Climate physical risk, transition spillovers and fiscal stability: an application to Barbados

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Abstract

Barbados is a country highly exposed to climate physical risks and to transition risks, where the latter could emerge as a result of a domestic disorderly transition, and from the introduction of climate policies by trading partners. Nevertheless, we still know little about the implications of climate scenarios on sovereign fiscal and financial stability. We contribute to filling this gap by studying the macroeconomic and public finance impacts of climate risks. It includes transition spillover risk, driven by the introduction of climate policies globally, which decrease international tourist arrivals to curb CO_2 emissions from flights, coherently with transition scenarios for aviation. It also accounts for chronic and acute physical climate risks, with the latter given by a country-specific model for tropical cyclones, calibrated on past meteorological data from the Caribbean region. To conduct our analysis, we tailor the EIRIN Stock-Flow Consistent behavioral model, and we calibrate it to the Barbadian economy. First, we find a potentially significant reduction of the Barbadian GDP due to transition spillover risk: up to 37.6% less in 2050, as a deviation from a business-as-usual path of touristic inflows. This further harms the debt-to-GDP ratio and debt sustainability. Second, implementing domestic climate policies may decrease GHG emissions by up to 75%. Importantly, the economic costs of decarbonization are smaller than the costs of unabated climate change. The results suggest that mitigating climate risks would benefit from economic diversification and from tailored financial instruments.

JEL: B59, Q50
Keywords: climate transition spillover risks; climate physical risk; balance of payment; public debt sustainability; sovereign risk; Stock-Flow Consistent model; Barbados.

1 Introduction

The 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) pointed out that climate impacts will be large and highly heterogeneous across countries, with developing economies being significantly more exposed to the negative impacts of chronic and acute physical risk [40]. Beyond climate physical risks, a country could be negatively affected by a disorderly introduction of climate policies and regulations. This is known as transition risk [59]. However, transition risk could also emerge for a country exporting high-carbon products as a consequence of the introduction of climate policies and regulations by its trading partners. This is defined as *climate transition spillover risk* [64, 29].

Mitigating and adapting to climate change requires patient private and public investments [47]. In the context of developing countries, scaling up capital for climate investments is particularly challenging due to the countries' limited fiscal space and limited or costly access to international markets [61]. Further, due to their tight budget constraints, climate investments compete with other spending priorities, e.g. welfare.

Countries in the Caribbean region, and among them Barbados, are a good example of climate risk exposure and vulnerability, and of challenges accessing and deploying climate finance. First, Barbados is highly exposed to physical risks, notably hurricanes, sea level rise, droughts and their implications on water scarcity [30]. This could negatively affect the economy and public finance via lower tax revenues [51]. Contingent liabilities issues could emerge, potentially increasing the fiscal costs, which, in turn, may lead to higher sovereign borrowing costs [2, 3]. However, while both investments in mitigation and adaptation are thus important for Barbados (see its Multi-hazard Disaster Management Plan), international financial institutions focused on funding mitigation and less so on adaptation.

Second, tourism is a main contributor to the GDP of Barbados, supported in particular by international tourists. Nevertheless, intercontinental air travel is a main contributor to Green House Gas (GHG) emissions [see 40, section 6.6.2.3.1]. In all low-carbon transition scenarios, air travel emissions are subject to large decrease, up to 90% by 2050 [34], and so routes. Barbados could then experience a sharp decline of incoming tourism, which in turn would negatively affect its economic performance, and public finance.

Third, Barbados is highly dependent on oil as an energy source. The introduction of climate transition policies in Barbados to deliver on the Paris Agreement pledges [30] would require to reduce the use of oil and switch to renewable energy sources. While the transition may help public finances by reducing the economic dependence on oil imports, it risks at the same time to prove disruptive for the economy, depending on its implementation.

Finally, the economic impacts of climate risks could cascade onto the financial system. Importantly, the banking sector of Barbados has already a high Non-Performing Loans (NPL) ratio. Thus, timely management of climate risks is crucial to prevent the reversal of years of progress in fiscal and financial consolidation.

In this paper, we assess the macroeconomic, public finance and sovereign risk implications of both climate physical risks, considering both acute and chronic impacts, and transition spillover risks. The latter is modelled as a shock on international tourism income, coherently with the decarbonization scenarios by 2050 (Net Zero (1.5°C) and Below 2°C). Our analysis contributes to the understanding of how climate risk considerations can be included in the design of green financial policies and debt instruments to help the country mitigate and adapt to climate change. To this aim, we study how climate policies to scale up green investments and decarbonize the economy can neutralize or reinforce these risks, with a focus on the implications for sovereign financial stability.

Our analysis is based on a tailored version of the EIRIN Stock-Flow Consistent behavioural model [28] calibrated on Barbados. To assess climate physical and transition spillover risk, we model variations from three base scenarios with EIRIN, making use of the following components:

(i) both transition and chronic physical risk, from the Network for Greening the Financial System (NGFS) scenarios [58];

(ii) aviation emissions trajectories from the scenarios of the World Energy Outlook of the International Energy Agency (IEA) [34], which we use to shock tourism income;

(iii) a stochastic model for the assessment of acute climate physical risk, obtained from the CLIMADA model [1, 7] and relying on past meteorological data for tropical cyclones.

