

# Debt, Growth, and the Carbon Lock-In

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## Abstract

Despite decades of climate policy initiatives and significant advances in decarbonization efforts, global CO<sub>2</sub> emissions continue to rise, suggesting the influence of structural factors that counteract mitigation gains. Here, we identify financial leverage as a fundamental mechanism that underpins this persistent overshoot. We build a stochastic macro-financial model that integrates credit dynamics, economic growth, bankruptcy risk, and cumulative carbon emissions. The model shows that growth driven by debt financing consistently increases cumulative emissions, thereby locking economies into high-carbon pathways despite reductions in emissions intensity. This arises from a double constraint: debt repayment requires sustained growth, while growth remains energy-dependent and thus generates emissions. When growth becomes increasingly dependent on leverage, financial instability and cumulative emissions rise, while gains in real wealth diminish, revealing a leverage frontier beyond which additional credit primarily generates risk.

Calibrating the model to multi-decade data for the United States, China, France, and Denmark, we find a robust coupling between debt accumulation, cumulative GDP, and cumulative emissions across distinct economic structures. These results challenge the feasibility of growth–emissions decoupling under prevailing credit-driven growth regimes and indicate that achieving net-zero targets requires aligning credit allocation with decarbonisation objectives.

**Keywords:** Leverage-driven growth, Default risk, Debt-emissions feedback, Carbon lock-in, Double materiality, Ecological macroeconomic modeling, Climate finance



Similar feedback loops exist in other fields such as biology. In biology, living cells adjust to environmental constraints by employing two complementary strategies: (i) decreasing their metabolic rate to consume less energy per unit time, or (ii) reconfiguring their metabolic pathways to optimize the use of available energy or alternative sources [11–14]. In a similar manner, economies that are confronted with resource constraints have the option to either (i) decrease the energy required per unit of output, thereby reducing the carbon intensity of GDP, or (ii) transition their energy mix to low-carbon sources [15]. An important limitation to this analogy between biology and economy, however, is that there is no biological equivalent of debt. Debt is thus inherent to financial systems; it facilitates growth on the promise of future expected gains in a manner that biological systems cannot, thereby establishing new mechanisms of instability due to an increase of emissions, resource depletion, socio-economic destabilization and ecosystem degradation [16, 17].

Motivated by this observation, we study in this paper the link between finance and climate change, focusing particularly on the role of debt. Another motivation for this study is that standard Integrated Assessment Models (IAMs), which typically represent emissions as a function of exogenous GDP growth [18, 19], do not model the financial system nor investors’ decisions. Thus, the feedback loop represented in Fig. 1 that couples the financial system and mitigation pathways is typically not taken into account by IAMs. Several authors have identified this shortcoming and have criticized IAMs for their lack of a financial system [7, 20].

To capture these feedback effects, we build a stochastic credit-risk model by combining deterministic macroeconomic models [4, 6, 21, 22], with Kelly’s gambling model [23]. In 1956, Kelly found a deep connection between information theory and gambling in horse races. This work then became highly influential in investment science [24, 25] and in evolutionary biology [26]. The model demonstrates that diversification of assets enables a mitigation of risk from environmental fluctuations, a goal that is also central in biology and ecology and is known under the name of bet-hedging [15, 26, 27]. In this analogy, the growth of the gambler’s capital is equivalent to the growth of the population, and the risk of bankruptcy is comparable to the extinction of the population. Kelly’s optimal strategy is known to be risky, and this observation hints at a general trade-off, the risk-return trade-off, between the risk of bankruptcy and the average long-term growth rate of the capital [28, 29].

The original Kelly’s model, however, does not include the possibility of bankruptcy nor the possibility of borrowing (debt). To address this issue, we build a stochastic credit-risk model, that merges the stochastic nature of growth in Kelly’s model with deterministic credit-risk models [4, 6]. In this way, once the borrower has taken out a loan, the debt accumulates with an interest rate at each time step, while the capital evolves stochastically. When the better pays back the debt, the capital is reset at a lower value. The evolution of the capital can thus be compared to a biased random walk with resetting [30–32], or to a coupled dynamics of money and anti-money variables [33].

In the following, we use this stochastic credit-risk model to investigate the role of credit expansion in driving economic growth and cumulative CO<sub>2</sub> emissions. Besides quantifying this causal relationship, our stochastic framework also establishes an optimal leverage frontier: the probability of long-term solvency approaches zero when the intrinsic growth rate (growth that originates within an economy, fueled by factors such as productivity improvements) falls below the effective interest rate, suggesting that structural financial instability is the ultimate effect of excessive borrowing. We also show that credit is the primary driver of several major economies and that this comes at the cost of increasing global dissipation in the form of emissions [20, 34]. We used country-level economic data to predict the cumulative emissions per capita for these countries. Cumulative CO<sub>2</sub> emissions, rather than CO<sub>2</sub> emissions, are a key quantity that captures the effect of economic activities in increasing global warming. We demonstrate that to fuel economic growth, credit is required, which has a cost in terms of CO<sub>2</sub> emissions.

Our contribution complements standard Integrated Assessment Models (IAMs), which typically do not aim to reproduce past emissions, GDP co-evolution, or assess the causal role of credit in driving the rise in emissions.

In contrast, our model uses empirical fiscal, macroeconomic, and climate data to explicitly link debt-financed growth with cumulative emissions, thereby offering a plausible explanation for the persistent proportionality between cumulative GDP and emissions, thus assessing the responsibility for cumulative carbon emissions even in countries with fast decarbonization trajectories. Our approach aligns more closely with recent works in macro-finance that analyze climate-related financial risk [20], and with studies in ecological macroeconomics [35, 36] and system dynamics [37] that attempt to take into account socio-environmental feedback loops similar to the debt-carbon spiral presented in this paper (Fig. 1).

