[c_j e^{-\int_t^{T_j} r_u du} \mathbb{1}_{\{T^* > T_j\}} | \mathcal{F}_t \right] \\ &+ N_{CloCo} \times \mathbb{E}_t^{\mathbb{Q}} \left[e^{-\int_t^{T_n} r_u du} \mathbb{1}_{\{T^* > T_n\}} | \mathcal{F}_t \right] \\ &+ N_{CloCo} \times \mathbb{E}_t^{\mathbb{Q}} \left[e^{-\int_t^{T_n} r_u du} \mathbb{1}_{\{T^* < T_n\}} | \mathcal{F}_t \right] \\ &+ \mathbb{E}_t^{\mathbb{Q}} \left[F(S^*, T_0, T^*, T_n, N_{\mathbf{CLoCo}}) | \mathcal{F}_t \right] \end{aligned} \quad (20)$$

where the equity forward $F(S^*, T_0, T^*, T_n, N_{\mathbf{CLoCo}})$ is defined to be identically zero for all time t.

4.4.1 Alternative CLoCo pricing models

An alternative approach that practitioners have used to price contingent convertible bonds is the so-called "credit derivative" approach. We include this approach as a means to interpret the pricing of the bond using a conventional spread asjustment[8] to a normal coupon-bearing bond with an effective CLoCo credit spread $s_{\mathbf{CLoCo}}(t)$. The price of a coupon-paying bond is written as:

$$\begin{aligned} P_{CloCo}(t, T_0, T_n) &= \sum_{j=1}^{m} c_j e^{(-y_{CloCo} * T_i)} \\ &+ N_{CloCo} e^{(-y_{CloCo} * T_n)} \end{aligned} \quad (21)$$

where $y_{CloCo} = r(t) + s_{CloCo}(t)$. The CLoCo credit spread can be calculated using:

$$s_{CloCo}(t) = (1 - R_{CloCo}) \times \lambda_{\mathbf{CLoCo}} \quad (22)$$

where λ_{CloCo} is given by the probability up to time t of an adverse climate policy. In terms of the survival probability indicator introduced, the survival probability is given by:

$$Q(0, t) = \mathbb{E}_t^{\mathbb{Q}} \left[\mathbb{1}_{\{T^* > t\}} \right] \quad (23)$$

Where u is the transition policy-triggered conversion time. The total probability that an adverse climate policy would be introduced is given by the integration of per-period transition scenario probabilities:

$$\int_0^T -dQ(0, t) dt = 1 - Q(0, T) \quad (24)$$

Using a Poisson distribution where the policy change may happen unexpectedly with intensity λ_{CLoCo}, the survival probability can be written as:

$$Q(0, t) = e^{-\int_0^t \lambda_{CloCo}(u) du} \quad (25)$$

The probability of an adverse climate policy is given by:

$$-dQ(0, t) = Q(0, t) \lambda_{CLoCo}(t) dt \quad (26)$$

where $\lambda_{CLoCo}(t)$ is constant, giving rise to the valuation of the CLoCo as given in equation 21.

In developing the model framework, impacts across other market factors can be included alongside the impact of default probabilities. One must consider the correlation between policy events and interest rate levels in evaluating the complete pricing formula. Indeed, the impact of using instruments such as CLoCo provides an option for firms to reduce their longer-term cost of funding relative to firms with a similar risk profile that do not issue CLoCos . This will form the basis of future studies.

4.4.2 Alternative CLoCo payoffs

In the pricing in equation 18, only the value of the notional was taken to convert at time T^*; alternative CLoCos can, of course, be constructed where the value of the outstanding coupons, as well as the notional, is converted, to equity, this

[8] Recognising that CLoCo pricing will, in general, be approached using conventional derivatives pricing methods outlined in section 4.4.

further simplifies the valuation of the bond to:

$$\begin{aligned} P_{\mathbf{CLoCo}}(t, T_0, T_n) &= \sum_{j=1}^{m} \mathbb{E}_t^{\mathbb{Q}}\left[c_j e^{-\int_t^{T_j} r_u du} \mathbb{1}_{\{T^* > T_j\}} | \mathcal{F}_t\right] \\ &+ N_{CloCo} \times \mathbb{E}_t^{\mathbb{Q}}\left[e^{-\int_t^{T_n} r_u du} \mathbb{1}_{\{T^* > T_n\}} | \mathcal{F}_t\right] \\ &+ N_{CloCo} \times \mathbb{E}_t^{\mathbb{Q}}\left[e^{-\int_t^{T_n} r_u du} \mathbb{1}_{\{T^* < T_n\}} | \mathcal{F}_t\right] \\ &+ \sum_{j=1}^{m} \mathbb{E}_t^{\mathbb{Q}}\left[c_j e^{-\int_t^{T_j} r_u du} \mathbb{1}_{\{T^* < T_j\}} | \mathcal{F}_t\right] \\ &+ \mathbb{E}_t^{\mathbb{Q}}\left[F(S^*, T_0, T^*, T_n, P_{\mathbf{CLoCo}}) | \mathcal{F}_t\right] \end{aligned} \tag{27}$$