On the first point, we are integrating in particular the carbon price paths from NGFS scenarios, which is the central domestic policy considered for low-carbon transition. It is complemented by secondary fiscal policies to support decarbonization, in line with the same NGFS scenarios. We are thus building on the joint analysis between transition and physical risk initiated in [28].

Our findings highlight the centrality of tourism as a channel of climate risks transmission to the Barbadian economy, and the indirect implications to the rest of the economy. In the most stringent low-carbon transition scenario (Net Zero 2050), the shock on tourism entails a deviation in GDP of -37.6% in 2050, relative to a business-as-usual path of touristic inflows.

Furthermore, we find that the domestic policies aiming at reducing GHG emissions operate in an orthogonal fashion to this, in so far as the high carbon prices of the NGFS scenarios are efficient in bringing down the emissions and maintaining the same economic output. Thus, climate policies should be implemented early while actively planning for potential disruptions of the touristic revenues.

Our results contribute to inform policy recommendations aimed to strengthen countries' climate financial risk assessment and management. Eventually this should inform the design of effective (and potentially coordinated) policies and financial instruments to mitigate and adapt to climate change.

The remainder of this paper is organized as follows: section 2 reviews the relevant literature and the current exposure of Barbados to climate risks; section 3 provides a summary of the EIRIN model and its data-driven calibration; section 4 provides information on the sourcing and integration of the different scenario components. Finally, section 5 presents the findings from the simulations conducted, and section 6 concludes and discusses our results.

2 Review of macro-financial relevant climate risks for Barbados

Barbados is facing multiple challenges given a situation where its economy is already under pressure. It had the debt-to-GDP ratio of the Caribbean region in 2017 [56], standing at 147%. Consequently, its interest-serving expenses accounted for 10.3% of its revenues in 2016 [56].

2.1 Challenges to decarbonize the economy of Barbados

A main challenge for Barbados in its transition to a low-carbon economy is its dependency on oil as a source of energy production. As reported by the International Renewable Energy Agency (IRENA), the share of renewable energy in Barbados was only 5.8% in 2018 [41, last available data]. The country is mostly dependent on imported oil for its electricity generation and in its energy mix more broadly.

Moreover, in 2020, the renewable energy used in electricity generation was only solar [41]. Johnston et al. [44] find that Barbados would have a suitable geography for the deployment of electricity production from floating offshore wind technology, as well as ocean thermal energy conversion in the long-run. However, in the short run, future development in renewable energy are expected to be mostly solar-based.

Barbados has benefited from development programs that aim to improve the energy efficiency of the country, as well as to increase its meager share of renewable [39, 36]. Nevertheless, it is still lagging behind most other countries in that regard, in part due to the lack of access to more diverse forms of renewable energy. Therefore, significant investment are required at the scale of the country to conduct its low-carbon transition.

2.2 The challenge of climate adaptation

The second aspect considered is climate physical risk. Barbados has been hit by several major hurricanes over the past two decades, most notably Irma and Maria in 2017, which worsened the debt burden of the country.[1] This exposure also reduces the leeway of the government in its financing, as Cevik and Jalles [18] show that physical risk vulnerability leads to a higher cost of borrowing.

With regard to rising sea level specifically, Barbados is economically winning from investing in more coastal infrastructure as it also drives revenues from tourism. Barbados also invests in adaptation efforts such as coastal protection [35], and it received a US$80 million contingent loan from the Inter-American Development Bank [38] for disaster relief financing. However, this may not be sufficient as the need for humanitarian help related to extreme weather has sharply increased in the past twenty years globally [14].

More generally, the challenge of development has been gaining prominence as damages from extreme weather events rose. Thus, international institutions such as the IMF have increased their focus on adaptation-related effort [26]. Natural disaster clauses on the debt stock of Barbados have been already introduced to limit the damages of disaster events on public finances by deferring the payments of both interest and principal [33].

2.3 Barbados' dependence on tourism

The last key element motivating this study is the dependence of the country on tourism. The sector directly accounted for 9% of GDP in Barbados in 2019 [16], and in 2015 it represented approximately 37% of jobs and 60.4% of exports were linked to tourism [37]. Thus, it plays a major economic and social role on the island.

However, the sector is vulnerable to climate risk. Physical risk can create lower demand (on top of the capital destruction) [67]. More importantly for this study, policies by other countries can also affect the flow of tourism, e.g. lesser subsidies for air transportation. And while we consider here the joint applications of climate risks, it also stands that it can compound with other shocks. Most recently, Barbados experienced an 80% decline in tourist arrivals in 2021 due to COVID-19, compared to 2019 [16]. The capacity of Barbados to weather exogenous shocks is then central, especially as Browne and Moore [9] found that second-round economic downturns inhibit tourists.