## 2 Model

We consider an investor who can borrow money at each time step  $\tau$  with the interest rate  $\rho_\tau - 1$  (real interest rate accounting for inflation [38]), thus increasing both its capital  $C_\tau$  and its debt  $D_\tau$ . The amount of borrowed money is quantified by the leverage  $L_\tau$ , which is defined as the ratio of the asset value to the cash needed to purchase it [5]. Since we consider an isolated investor, borrowing to an external actor, the leverage can be larger than 1, whereas in a closed economic system, the total leverage should be 1. The evolution of the capital is stochastic as in Kelly’s model [24, 25], and is quantified by the intrinsic growth rate (or capital return)  $\gamma_\tau - 1$ . The model does not explicitly describe variables such as labor, employment rate or wages, all of which can exhibit complex dynamics [3, 4, 7]. Instead, it focuses on the coupling between the capital and the debt. At each time step, the investor can pay back their debt, and bankruptcy occurs if the debt exceeds the capital when repayment is due. Therefore *solvency* means that the debt can always be paid back because  $(\gamma_\tau C_\tau > D_{\tau+1})$ . We call  $\gamma_\tau C_\tau - D_{\tau+1}$  the *net capital*, whose sign indicates if bankruptcy will happen in case of payback. In the following sections, we outline two different strategies that represent distinct real-world debt-financed growth regimes. The mathematical model is further detailed in Methods and in sections 1.4 and 1.5 of SI where we explain how our framework relate to known macro-economical models [3, 4, 6, 21, 22].

### 2.1 Finite leverage — one time borrowing (strategy A)

First, we assume that the investor initially borrows money but never borrows afterwards. We refer to this strategy as strategy A, which is akin to an individual taking out a loan to buy a house. In this case, the gross capital evolves as in the classical Kelly’s model, and the debt evolves with a constant interest rate  $\rho - 1$ . At the time of payback, the capital can become negative, and in that case, bankruptcy occurs. Under the assumption of no bankruptcy, we can define the long-term growth rate as the growth rate of the capital when  $\tau \rightarrow \infty$ . However, there is a non-zero probability of hitting bankruptcy when the debt is paid back, and the larger the leverage, the more likely the bankruptcy in this model.

### 2.2 Persistent leverage — periodic borrowing (strategy B)

Let us instead assume that the investor borrows money at each time step, with leverage  $L_\tau$  (now time-dependent), which we refer to as strategy B. This strategy is rather that of a state or a company taking on credit yearly to ensure its budget balance. In this case, before payback, the gross capital evolves as in the standard Kelly’s model, with a modified stochastic growth rate, and the debt still evolves with an interest rate  $\rho - 1$ . We can separate the value added from production, and that which is due to borrowing in the dynamics, and define the stochastic *intrinsic growth rate* as the growth rate to which the contribution of borrowing [21] is subtracted.

## 3 Results

### 3.1 Lock-in of carbon emissions

Now, we scale up the above model based on strategy B to describe the wealth and the carbon emissions of a given country. Let  $C_\tau$  represent the economic wealth in the year  $\tau$  of that country, and let us assume that an external bank lends money each year to that country. As a result, its debt, encapsulated by the variable  $D_\tau$ , increases. Let us also assume that the leverage is constant within the time frame considered. Empirically, the estimated leverage  $L_\tau$  remains indeed fairly stable within each economy, varying by only a few percent across years (as shown in Fig. S1 in the Supplementary Information). This supports the hypothesis of a quasi-stationary financial amplification of growth.

In practice, the GDP during a given period is often used as a measure of economic wealth and has also been criticized for this reason [39, 40]. With that in mind, we further assume that this economic wealth represents the capital invested in various industries that consume energy to produce carbon emissions at time  $\tau$ , described by the function  $\epsilon(\tau, C_\tau)$ . This function should be an increasing function of the capital, as observed in practice [41], and its average should increase with leverage (i.e., the ratio of total money invested to money borrowed).

We connect the emissions to the carbon intensity of the economy thanks to the Kaya relationship [18, 42–44]:

$$\epsilon(\tau, C_\tau) = C_\tau \times I(\tau), \quad (1)$$

where  $I(\tau)$  is the carbon intensity of the economy, measured by the carbon cost of one unit of *GDP* [42]. The parameter  $I(\tau)$  is typically a decreasing function of  $\tau$  [18, 42, 44] because energy mixes tend to incorporate more renewable energies over time. Note that  $I(\tau)$  can decrease for two main reasons, as illustrated in Fig. 1, either the energy cost of *1USD* decreases, meaning that money is used in less energy-intensive activities, or the carbon cost of energy decreases, meaning that the energy mix of a country includes "greener" energies. However, this does not mean that cumulative emissions are reduced, as we will see.

Let us now examine the lock-in effect arising from path-dependent cumulative emissions. Public debt can be a powerful tool for investing in the transition, but it can also be used to pursue carbon-intensive economic activities; the difference between the two is encapsulated in the concept of carbon intensity. As this quantity changes with time [42], the cumulative emissions corresponding to a particular trajectory for a country's GDP will also depend on the trajectory of the carbon intensity of this economy. We can measure the lock-in effect using the *path-dependent intensity*:

$$\mathfrak{J}_\tau(\{C_\tau\}) = \frac{\sum_{\tau'=0}^{\tau} I(\tau') C_{\tau'}}{\sum_{\tau'=0}^{\tau} C_{\tau'}}, \quad (2)$$

which compares cumulative carbon emissions to cumulative GDP over a given period. This quantity represents the cumulative carbon emissions for a given amount of money invested. Contrary to carbon intensities, this variable is path-dependent, similarly to heat and work in thermodynamics [45]. This quantity allows for assessing the actual responsibility of countries for cumulative carbon emissions over a given period, irrespective of recent decarbonization efforts captured by carbon intensity.

In SI 2.3, we demonstrate that if carbon intensities  $I(\tau)$  strictly decrease, then  $\mathfrak{J}_\tau(\{C_\tau\})$  also decreases over time. We then study the influence of the decarbonization rate (or efficiency of innovations) in SI 2.3 and conclude that if  $I(\tau)$  is decreasing linearly, the difference between  $\mathfrak{J}_\tau(\{C_\tau\})$  and  $I(\tau)$  stabilizes to a finite value. If  $I(\tau)$  decreases faster than linearly, the difference tends to  $+\infty$ , whereas if it decreases more slowly than linearly, the difference first increases and then tends to 0. In practice, this means that the faster decarbonization occurs, the more early carbon-intensive years will matter in the path-dependent intensity. On the contrary, for

slow decarbonization, recent years matter more in the path-dependent intensity, making it closer to the carbon intensity.