where $F(S^*, T_0, T^*, T_n, P^*_{\mathbf{CLoCo}})$ is the equity forward where the instantaneous value of the cash term of the forward $P^*_{\mathbf{CLoCo}}$ is the value of the outstanding notional and coupons of the bond at the time on conversion T^*.

4.5 Liquidity considerations

Whilst it is evident that currently, investors in firms that may issue CLOCOs have an implicit view of the risks of the firm, including climate transition-related risks (see section 3.3.1), for the CLoCo to be effective, will require a liquid market. To enable widespread engagement with the bond by issuing firms and their investors, this will naturally require not only sensible pricing that reflects the risk appetite of firms and investors but also the desire for banks to provide liquidity for the issuances. furthermore, the increase in liquidity in the issuance creates an opportunity to provide a market in derivatives to hedge transition risks associated with the bond. Ultimately, this would give rise to a market-implied view of transition risks. There are also some regulatory limitations, such as the Non-modellable risk factor requirements that require banks to increase capital for instruments that trade fewer than 24 days in a year, alongside liquidity risk capital adjustments that may arise on a bank's sales trading desk. However, it is anticipated through considered structuuring of the features of an issued CLoCo an attractive risk-return profile would become more actively traded in practice. As the benefit for the bond will be a function of its liquidity, banks or actively trading asset managers would have some improved visibility on relative levels of liquidity and have some indications of the BID and ASK of such instruments to infer the liquidity premium. This can naturally be used to derive a liquidity-adjusted spread adjustment within a pricing framework highlighted in section 4.4. To the extent that firms can provide a view on the liquidity premium applied to the price upon transaction and the BID/ASK spreads, it would be informative from a regulatory perspective to track the price history and the implied model transition risk spread to infer market maker and investor views on the transition risk implied by each instrument. Consequently, building a transition risk curve for firms and regions will be possible.

4.6 Designing hedge instruments for climate transition risk

With the establishment of instruments such as the CLoCo, inevitably, this will create a desire to hedge the specific risks of the instrument, whether this is the resulting impact of an equity holding or the specific nature of the transition risk. A number of hedging instruments can be synthesised from CLoCos. For example, as can be seen from the pricing formula for the CLoCo as structured in equation 19, it may be possible to synthesise an asset swap whereby one of the legs is a CLoCo and the other leg a standard coupon-bearing bond with the same knock-in features as the coupon payments leg as the CLoCo.

Whilst the pricing of the CLoCo highlighted in this paper has been designed to eliminate the value of the equity component, investors do have an exposure to equity risk contingent on default. A firm that converts a given amount of CLoCo bond notional will incur an adjustment to its stock price from the effective dilution implied by its conversion. Investors may wish to hedge this equity-holding risk. Firms issuing CLoCos would need to engage their investor base regarding the reasons for conversions, such as enhanced further investment in a lower-cost technology.

5 Summary

In this paper, we have introduced a number of concepts for developing an understanding of transition risk probabilities. We have built on concepts put forward by a number of authors such as (Kenyon, Macrina, and Berrahoui, 2023b), (D. Kainth and Rebonato, 2024 and F. Venmans, 2022) and frameworks that leverage detailed firm-level agent-based models such as (Cormack et al., 2020)to build a framework that is used by firms and their financial counterparties to assess transition risks.

Climate financial risk modelling is developing significantly, enabling improved risk assessment of the set of external risks impacted firms. Recent developments in risk assessment from bodies such as ISDA (ISDA, 2024) leverage agent-based models to estimate the impacts of various market factors. Models such as (Cormack et al., 2020)) that can model the impact of transition policies, impacts on demands, and costs permit a view for investors on the balance sheet and future market impact. With these insights, firms looking to assess their forward-looking financial performance can improve their risk management and resilience planning. Furthermore, such model frameworks permit banks to build financial products that provide innovative hedging solutions. Innovations in risk frameworks and an improved understanding of transition probabilities enable instruments such as the CLoCo to be structured and an enhanced risk assessment performed on the range of valuations of the instrument, contingent on the set of uncertainties. Specifically, the ability to embed the impacts of the policy uncertainty and their impacts in the risk modelling framework can give rise to a clearer understanding of transition risk probabilities, enabling pricing of instruments such as the CLoCo.