[1] See https://www.theguardian.com/environment/2022/nov/09/leaders-urged-to-reform-finance-to-aid-the-poorest-hit-by-the-climate-crisis.

3 Model description

We tailor and apply the EIRIN macroeconomic model to Barbados, extending on [54, 28, 29]. This section provides an overview of the core mechanism of the model, as well as the sources and details of its calibration.

3.1 Model overview

EIRIN is a Stock-Flow Consistent (SFC) model[2] of an open economy composed by a limited number of heterogeneous and interacting agents of the real economy and financial system. Agents are heterogeneous in terms of source of income and wealth, and of preferences.

Agents are represented by their balance sheet entries, which are calibrated on real data (when possible), and connected in a network. The SFC model's characteristics make it possible to trace a direct correspondence between stocks and flows, thus increasing the transparency of shocks' transmission channels.

EIRIN is an SFC behavioral model, meaning that agents' decisions are informed by behavioral rules, expectations and heuristics. In addition, EIRIN's agents are endowed with adaptive expectations about the future. The departure from traditional forward-looking expectations allows us to consider the impact of expectations on lack of market coordination and mispricing on the economic outcome of climate change and of the transition.

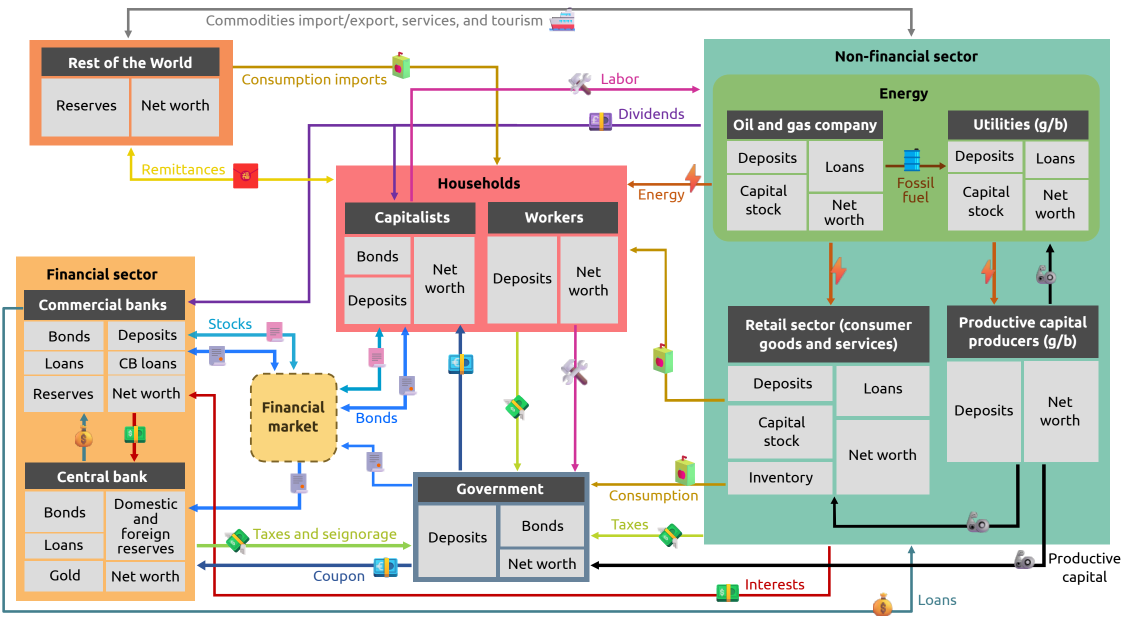


Figure 1: The EIRIN model framework: capital and current account flows of the EIRIN economy. For each sector and agent, a representation in terms of assets and liabilities is provided. The dotted lines represent the capital account flows, while the solid lines represent the current account flows.
Source: Gourdel et al. [28].

[2]See for instance Caverzasi and Godin [15], Dafermos et al. [19], Dunz et al. [23], Naqvi and Stockhammer [57], Ponta et al. [63], Caiani et al. [11], Carnevali et al. [12], and Bovari et al. [6].

The capital and current account flows that structure the model are represented in Figure 1. The model is composed of five sectors i.e. the non-financial sector, the financial sector, households, the government and the foreign sector. The non-financial sector is composed of

(i) two energy firms (EnB and EnG, brown and green respectively) that supply energy to households and to firms as an input factor for production (red solid line);

(ii) an oil and mining firm that supplies EnB in fossil fuel;

(iii) a capital intensive producer Fk (for consumption goods) and a labor-intensive producer Fl (for service, tourism, agriculture) that provide heterogeneous consumption products to households (yellow solid line);

(iv) two productive capital producers (KpB and KpG, brown and green respectively), which supply all the above.