A higher path-dependent intensity strengthens the lock-in effect, since  $CO_2$  emissions cannot be reset to zero annually. We show path-dependent intensities, as well as intensities in Fig. 2. We observe that the orders of magnitude differ widely among countries. We also observe that even if carbon intensities decrease over time, path-dependent intensities remain practically unchanged over a 20-year period. This means that cumulative emissions are largely proportional to cumulative GDP, despite efforts to reduce the annual carbon intensity.

The difference between annual carbon intensity and path-dependent intensity is studied more closely in the Supplementary Information. In Fig. 2C, we show the correlation between cumulative emissions per capita (since 1998) and cumulative GDP (since 1998) for each country. When the carbon intensity decreases with time while the economy grows,  $\mathfrak{J}_\tau(\{C_\tau\})$  is larger than  $I(\tau)$ . The difference between these two quantities depends on the long-term growth rate  $W$  and on the amplitude of the fluctuations in the economy measured by  $\sigma_X$ . We observe that even under steady decarbonization, the ratio of cumulative emissions to cumulative GDP remains higher than the annual carbon intensity. Moreover, larger economic fluctuations - as captured by  $\sigma_X$  - amplify the difference between  $\mathfrak{J}_\tau(\{C_\tau\})$  and  $I(\tau)$ . This phenomenon arises because periods of economic expansion, characterized by high carbon intensity, are followed by recessions with lower carbon intensity. In this case, reducing the annual carbon intensity has little effect on the path-dependent carbon intensity, yielding a larger degree of carbon lock-in.

The trends for  $\mathfrak{J}_\tau(\{C_\tau\})$  and  $I(\tau)$  are similar across all countries, with varying carbon intensities. For countries with small GDP per capita, the relationship is almost linear but bends as a power law with an exponent slightly smaller than one at larger GDP per capita, as shown in Fig. 2C. The lower this exponent, the more significant the efforts to decarbonize the economy.

By shifting consumption forward and increasing annual GDP per capita, debt increases cumulative emissions. This result is robust even if debt is used to decrease the annual carbon intensity,  $I(\tau)$ , because cumulative emissions are path-dependent.

### 3.2 Energetic and dissipative cost of an economy

Considering a period  $t$ , we can write the cumulative emissions  $\mathcal{E}(t)$  as:

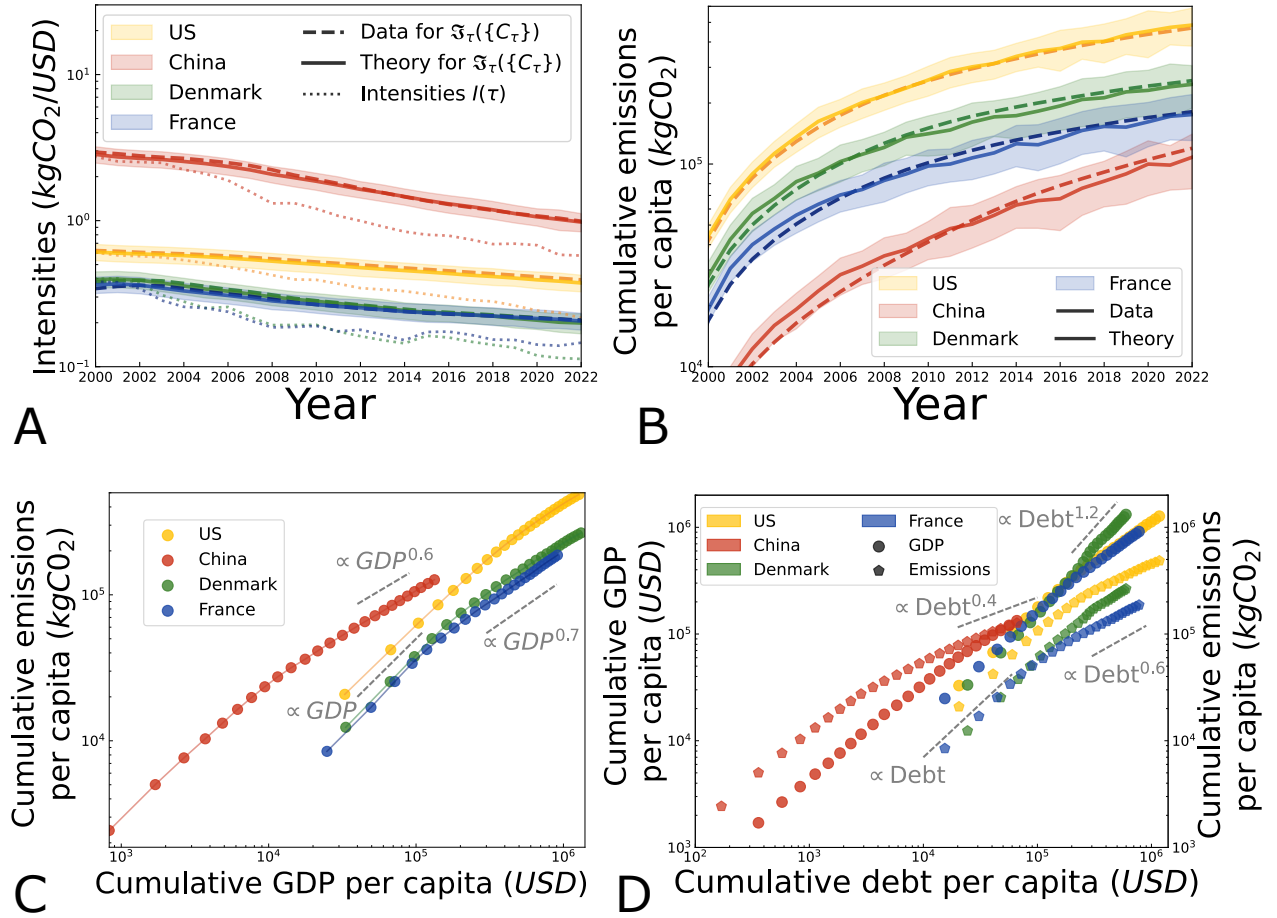
$$\mathcal{E}(t) = \sum_{\tau \leq t} \epsilon(C_\tau, \tau), \quad (3)$$