Whilst it is recognised that the development of a market in CLoCos will take a while and faces initial increased bank capital costs within the global banking sector (e.g. Basel IV - FRTB), the instrument offers an opportunity for firms to restructure their capital at the moment they need, rather than face the challenge of raising finance when market conditions for transition firms after a policy announcement will likely be disadvantageous.

Establishing a liquid market in CLoCos brings several more comprehensive benefits to the firms, banks, and assets managers and provides a means to hedge transition policy risks widely and permit more comprehensive structuring of other hedging instruments (e.g. callable swaps triggered by a policy change). Such a more comprehensive market would allow other stakeholders to assess the potential economic impact or advantage of policy choices within their economies. A market in CLoCos will provide a means for investors, banks, and financial regulators to agree on the price of transition risk; this would help standardise such risks and improve transparency. Furthermore, hedging (or mitigating) transition risks may provide improved stability, reduce policy uncertainty, and improve economic robustness. Such an instrument as the CLoCo may allow regulators to enable faster transitions should new lower-cost technologies be developed.

In future work, we intend to utilise detailed ABM frameworks for macro and microeconomics to build and explore the set of probability measures for decarbonisation and provide a pricing model with examples for the CLoCo covering the interaction of wider factors such as interest rates and defaults. Further work will also involve the development of firm-level ABM framework with the integration of the the use of CLoCos for a firm's capital structure optimisation.

Bibliography

Bank of England (2022). *"Results of the 2021 Climate Biennial Exploratory Scenario (CBES)"*. URL: https://www.bankofengland.co.uk/stress-testing/2022/results-of-the-2021-climate-biennial-exploratory-scenario.

Carbon Data Project (2024). *CDP - Corporate response dataset*. URL: https://www.cdp.net/en/.

Commision, European (2022). *Corporate sustainability due diligence*. URL: https://commission.europa.eu/business-economy-euro/doing-business-eu/corporate-sustainability-due-diligence_en.

Cormack, C. and G. Shrimali (2023). *The Challenge of Climate Risk Modelling in Financial Institutions - Overview, Critique and Guidance*. URL: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4669195.

Cormack et al., ed. (2020). *Estimating Financial Risks from the Energy Transition: Potential Impacts from Decarbonization in the European Power Sector*. 4th ed. 13 vols.

D. Kainth, L. Melin and R. Rebonato (2024). *Climate Scenario Analysis and Stress Testing for Investors: A Probabilistic Approach*. URL: https://climateimpact.edhec.edu/sites/ercii/files/ercii_publication_climate_scenario_stress_testing_investors_jan24.pdf.

Dimitris Bertsimas Vishal Gupta, Ioannis Ch. Paschalidis (2011). *Inverse Optimization: A New Perspective on the Black-Litterman Model*. URL: https://www.mit.edu/~dbertsim/papers/Finance/Inverse%20Optimization%20-%20A%20New%20Perspective%20on%20the%20Black-Litterman%20Model.pdf.

England Prudential Regulation Authority, Bank of (April, 2019). *Enhancing banks' and insurers' approaches to managing the financial risks from climate change*. Online Resource. Bank of England. URL: https://www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/supervisory-statement/2019/ss319.pdf?la=en&hash=7BA9824BAC5FB313F42C00889D4E3A6104881C44.

Europen Central Bank (2023). *The Road to Paris: stress testing the transition towards a net-zero economy*. URL: https://www.ecb.europa.eu/pub/pdf/scpops/ecb.op328~2c44ee718e.en.pdf?7793485730460e4e0b4e170237eb7429.

Europen Commission (2023). *Carbon Border Adjustment Mechanism (CBAM)*. URL: https://trade.ec.europa.eu/access-to-markets/en/news/carbon-border-adjustment-mechanism-cbam.

F. Venmans, B. Carr (2022). *The unconditional probability distributions of future emissions and temperatures*. URL: https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2022/11/working-paper-382-Venmans-and-Carr.pdf.

Gidden, Matthew J. et al. (2018). "Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century". In: *Geoscientific Model Development Discussions*, pp. 1–42. DOI: 10.5194/gmd-2018-266.

Goverment, UK (2022a). *Boiler Upgrade Scheme*. URL: https://www.find-government-grants.service.gov.uk/grants/boiler-upgrade-scheme-1.

Goverment, United State (2022b). *Inflation Reduction Act of 2022*. URL: https://www.energy.gov/lpo/inflation-reduction-act-2022.

Government, UK (2023). *Zero emission vehicle (ZEV) mandate consultation: summary of responses and joint government response*. URL: https://www.gov.uk/government/consultations/a-zero-emission-vehicle-zev-mandate-and-co2-emissions-regulation-for-new-cars-and-vans-in-the-uk/outcome/zero-emission-vehicle-zev-mandate-consultation-summary-of-responses-and-joint-government-response.