The energy firms and the consumption good producers require capital as an input factor for production. To build-up their capital stock, they invest in capital goods (black dashed line), which are produced by the capital good producer. To finance investment expenditures, firms can borrow from the commercial bank (red dotted line), which apply an interest rate to their loans (red solid line). Households, firms and the government have deposits in the commercial bank (green dashed line). The commercial bank also holds reserves at the central bank (blue dotted line), which provides refinancing lines (red dotted line). The government pays public employees (pink dashed line) and provides emergency relief or contracts non-financial firms (blue solid line). The government collects tax revenues from households and firms (orange solid line) and finances its current spending by issuing sovereign bonds (blue dotted line). Sovereign bonds are bought by capitalist households, by the commercial bank, and by the central bank. The government pays coupon interests on sovereign bonds (dark blue line). Households are divided into workers and capitalists, based on their functional source of income: workers receive wage income (pink dashed line); capitalists own domestic firms, from which they receive dividend income (purple solid line), and coupon payments for their sovereign bond holdings (dark blue line). The foreign sector provides remittances (gray dotted line) and consumption goods to households (dark gray solid line). The foreign sector generates tourism flows and spending in the country, purchases services and industry goods, and sells resources to firms as inputs for the production (gray solid line).

3.2 Markets and sequence of events

EIRIN's agents and sectors interact with each other through a set of markets. Their operations are defined by the sequence of events occurring in each simulation step, which is the following:

1. Policymakers make their *policy decisions.* The central bank sets the policy rate according to a Taylor-like rule. The government adjusts the tax rates on labor and capital income, on corporate earnings, and on value added, to meet its budget deficit target.
2. The *credit market* opens. The bank sets its maximum credit supply according to its equity base. If supply is lower than demand, proportional rationing is applied and prospective borrowers revise down their investment and production plans accordingly.
3. *Real markets* open in parallel, they include the market for *consumption goods and services*, the *energy* market, the *labor* market and the *raw materials* market. Prices of the exchanged goods or services are determined, then the nominal or real demand and supply are provided by the relevant agent in each market. Finally, transactions occur, generally at disequilibrium, i.e. at the minimum between demand and supply.
4. The *financial market* opens. The capitalist household and the bank determine their desired port-

folio allocation of financial wealth on securities. The government offers newly issued bonds to finance a budget deficit, which includes green investments. The central bank may perform quantitative easing policies and enter the bond market as a buyer of sovereign bonds. Then, new asset prices are determined.

5. All transactions and monetary flows are recorded, taxes paid are determined, and the balance sheets of the agents and sectors of the EIRIN economy are updated accordingly.

3.3 Agents and sectors' behaviors

We detail below the key mechanisms and behaviors that guide the model, starting by introducing the most common notations used. Let i and j be two agents. Then, p_i is the price of the output produced by i, while $p_i^\star$ is the price of the security issued by i. $D_{i,j}$ is the demand by j of what i produces, and $\mathbf{D}_i = \sum_j D_{i,j}$. Moreover, $\mathbf{q}_i$ is the total production of i and $q_{i,j}$ is the part of it that is given to j. We also denote by M_i the liquidity of i, akin to holdings of cash, and by K_i its stock of productive capital where applicable.

Building on Goodwin [27], **households** are divided into two classes. Income class heterogeneity is functional to assess the distributive effects of the policies introduced in the low-carbon transition and on the channels of inequality. First, the working class (Hw) lives on wages, with gross revenues

$$Y_{\mathrm{Hw}}^{\mathrm{gross}} = \sum_i N_i \times w_i \tag{1}$$

where w_i the wage paid by i and N_i the size of the workforce it employs (we omit the time dimension for simplicity as all variables are contemporaneous). The labor market mechanism determines the final workforce N_i of each agent, based on the total N_{tot} of workers available and the demand for labor of firms [see 28, for details]. It also determines the salary level $w_i(t)$ paid by i, based on the skills required by the firms. Second, the capitalist class (Hk) earns its income out of financial markets, through government bonds' coupons and firms dividends:

$$Y_{\mathrm{Hk}}^{\mathrm{gross}} = \mathfrak{c} \times n_{\mathrm{Hk,G}} + \sum_i d_i \times n_{\mathrm{Hk},i}, \tag{2}$$

where d_i is the dividend of i, $\mathfrak{c}$ is the coupon's rate, and $n_{i,j}$ is the number of securities issued by j and held by i. Both households are then taxed, with θ_{Hw} the rate of the income tax, and θ_{Hk} the rate of the tax on profits from capital. Furthermore, both household classes receive net remittances Rem_i from abroad, which is a net positive for Barbados.