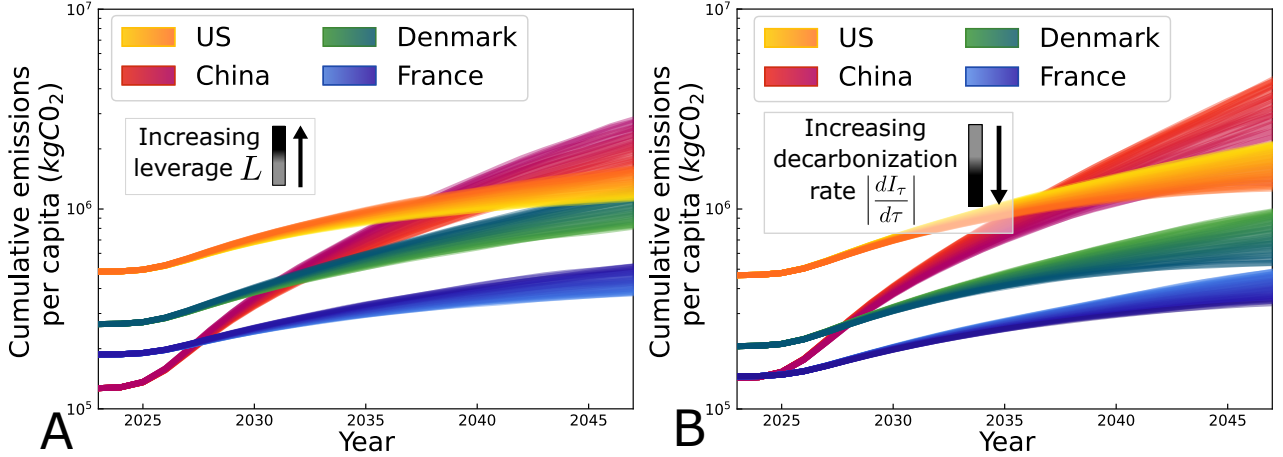
assuming in a first approximation that yearly carbon intensity  $I(\tau)$  does not depend explicitly on  $C_\tau$ , it has historically been measured as almost linear in most countries [42]. Therefore, writing  $I(\tau) = I_0 - \eta(\tau - \tau_0)$ ,

$$\mathcal{E}(t) = I_0 \sum_{\tau \leq t} C_\tau - \eta \sum_{\tau \leq t} \tau C_\tau. \quad (4)$$

Using this formula for the US *GDP* data between 1990 and 2020, we obtain cumulative carbon emissions of  $\mathcal{E} = 7 \times 10^5 kg CO_2/capita$ , close enough to the real value of  $6 \times 10^5 kg CO_2/capita$  on Fig. 2B.

We have analyzed data for the US deficit [46] and found that the added deficit in 2023 is  $1.7 \times 10^{12} USD$ , resulting in a deficit per capita of  $5.1 \times 10^3 USD$  in 2023. From this, we can obtain a value of the leverage in 2023 of  $L = 1.06$ . If we use strategy B to describe the growth of the US economy, the *intrinsic growth rate* (that is, the growth rate minus debt-funded spending) is:





**Fig. 3** **A** *Effect of leverage*: predictions for cumulative emissions (starting from 1998) depending on leverage in different countries. For each country, the color gradient indicates increasing leverage from 1.00 to 1.05, resulting in higher cumulative emissions per capita. A linearly decreasing carbon intensity has been assumed, with different parameters for each country [42], based on consumption-based emissions from 1998 to 2022. We also assume that the distributions of  $\gamma$  remain constant for each country. We use  $W = \langle \ln(\gamma_\tau) \rangle$  and  $\sigma_X$  (see values in Methods), as well as a fixed value of leverage, as inputs for the model. As expected, the larger the leverage, the greater the potential for GDP growth, leading to higher cumulative emissions despite decreasing carbon intensities. Changes by a few percent in leverage are enough to trigger changes of almost 1 order of magnitude in cumulative emissions per capita after 25 years. **B** *Effect of policies*: Predictions for cumulative emissions (starting from 1998) depending on how strong the effort is to reduce carbon intensity. For each country, the color gradient corresponds to increasing  $|dI_\tau/d\tau|$  (where  $dI_\tau/d\tau$  is negative), indicating an increasing effort to reduce the carbon intensity of the economy.  $|dI_\tau/d\tau|$  varies between 0 and 1.5 times the current trend for each country. We observe that for high enough values of  $|dI_\tau/d\tau|$ ,  $I_\tau$  becomes negative (carbon capture), leading to decreasing cumulative emissions. The leverage is taken equal to the average leverage measured over the period 1998 – 2022 for each country.

$$\gamma_{eff,\tau} = \frac{C_{\tau+1} - C_\tau}{C_\tau} - (L - 1). \quad (5)$$

Studying this quantity allows for the decorelation of the value added from credit to the added value (accounting for depreciation and production). On average, since 1980, this value is close to 0. Using data [47–49] for US GDP per capita since 1960, we can compute its growth rate. However, as mentioned earlier, we must distinguish the *intrinsic growth rate* from growth due to credits.

While the public deficit can stimulate economic activity within a Keynesian framework [50, 51] (national income is proportional to government spendings through a Keynesian multiplier [22, 52]), it also increases cumulative carbon emissions in proportion to the path-dependent carbon intensity. This highlights that even growth-stimulating fiscal policies contribute to emissions lock-in unless accompanied by structural reductions in carbon intensity, and raises the need to question growth targets themselves.

Usually, the goals to limit global warming are set in terms of total cumulative  $CO_2$  emissions  $\mathcal{E}$  [42, 53–56], where a given scenario corresponds to a maximal amount of  $CO_2$  emitted over a time domain. We can compare the data on cumulative  $CO_2$  emissions with the model’s expected emissions and obtain a satisfactory match, as shown in Fig. 1B. We can then use the model to predict emissions for the following years, as shown in Figs. 3A and B, depending on the leverage (used to maintain GDP growth) or growth rate  $W$ . We observe that cumulative emissions increase with both leverage and growth rate. Using the temperature anomaly as proportional to  $CO_2$  emissions [42, 53], we can deduce that the temperature would rise accordingly. However,

our results depend on the specific economies of the countries under study and do not capture cumulative emissions on a global scale, nor do they account for global changes in consumption habits.