– (2024). *Pathway for zero emission vehicle transition by 2035 becomes law*. URL: https://www.gov.uk/government/news/pathway-for-zero-emission-vehicle-transition-by-2035-becomes-law.

Guardian, The (2024). *Big carmakers lobbied UK to weaken or delay electric car rules*. URL: https://www.theguardian.com/business/2024/jan/03/big-carmakers-lobbied-uk-to-weaken-or-delay-electric-car-rules#:~:text=There%20was%20also%20a%20provision,unable%20to%20meet%20the%20targets..

ISDA (2024). *Climate Scenario Analysis in the Trading Book – Phase II*. URL: https://www.isda.org/2024/02/12/climate-scenario-analysis-in-the-trading-book-phase-ii/.

Kenyon, Chris, Andrea Macrina, and Mourad Berrahoui (2023a). "CO2eVA: Pricing the Transition of Scope 3 Emissions". In: *Risk, Cutting Edge: Climate Finance, Risk.net.* URL: https://dx.doi.org/10.2139/ssrn.4136710.

– (2023b). "The carbon equivalence principle: methods for project finance". In: *Risk, Cutting Edge: Climate Finance, Risk.net.* URL: http://dx.doi.org/10.2139/ssrn.4035833.

Krach, F. et al. (2023). "The Financial Impact of Carbon Emissions on Power Utilities Under Climate Scenarios". In: *International Journal of Theoretical and Applied Finance (forthcoming)*. URL: https://dx.doi.org/10.2139/ssrn.4571086.

Martynova, Natalya and Enrico Perotti (2018). "Convertible bonds and bank risk-taking". In: *Journal of Financial Intermediation* 35. Banking and regulation: the next frontier, pp. 61–80. ISSN: 1042-9573. DOI: https://doi.org/10.1016/j.jfi.2018.01.002. URL: https://www.sciencedirect.com/science/article/pii/S1042957318300081.

McKinsey and Company (2022). *The Net-Zero Transition, What it WOuld Cost, What it Could Bring.* URL: https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/the%20net%20zero%20transition%20what%20it%20would%20cost%20what%20it%20could%20bring/the-net-zero-transition-what-it-would-cost-and-what-it-could-bring-final.pdf.

National Audit Office UK (2024). *Low heat pump uptake slowing progress on decarbonising home heating*. URL: https://www.nao.org.uk/press-releases/low-heat-pump-uptake-slowing-progress-on-decarbonising-home-heating/.

NGFS (2022). *NGFS Scenarios for central banks and supervisors*. URL: https://www.ngfs.net/sites/default/files/medias/documents/ngfs_climate_scenarios_for_central_banks_and_supervisors_.pdf.pdf.

Nordhaus, William D. (Feb. 1992). *The 'DICE' Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming*. Cowles Foundation Discussion Papers 1009. Cowles Foundation for Research in Economics, Yale University. URL: https://ideas.repec.org/p/cwl/cwldpp/1009.html.

Poledna, Sebastian et al. (2023). "Economic forecasting with an agent-based model". In: *European Economic Review* 151, p. 104306. ISSN: 0014-2921. DOI: https://doi.org/10.1016/j.euroecorev.2022.104306. URL: https://www.sciencedirect.com/science/article/pii/S0014292122001891.

Reuters (2023). *China solar panel costs drop 42% from year ago - report*. URL: https://www.reuters.com/world/china/china-solar-panel-costs-drop-42-year-ago-report-2023-12-14/.

Riahi, Keywan et al. (2017). "The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview". In: *Global Environmental Change* 42, pp. 153–168. DOI: 10.1016/j.gloenvcha.2016.05.009.

Rogelj, Joeri et al. (2018). "Scenarios towards limiting global mean temperature increase below 1.5 °C". In: *Nature Climate Change* 8.4, pp. 325–332. DOI: 10.1038/s41558-018-0091-3.

TwoSigma (2020). *ESTIMATING GLOBAL INVESTOR VIEWS WITH REVERSE OPTIMIZATION*. URL: https://www.twosigma.com/wp-content/uploads/SV_Estimating-Global-Investor-Views-with-Reverse-Optimization.final_.pdf.

UK Department for Energy Security and Net Zero (2017). *Electricity Market Reform: Contracts for Difference*. URL: https://www.gov.uk/government/collections/electricity-market-reform-contracts-for-difference.

– (2023). *NGFS Climate Scenarios Technical Documentation*. URL: https://www.ngfs.net/sites/default/files/media/2024/01/16/ngfs_scenarios_technical_documentation_phase_iv_2023.pdf.