All households pay their energy bill. This leaves them with Y_i^{disp} as net disposable income: $\forall i \in \{\mathrm{Hw}, \mathrm{Hk}\}$,

$$Y_i^{\mathrm{disp}} = \underbrace{(1-\theta_i) \times Y_i}_{\text{net income}} - p_{\mathrm{En}} D_i^{\mathrm{En}} + \mathrm{Rem}_i \tag{3}$$

Households' consumption plans (Eq. (4)) are based on the Buffer-Stock Theory of savings [20, 13]. It balances the *impatience* of households of consuming all their income and wealth right away with their *prudence* about the future, preventing them to draw down their assets too far:

$$C_i = Y_i^{\mathrm{disp}} + \rho \left(M_i - \phi \times Y_i^{\mathrm{disp}} \right) . \tag{4}$$

The parameter ϕ defines quasi wealth-level target that households pursue, relative to their disposable income, while ρ characterizes the speed at which they save or consume to reach this target. Then, households split their consumption budget C_i. They import a share ζ_0 from the rest of the world, and they allocate a share ζ_1 of the remainder to services, with the last part for consumption goods:

$$D_{\mathrm{Fl},i} = (1-\zeta_0)\times\zeta_1\times C_i \quad \text{and} \quad D_{\mathrm{Fk},i} = (1-\zeta_0)\times(1-\zeta_1)\times C_i \,.$$

The **service firm** Fl (also called labor-intensive) and **consumption goods producer** Fk (also referred to as capital-intensive) produce an amount $\mathbf{q}_j$ of their respective outputs by relying on a Leontief technology. This implies no substitution of input factors, meaning that if an input factor is constrained (e.g. limited access to credit to finance investments), the overall production is proportionately reduced:

$$\forall j \in \{\mathrm{Fl}, \mathrm{Fk}\}, \quad \mathbf{q}_j = \min\left\{\gamma_j^N N_j,\ \gamma_j^K K_j\right\},$$

where γ_j^N and γ_j^K are the productivity coefficients of labor and capital respectively. The labor productivity follows a Verdoorn-augmented linear specification based on Philippon [62] and Lavoie [48].

The two firms set their respective price as a mark-up μ_j on their labor costs w_j/γ_j^N, capital costs $\kappa_j L_j$, energy costs $p_{\mathrm{En}} q_{\mathrm{En},j}$, and resource costs $p_R q_{R,j}$, such that $\forall j \in \{\mathrm{Fl}, \mathrm{Fk}\}$,

$$p_j = (1+\mu_j)(1+\theta_{\mathrm{VAT}})\left[\frac{w_j}{\gamma_j^N} + \frac{\kappa_j L_j + p_{\mathrm{En}} q_{\mathrm{En},j} + p_R q_{R,j}}{\mathbf{q}_j}\right]. \tag{5}$$

Higher prices of consumption goods and services driven by higher firms' interest payments on loans, more expensive imports, more expensive energy and/or labor costs, constrain households' consumption budgets, which in turn lower aggregate demand. This represents a counterbalancing mechanism on aggregate demand.

The minimum between real demand of the two consumption goods and the real supply determines the transaction amount $\tilde{\mathbf{q}}_j$ that is traded in the goods market:

$$\tilde{\mathbf{q}}_{\mathrm{Fk}} = \min\left(\mathrm{IN}_{\mathrm{Fk}} + \mathbf{q}_{\mathrm{Fk}}, \mathbf{D}_{\mathrm{Fk}}/p_{\mathrm{Fk}}\right) \tag{6}$$

$$\tilde{\mathbf{q}}_{\mathrm{Fl}} = \min\left(\mathbf{q}_{\mathrm{Fl}}, \mathbf{D}_{\mathrm{Fl}}/p_{\mathrm{Fl}}\right). \tag{7}$$

The supply of capital intensive consumption goods also takes firms' inventories ($\mathrm{IN}_{\mathrm{Fk}}$) into account. In case that demand exceeds supply, all buyers are rationed proportionally to their demand. The newly produced but unsold products add up to the inventory stock of Fk's inventories. Finally, both producers make a production plan $\hat{q}_j$ for the next simulation step based on recent sales and inventory levels.

The **energy sector (En)** is divided into renewable and fossil fuel energy producers (EnG and EnB respectively). It produces the energy that is demanded by households for consumption and by firms for production. We assume that all demand is met, even if EnB might have to buy energy from the foreign sector, such that $\mathbf{q}_{\mathrm{En}} = \mathbf{D}_{\mathrm{En}}$. Households' energy demand is inelastic (i.e. the daily uses for heat and transportation), while firms' energy requirements are proportional to their output. The fossil energy company requires capital stock and oil (mostly from the foreign sector) as input factors for production. The renewable energy company requires only productive capital but in higher quantity. The energy price is endogenously set from the unit cost of both firms [see 28, for details].

Hw and Hk subtract the energy bill from their wage bill as shown by their disposable income, while firms transfer the costs of energy via mark-ups on their unit costs to their customers (equation (5)). To be able to deliver the demanded energy, the energy producer require capital stock and conducts investment to compensate capital depreciation and expand its capital stock to be able to satisfy energy demand [see 28, for details]. The **oil and mining** company MO supplies EnB in oil and exports to the rest of the world as well. A difference relative to [28, 29] is that EnB also imports from the rest of the World to produce energy, which reflects the dependence on imported oil.