### 3.3 Study of the solvency probability

Uncertainties in the economy cannot be ignored, as they can lead to bankruptcy and a lack of solvency. We can relate the probability of bankruptcy to the probability that a biased random walk is smaller than a threshold at payback time, which is fixed  $t_p$  [30, 57, 58]. We emphasize that bankruptcy does not correspond to the existence of a time where the debt is larger than the gross capital (or first passage time), but to the fact that at the time of payback  $t_p$ , the debt is larger than the gross capital. The solvency probability is a related quantity that represents the likelihood that debt can be paid back before capital depletion.

#### *Strategy A*

We find that the probability of solvency depends mainly on the difference between the long-term growth rate and the logarithm of the interest rate. Interestingly, three regimes are possible depending on the sign of this difference, each yielding a different optimal strategy. If the long-term growth rate is strictly larger than the logarithm of the interest rate, the probability of solvency goes to 1 as payback time increases, while the opposite trend is observed (solvency probability going to 0) if the long-term growth is strictly lower than the logarithm of the interest rate. Thus, there is no pressure to payback in the first case, while the payback should occur as early as possible in the second case to avoid bankruptcy. In addition, there is a limiting case, where the solvency probability approaches 1/2 as the payback time tends to infinity.

#### *Strategy B*

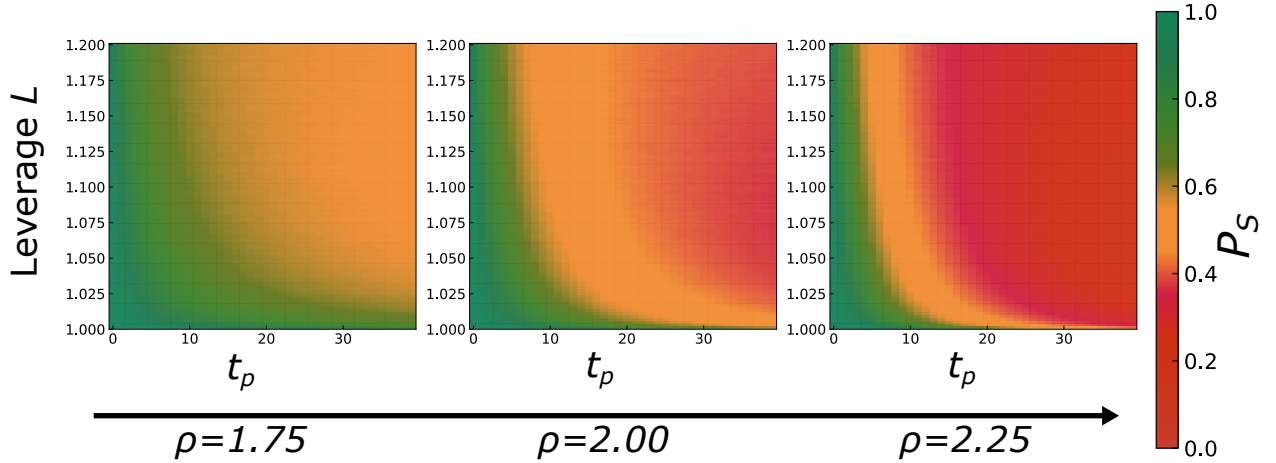
In the case of strategy B, unlike the case of strategy A, the solvency probability cannot be written in a closed form. We derive instead a recursive equation for the net capital from which we deduce that this solvency probability is a decreasing function of leverage, provided that the intrinsic growth rate is lower than the interest rate and leverage is sufficiently close to 1. We observe this trend in Fig. 4 and provide details of the calculations in the Methods section and in the Supplementary Information.

Typically, the solvency is lower under strategy B because a higher risk must be taken to maintain a higher growth rate. For  $L_\tau \sim 1$ , this solvency probability (strategy B) is smaller than for strategy A, since the investor relies more on leverage in strategy B than in A.

We then examine the impact of leverage and payback time on the probability of solvency. As expected, we observe that solvency probability generally decreases with both leverage and payback time, as illustrated in Fig. 4. In other words, debt leads to short-term GDP gains, even if it results in an increased long-term risk and enhanced cumulative carbon emissions, especially when the debt grows faster than GDP. In SI 2.4 and 2.5, we further explore solvency in both models. Notably, we find that high leverage strategies are optimal when the objective is the maximization of the growth rate for a given level of risk as measured by the solvency probability. However, these strategies are only optimal because environmental costs are ignored. In practice, high leverage strategies typically lead to large carbon emissions, particularly for carbon-intensive economies, as discussed above.

## 4 Discussion

Our analysis reveals that debt-financed growth structurally amplifies emissions. Specifically, the leverage  $L$  boosts GDP  $C_\tau$ , while the slow decline in carbon intensity  $I(\tau)$  leads to cumulative emissions that remain



**Fig. 4** Illustration of trade-off between solvency and payback time. Solvency probability  $P_S$  is shown for model B with the color scale as a function of payback time  $t_p$  and interest rate  $\rho - 1$ . Solvency becomes less likely with time in this model whenever  $\langle \gamma \rangle < \rho$  for all leverages  $L$ , *i.e.* when debt increases faster than the capital. This means that this strategy is not viable on long timescales, and is just a way to increase short-term GDP (resulting in increased carbon emissions).

nearly proportional to cumulative GDP. This confirms previous studies [41], [59], [60]. By separating the growth due to deficits from the intrinsic growth, we have confirmed that the economic growth of several countries is closely tied to deficits.

A second important observation is that although the intensity of carbon  $I(\tau)$  generally declines due to technological improvements and efforts to develop clean energy, increasing the leverage  $L$  always amplifies GDP ( $C_\tau$ ), compensating technological gains in clean energy production. As a result, we predict that total emissions  $\epsilon(t)$  will continue to increase in the coming decades.