Both Fl and Fk make **endogenous investment decisions** based on the expected production plans $\hat{q}_i$ that determine a target capital stock level $\hat{K}_i$. The target investment amount $I_i^\dagger$ is set by the target capital level $\hat{K}_i$, considering the previous capital endowment $K_i(t-1)$ subject to depreciation $\delta_i \times K_i(t-1)$ and potential[3] capital destruction as a consequence of natural disaster shocks $\hat{\xi}(t) \times K_i(t-1)$, hence

$$I_i^\dagger(t) = \max\left\{\hat{K}_i(t) - K_i(t-1) + \delta_i \times K_i(t-1) + \hat{\xi}(t) \times K_i(t-1), 0\right\} \tag{8}$$

Differently from supply-led models [e.g. 65], in EIRIN investment decisions are fully endogenous, and they are based on firms' Net Present Value (NPV). This in turn is influenced by six factors, i.e (i) investment costs, (ii) expected future discounted revenue streams (e.g. endogenously generated demand), (iii) expected future discounted variable costs, (iv) the agent's specific interest rate set by the commercial bank, (v) the government's fiscal policy, and (vi) governments' subsidies. More precisely, the planned investment is given by

$$I_i^\star(t) = \left(\varphi_i \times M_i(t-1) + \Delta^+ L_i(t)\right) / p_{\mathrm{Kp},i}(t), \tag{9}$$

where φ_i is the share of liquidity that i uses to finance investment, $\Delta^+ L_i$ is the part that comes from new credit, and $p_{\mathrm{Kp},i}$ is the average price of capital, which depends on the ratio of green and brown, at unit prices p_{KpG} and p_{KpB} respectively. The NPV calculations allow us to compare the present cost of real investments in new capital goods to the present value of future expected (positive or negative) cash flows, and it constrains what can be financed through credit. We differentiate in that regard between low-carbon and high-carbon capital, that is, for a level ι of investment, the related NPVs are

$$\mathrm{NPV}_i^{\mathfrak{g}}(\iota, t) = -p_{\mathrm{KpG}}(t) \times \iota + \sum_{s=t+1}^{+\infty} \frac{\mathrm{CF}_i^{\mathfrak{g}}(\iota, t, s)}{(1+\kappa_i)^{s-t}} \tag{10}$$

$$\mathrm{NPV}_i^{\mathfrak{b}}(\iota, t) = -p_{\mathrm{KpB}}(t) \times \iota + \sum_{s=t+1}^{+\infty} \frac{\mathrm{CF}_i^{\mathfrak{b}}(\iota, t, s)}{(1+\kappa_i)^{s-t}} \tag{11}$$

where $\mathrm{CF}_i^{\bullet}(\iota, t, s)$ describes the total expected cash flows expected at s from the new investment [see 28, for the details of the cash flow calculations]. Cash flows are discounted using the sector's interest rate κ_j set by the commercial bank. This computation imposes a limit on investment such that:

$$\Delta^+ L_i(t) \le \max\left\{\iota \in [0, I_i^\dagger(t)] :\ \mathrm{NPV}_i^{\mathfrak{g}}(\iota, t) \ge 0 \text{ or } \mathrm{NPV}_i^{\mathfrak{b}}(\iota, t) \ge 0\right\}. \tag{12}$$

The final realized investment $I_i(t)$ is divided into green and brown capital such that $I_i = I_i^{\mathfrak{g}} + I_i^{\mathfrak{b}}$. Then, it is potentially constrained by the supply capacity of the producers.

The **capital goods producers** (Kp, divided into green and brown capital producers, KpG and KpB

[3] Note that $\hat{\xi}(t)$ denotes the expectation of the physical shock, as the realized value $\xi(t)$ is observed at the end of the period only.

respectively) supply capital goods to fulfill the production capacity of Fl, Fk and En, and the investment by the government G:

$$\begin{aligned} \mathbf{q}_{\mathrm{KpB}} &= I^{\mathfrak{b}}_{\mathrm{Fl}} + I^{\mathfrak{b}}_{\mathrm{Fk}} + I_{\mathrm{EnB}} + I^{\mathfrak{b}}_{\mathrm{G}} \leq \mathbf{D}_{\mathrm{KpB}}, \\ \mathbf{q}_{\mathrm{KpG}} &= I^{\mathfrak{g}}_{\mathrm{Fl}} + I^{\mathfrak{g}}_{\mathrm{Fk}} + I_{\mathrm{EnG}} + I^{\mathfrak{g}}_{\mathrm{G}} \leq \mathbf{D}_{\mathrm{KpG}} \,. \end{aligned} \tag{13}$$

Newly produced capital goods will be delivered to the consumption good producers and the energy firm at the next simulation step. The capital good producers rely on energy, labor and raw material (RM) as input factors. The capital good price p_{Kp} is set as a fixed mark-up μ_i on unit costs: $\forall i \in \{\mathrm{KpG}, \mathrm{KpB}\}$,

$$p_i = (1 + \mu_i) \times \left(\frac{w_i}{\gamma_i^{N}} + \frac{p_{\mathrm{En}}}{\gamma_i^{\mathrm{En}}} + \frac{p_{\mathrm{RM}}}{\gamma_i^{\mathrm{RM}}} \right) \,. \tag{14}$$

In the financial sector the **commercial bank** BA provides loans and keeps deposits. The commercial bank endogenously creates money [43], meaning that it increases its balance sheet at every lending (i.e. the bank creates new deposits as it grants a new credit). This is consistent with most recent literature on endogenous money creation by banks [52]. The EIRIN economy money supply is displayed by the level of demand deposits, including for all other agents in the domestic economy (i.e. excluding the foreign sector). Furthermore, the bank gives out loans to finance firms' investment plans. The bank sets sector-specific interest rates that affect firms' capital costs and NPV calculations. Thus, credit demanded by firms may be rationed due to insufficient equity capital on the bank's side, in which case credit is allocated proportionally to the amount demanded. When confronted with credit rationing, firms have to scale down their investment plans, while the bank stops paying dividends, thus retaining all net earnings in order to increase its equity capital. Details on the interest rate settings and granted loans are provided in 3.4.

The **central bank** (CB) sets the risk-free interest rate ν according to a Taylor like rule [66]. The EIRIN implementation of the Taylor rule differs from the traditional one because we do not define the potential output based on the Non-Accelerating Inflation Rate of Unemployment (NAIRU) [4]. Indeed, NAIRU's theoretical underpinnings are rooted in general equilibrium theory, while EIRIN is not constrained to equilibrium solutions and focuses on the analysis of out-of-equilibrium dynamics. Thus, it would not be logically consistent to adopt a standard Taylor rule and NAIRU.

The interest rate in EIRIN indirectly affects households consumption via price increase stemming from firms that adjust their prices based on higher costs for credit. Households have a target level of wealth stemming from the buffer-stock theory of saving but do not inter-temporally maximize their consumption behavior. This prevents monetary policy to have a crowding-out effect on household consumption. The policy interest rate depends on the inflation $\pi - \bar{\pi}$ and output gaps (measured as employment gap $u - \bar{u}$, i.e. the distance to a target level of employment $\bar{u}$):

$$\nu(t) = \omega_\pi(\pi(t) - \bar{\pi}) - \omega_u(u(t) - \bar{u}) \tag{15}$$

In particular, π is the one-period inflation of the weighted basket of consumption goods and services (with a computation smoothed over a year, i.e. m periods):

$$\pi(t) = \frac{\mathbf{q}_{\mathrm{Fl}}(t)}{\mathbf{q}_{\mathrm{Fk}}(t) + \mathbf{q}_{\mathrm{Fl}}(t)} \times \left(\frac{p_{\mathrm{Fl}}(t)}{p_{\mathrm{Fl}}(t-m)} \right)^{1/m} + \frac{\mathbf{q}_{\mathrm{Fk}}(t)}{\mathbf{q}_{\mathrm{Fk}}(t) + \mathbf{q}_{\mathrm{Fl}}(t)} \times \left(\frac{p_{\mathrm{Fk}}(t)}{p_{\mathrm{Fk}}(t-m)} \right)^{1/m} - 1 \tag{16}$$

The inflation gap is computed as the distance of the actual inflation π to the pre-defined target inflation rate $\bar{\pi}$. Moreover, the central bank can provide liquidity to BA in case of shortage of liquid assets.

The **foreign sector** (RoW) interacts through tourism import, consumption good exports, intermediate good exports, consumption good imports, oil, raw materials supply, and potential energy export to the domestic economy. The supply is provided unbounded and at an exogenous "world" price to meet the domestic production needs. Tourists inflows consist in the consumption of labor-intensive consumption goods. Raw material, consumption good and intermediate good purchases by the foreign sector are a calibrated share of the domestic GDP.

A government (G) is in charge of implementing the fiscal policy, via tax collection and public spending, including welfare expenditures, subsidies (e.g. for households' consumption of basic commodities), wages of civil servants, and its own consumption. To cover its expenses, the government raises taxes and issues sovereign bonds, which are bought by the capitalist households, by the commercial bank and by the central bank. The government pays a coupon $\mathfrak{c}$ on its outstanding bonds n_{G}. Taxes are applied to labor income (wage), to capital income (dividends and coupons), and profits of firms. To meet its budget-balance target, the government adjusts its tax rate. In case of a budget deficit, the tax rates are increased by a fixed amount, and conversely decreased by the same amount in case of a budget surplus exceeding a given threshold. Otherwise, the tax rates are kept constant.

Furthermore, if the government's deposits are lower than a given positive threshold $\bar{M}$, i.e., $M_{\mathrm{G}} < \bar{M}_{\mathrm{G}}$, the government issues a new amount $\Delta \mathbf{n}_{\mathrm{G}} = \frac{\bar{M}_{\mathrm{G}} - M_{\mathrm{G}}}{p^{\star}_{\mathrm{G}}}$ of bonds to cover the gap, where $p^{\star}_{\mathrm{G}}$ is the endogenously determined government bond price. The government spending is a fixed percentage of revenues from taxes. During crises, this spending contributes to avoid credit crunch, and compensates households' and firms' liquidity constraints [10].