We calibrated the model over multi-decade windows using observed macroeconomic data, extracting each country’s effective leverage  $L$  (the average ratio of deficit-financed spending to GDP), the intrinsic growth rate  $\gamma$  (the underlying growth rate absent new borrowing), and an interest rate  $\rho - 1$ . This data-driven approach is not a free fit, but rather implements recorded deficits, public debt, and GDP to set model parameters. Therefore, the model’s predictions can be directly compared to the actual outcomes.

To our knowledge, this is the first model to explicitly link fiscal leverage with cumulative CO<sub>2</sub> emissions and to calibrate it using multi-decade country-level data. Indeed, economic growth is typically treated as exogenous or as the result of a production function in Integrated Assessment Models (IAMs), such as DICE, REMIND, or MESSAGEix, without explicitly modelling credit dynamics [61, 62]. Similarly, the majority of climate-finance studies focus on transition risks or stranded assets [20], rather than quantifying the structural amplification of GDP growth and emissions by leverage. Our method is similar to macro-energy analyses that connect debt and energy consumption [2, 63]. However, it goes further by calibrating the leverage  $L$ , intrinsic growth  $\gamma$ , and interest rate  $\rho - 1$  based on historical data. This allows for the direct prediction and validation of cumulative emissions trajectories. For all four considered countries, the model accurately tracks the cumulative CO<sub>2</sub> emissions per capita alongside economic growth (Fig. 2B and SI), confirming that cumulative emissions are closely coupled with cumulative GDP, thus resulting in a persistent carbon lock-in effect. We observe that, despite differences in decarbonization efforts, each additional unit of GDP has historically carried a largely

invariant carbon cost over the long run (within the calibration period), with a near-proportional relationship between total economic output and total emissions. For example, using a time-declining carbon intensity  $I(t)$  for the US, the integration of our model from 1990 to 2020 yields cumulative per capita CO<sub>2</sub> emissions of the order  $7 \times 10^5$  kg, in good agreement with the observed value of  $\sim 6 \times 10^5$  kg. A similar close agreement is found for China, France, and Denmark (Fig. 2B), as evidenced by the overlapping model trajectories and historical data points. This level of precision indicates that our leveraged growth model captures a first-order causal driver of emissions: debt-fuelled economic expansion. Hence, it can provide a partial explanation for why emissions have continued to increase in line with commodity production, despite gains in energy efficiency in many sectors. The differences between countries in economic structure and debt dynamics are reflected in the calibrated parameters and outcomes. We find that the United States is heavily dependent on deficit spending to sustain its growth. Indeed, since 1980, its intrinsic growth rate has averaged only one percent per year, with substantial variability. In other words, most of the US GDP growth since 1980 can be attributed to credit expansion (public deficit and debt accrual) rather than to productivity gains [64]. Our calibration leads to an average leverage slightly above 1 for the US, rising to  $L \approx 1.06$  in 2023 amid large federal spending. This credit-driven growth is reflected in the model’s ability to reproduce the persistent increase in cumulative US CO<sub>2</sub> emissions at the end of the 1990s until just before the global financial crisis of 2008 (GFC) [65].

Quantitatively, the correspondence between modeled and observed cumulative CO<sub>2</sub> is such that a simple linear regression of one against the other would yield a slope near 1, *i.e.* cumulative emissions are almost a linear function of cumulative GDP (see Fig. 2C). The scatter of points around that line is small, which primarily reflects year-to-year economic variability rather than structural error in the model. This accordance is relevant, given that we did not calibrate the model by fitting it to emissions data, but rather derived emissions from independently calibrated economic parameters and an exogenous decline in carbon intensity. The observed results reveal that the coupling between economic output and emissions (illustrated by the Kaya identity, [66]) is grounded in the macro-financial structural dynamics of growth and investment.

An additional insight from our framework is that debt-driven growth imposes financial risks and constraints. Our stochastic analysis of the solvency probability (Fig. 4 and SI) shows that when the intrinsic growth rate  $\langle \gamma \rangle$  falls below the interest rate  $\rho - 1$ , the probability of long-term solvency decays towards zero, regardless of leverage  $L$ . In other words, maintaining growth through excessive borrowing ultimately becomes unsustainable and carries an endogenous risk of default. This result imposes a natural constraint on fiscal stimulus strategies. Even before critical climate transitions are reached, macro-financial dynamics may trigger deleveraging and systemic destabilizations. From a control theory perspective, this identifies an optimal leverage level on the Pareto front, beyond which additional credit raises default risk more than it supports sustainable growth [28, 67, 68].

In this sense, the model provides a quantitative link between carbon debt and financial debt: high-leverage, high-emission growth paths not only increase cumulative CO<sub>2</sub> emissions but also increase the risk of abrupt macroeconomic adjustments if interest rates rise or economic growth slows. Policies that are based on debt-financed growth should be assessed for their climate implications and the risk they pose of triggering financial instability and default.

One key limitation of the model is its tight coupling of public debt and GDP. We assume that each country’s government borrows a fixed fraction of GDP each year (the leverage  $L$  above 1 corresponds to a primary deficit ratio) and that this borrowing directly and immediately adds to that year’s GDP. In reality, the relationship between debt and growth is more complex: private credit creation (by banks and firms) can also drive variability, and not all deficit spending translates into GDP in the short run (in fact, the fiscal multiplier can vary). Our model effectively treats deficit-financed spending as equally productive as other spending, whereas inefficient investments or financial sector leakages could reduce the growth payoff of debt. In addition, identifying the

primary deficit with new capital investment is an oversimplification. In fact, governments may borrow for many reasons, and not all borrowing fuels productive capacity. A more advanced model would require integrating both public and private debt dynamics and the ability to distinguish between productive investment and pure demand stimulus. Such a complementary analysis of private debt could be conducted, as done previously with macroeconomic models of financial instability [3, 7].

Another important limitation is the model’s lack of sectoral differentiation in its treatment of emissions. We model each country as a single homogeneous production unit, with a single aggregate carbon intensity of output, in a manner similar to the Nordhaus model [19, 69–71]. This implies that we do not account for changes in the composition of GDP from high-carbon sectors (such as heavy industry) to low-carbon sectors (such as services). For example, within a country, some industries can rapidly decarbonize (such as renewables in power generation), while others lag behind (such as air travel or defense) [72, 73]. Our one-sector approach averages these dynamics out. Additionally, we assume that the same carbon intensity function  $I(t)$  applies regardless of the amount produced, thereby ignoring any nonlinear feedback (such as resource constraints, climate risks, or price effects) that may occur. In reality, a large increase in credit use (as in China’s case) can temporarily increase carbon intensity by increasing investment in construction and infrastructure. Our model partially reflects this by calibrating  $I(t)$  piecewise (using historical data to set  $I_0$  and a decline rate  $\eta$ ). China’s financial system structure may partially explain the apparent decoupling between GDP growth and territorial CO<sub>2</sub> emissions. Unlike market-based systems, in which credit allocation is determined by profit expectations, China’s state-dominated banking sector sets lending priorities based on policy objectives. A large-scale financing of renewables, electrified transport, and grid infrastructure is facilitated by the government’s determination of which sectors are eligible for credit. According to the model, this centralised allocation temporarily reduces the leverage–emissions gap by increasing the effective decarbonization rate  $\beta$  in comparison to the growth rate  $\gamma$ .

Denmark presents another informative and distinctive boundary case for our framework, owing to its limited public borrowing and persistent fiscal surpluses. As illustrated in the Supplementary Information, Denmark’s territorial emissions have decreased, while its consumption-based emissions have remained relatively constant, indicating that no actual decoupling has occurred. This discrepancy suggests that fiscal restraint alone is insufficient to guarantee a reduced carbon footprint when emissions are outsourced through trade. In the Supplementary Information, we compare territorial and consumption-based estimates (Fig. S2) and find that offshoring of emissions can significantly alter apparent decoupling trends (a phenomenon also referred to as carbon leakage [74]). Despite their high consumption-based footprint, countries that relocate carbon-intensive production abroad appear to decrease their emissions-to-GDP ratio [75]. To address this issue, network-based allocation methods developed by Van den Ende et al. (2025) offer a rigorous approach to quantify responsibility for emissions along global value chains, which complements territorial accounting [76].

It’s worth noticing that our analysis does not currently include private credit and investment flows, which can be significant drivers of emissions and capital formation [77]. The current representation of the leverage term  $L_t$  is based on public fiscal deficits, which account only for the government’s contribution to output growth through borrowing. Nevertheless, alternative data sources, such as total credit to the non-financial sector or capital market issuance, could be used to illustrate the intensification of growth through private investment flows. This expansion would enable the model to quantitatively describe mechanisms, such as those specifically identified in recent analyses on institutional investors and insurers, that persist in financing the expansion of fossil fuels despite climate commitments [78], [79].

Financial debt and carbon debt are two sides of the same anticipatory system: the former brings future wealth forward, while the latter consumes the energy of the future. Our stochastic credit-risk model, when scaled up to the macroeconomic level, shows that there are both physical and financial limits to debt-driven growth. It is an important message because the idea that there are limits to growth, even when allowing for

innovation, is not widely accepted among economists [80]. Here, we show that as long as credit rests on the promise of material expansion, each euro borrowed creates a double debt — a financial and a climatic one. The great challenge of the twenty-first century will be to decouple prosperity from the credit lever, so that the growth of well-being is no longer tied to the growth of carbon.

## Methods

### *Definition of the stochastic credit-risk model*

Our stochastic credit-risk model is defined by the following dynamical equations for the capital  $C_\tau$  and the debt  $D_\tau$  at time  $\tau$ :

$$C_0 = B_0 + C_{\text{ini}} = LC_{\text{ini}}, \quad (6)$$

$$C_{\tau+1} = \gamma_\tau C_\tau + B_{\tau+1} - \left( \sum_{\tau'=0}^{\tau} \delta_{\tau, t_p(\tau')} \right) D_{\tau+1}, \quad (7)$$

$$D_0 = B_0 = (L - 1)C_{\text{ini}}, \quad (8)$$

$$D_\tau = \sum_{\tau'=0}^{\tau-1} \Theta(t_p(\tau') - \tau) \rho_{\tau'}^{\tau-\tau'} B_{\tau'}, \quad (9)$$

where in the first equation,  $C_{\text{ini}}$  is the amount invested initially by the investor, and  $B_0$  is the initial amount borrowed. The leverage is  $L = (B_0 + C_{\text{ini}})/C_{\text{ini}}$ . The second equation describes the growth of the capital from time  $\tau$  to time  $\tau + 1$ . The model uses discrete time, as in Kelly's original model. However, extending it to continuous time is straightforward. At each time step, the capital is multiplied by  $\gamma_\tau$ , which accounts for inflation [38]. This parameter represents the stochastic instantaneous growth rate at time  $\tau$ . The evolution of the debt is described by the last two equations. The interest rate  $\rho_\tau - 1$  is the factor by which the amount borrowed is multiplied at each time step, in other words, the debt due to the amount borrowed at time  $\tau'$ , is multiplied by  $\rho_{\tau'}^{\tau-\tau'}$  if it has not been paid back at time  $\tau$ . In general, the interest rate is larger than 0 ( $\rho > 1$ ), so that the debt keeps increasing, and the borrower ends up paying more than the amount borrowed. If  $\gamma_\tau > 1$ , the gross capital increases provided that there is no borrowing or payback at this time. The second term represents the amount borrowed at time  $\tau$ ; it can be 0 if the borrower does not borrow at this step, or a positive value. The third term represents the possible payback of the debt (debt clearing) at time  $\tau + 1$ , and will either be equal to 0 (no payback), or to  $D_{\tau+1}$ .

In the second and fourth equation,  $t_p(\tau')$  indicates the time when the amount borrowed at  $\tau'$  is paid back. In the second equation, if a payback happens at time  $\tau$ ,  $\exists \tau', \tau = t_p(\tau')$ , and thus  $(\sum_{\tau'} \delta_{\tau, t_p(\tau')}) = 1$ , then the capital is reduced by the service of the debt, otherwise  $(\sum_{\tau'} \delta_{\tau, t_p(\tau')}) = 0$  and there is no such reduction. In the last equation, the Heaviside function  $\Theta$  function allows us to know if the payback has occurred at time  $\tau$  (indeed  $\Theta(t_p(\tau') - \tau) = 0$  if  $\tau > t_p$ , meaning that the debt is erased after it has been paid back).

### *Strategy A*

We assume that the investor initially borrows money ( $B_0 > 0$ ) but never borrows afterwards,  $\forall \tau \geq 1, B_\tau = 0$ . We refer to this strategy as strategy A, which is akin to an individual taking out a loan to buy a house. In practice, the investor can borrow  $B_0$  and invest  $C_{\text{ini}}$  from its personal capital, and the leverage is then  $L = (B_0 + C_{\text{ini}})/C_{\text{ini}}$ . In this case, for  $\tau < t_p$ , the gross capital evolves as in the standard Kelly's model with an initial investment of  $B_0 + C_{\text{ini}}$ , and the debt evolves with an interest rate  $\rho - 1$ . At the time of payback,

the capital can become negative, which could not happen within the purely multiplicative dynamics of Kelly's model. Bankruptcy occurs if  $C_{t_p}$  is negative, or equivalently if

$$\prod_{\tau' \leq t_p} \gamma_{\tau'} < 1 - \frac{1}{L}, \quad (10)$$

meaning that the larger  $L$  is, the more likely the bankruptcy. Under the assumption of no bankruptcy, we can also define the long-term growth rate  $W = \mathbb{E}(\ln(\gamma))$ . Note that due to the concavity of the logarithm, we have generally for any probability distribution of  $\gamma$ ,  $\ln(E) \geq W$ , with  $E = \mathbb{E}(\gamma)$ . However, there is a non-zero probability of hitting bankruptcy when the debt is paid back (at  $t_p$ ).

### Strategy B

Within strategy B, the investor borrows to an external actor at each time step with a time dependent leverage  $L_\tau$ . The dynamics is then (except for the time of payback):

$$\begin{aligned} C_{\tau+1} &= (\gamma_\tau + (L_\tau - 1)) C_\tau, \\ D_{\tau+1} &= \rho D_\tau + (L_\tau - 1) C_\tau. \end{aligned} \quad (11)$$

Now, in addition to the long-term growth rate  $W$  defined as before, one can also consider the short-term growth rate  $\omega(t_p)$  (defined in SI section 1.1). We explicitly separate the value linked to production from the value added through borrowing, in the stochastic *intrinsic growth rate*:

$$r(\tau) = \frac{C_{\tau+1} - C_\tau}{C_\tau} - (L_\tau - 1) = \gamma_\tau - 1. \quad (12)$$

### Solvency in Strategy A

The solvency probability  $P_S(t_p)$  for a fixed payback time  $t_p$  can be computed explicitly in this case. To do so, we introduce the stochastic variable  $X_{\tau'} = \ln(\gamma_{\tau'}/\rho)$ , which represents increments of the long-term growth rate. This variable has mean  $m = W - \ln(\rho)$  and variance  $\sigma_X^2$ . Then, we show in Supplementary Information that

$$P_S(t_p) = \frac{1}{2} \left( 1 + \operatorname{erf} \left( \frac{t_p m - \ln(1 - \frac{1}{L})}{\sqrt{2t_p} \sigma_X} \right) \right). \quad (13)$$

From this equation, we find that three regimes are possible depending on the sign of  $m$ . If  $m > 0$ ,  $P_S(t_p \rightarrow \infty) \rightarrow 1$ , solvency is guaranteed, and there is thus little pressure to pay back the debt. If  $m < 0$  instead,  $P_S(t_p \rightarrow \infty) \rightarrow 0$  and the convergence is faster as  $\sigma_X$  decreases, but in this case, the best course of action is to pay back the debt as soon as possible to avoid bankruptcy. The case  $m = 0$  is a limiting case where  $P_S(t_p \rightarrow \infty) = \frac{1}{2}$ .

### Solvency in Strategy B

The expression for the solvency probability in this case is

$$P_S(t_p) = \mathbb{P} \left( X_{t_p} \geq 1 - \frac{1}{L} \right), \quad (14)$$

with  $X_{t_p}$  now defined by  $X_{t_p} = \Pi_{t_p} - (L - 1) \sum_{t \leq t_p - 1} \Pi_t / \rho$  with  $\Pi_t = \prod_{1 \leq \tau' \leq t} (\gamma_{\tau'} + (L - 1)) / \rho$ . We identify two regimes in this case, which are controlled by the sign of  $\langle \gamma \rangle - \rho$ . Under the assumption that fluctuations in the economy are not too large, we expect the solvency probability to be a decreasing function of time when  $\langle \gamma \rangle < \rho$ , whereas the opposite is expected for  $\langle \gamma \rangle > \rho$ . Thus, we recover a well-known condition that sets the stability of public debt with respect to GDP [38]. From this, we conclude that debt tends to rise faster on average than capital as long as the *intrinsic growth rate* is smaller than the interest rate  $\rho - 1$ .

### Data analysis

We have extracted from economic data of four countries (China, US, Denmark and France) in the time frame 1998 – 2022, parameters of the model as shown in Table 1.

	China	US	Denmark	France
Average leverage $\langle L_\tau \rangle$	$1.025 \pm 0.023$	$1.051 \pm 0.040$	$0.997 \pm 0.029$	$1.040 \pm 0.018$
Average interest rate $\langle \rho_\tau \rangle - 1$	$0.131 \pm 0.101$	$0.013 \pm 0.051$	$0.018 \pm 0.237$	$0.008 \pm 0.088$
Average long-term growth rate $W$	$0.088 \pm 0.086$	$-0.018 \pm 0.059$	$0.032 \pm 0.089$	$-0.020 \pm 0.090$
Average intrinsic growth rate $\langle \gamma_\tau \rangle - 1$	$0.096 \pm 0.095$	$-0.017 \pm 0.056$	$0.036 \pm 0.091$	$0.017 \pm 0.088$

**Table 1** Estimations of key parameters of the model from economic data of GDP and deficits of four different economies.

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