The interactions among agents, sectors and markets of the EIRIN economy are presented in Figure 2. For a detailed description of all sectors, market interactions and behavioral equations, refer to Monasterolo and Raberto [54, 55], Dunz et al. [21], and Gourdel et al. [28].

3.4 Bank's credit channel

A key determinant of the credit market is the interest rate applied to firms, based on sector-specific and macroeconomic indicators. In addition, credit can be constrained depending on the profitability of investment and on the bank's lending capacity.

Let ν be the risk-free interest rate, which is the sum of the policy rate and the bank's net interest margin (NIM). Given the annualized probability of default PD_i of sector i, we seek to determine its interest rate $\hat{\kappa}_i$ on loans from the bank. We set it to verify

$$\underbrace{\hat{\kappa}_i - \nu}_{\text{credit spread}} = \mathrm{PD}_i \times (1 - \mathfrak{r}^*_i), \tag{17}$$

where $\mathfrak{r}^*_i$ is the expected recovery rate of i, and is computed as a simple average of the observed recovery rates observed over mem periods. The calculation of the PDs is performed following the Merton valuation approach. Then, to determine the actual rate applied, we let the possibility of bridging only part of the distance between the previous interest rate and the target one. That means, denoting as κ_i the realized interest rate at t we have

$$\kappa_i(t) = \kappa_i(t-1) + \mathrm{sm}_{\kappa} \times (\hat{\kappa}_i(t) - \kappa_i(t-1)), \tag{18}$$

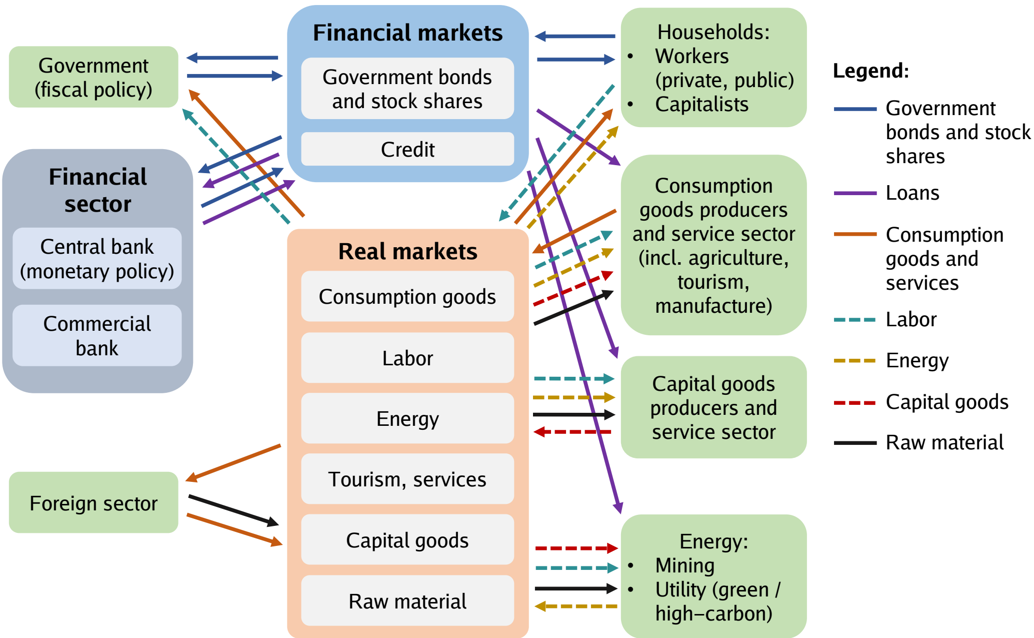


Figure 2: Interaction of EIRIN's agents, sectors and markets.
Green boxes include agents and sectors, while the light blue box contains financial markets and light orange box includes the real markets.
Source: adapted from Gourdel et al. [29].

where $\text{sm}_k appa \in]0,1]$ is the interest adjustment speed.

Another key aspect is how much the bank is ready to lend at a time t. The maximum credit supply of the bank is set by its equity level E_{BA} divided by the Capital Adequacy Ratio parameter $\mathcal{E}_{\text{CAR}}$, in order to comply with banking regulator provisions. The other important information is the demand for new credit $\mathbf{D}_{\text{BA}}(t)$ and the previous credit level $\mathbf{L}(t-1)$. The additional credit that the bank can provide at each time step is given by its maximum supply, minus the value of loans already outstanding, so that the total of loans makes its realized capital adequacy ratio remains over $\mathcal{E}_{\text{CAR}}$:

$$\Delta^+\mathbf{L} = \min\left\{\mathbf{D}_{\text{BA}}(t), \frac{E_{\text{BA}}(t-1)}{\mathcal{E}_{\text{CAR}}} - \mathbf{L}(t-1)\right\} . \tag{19}$$

3.5 Defaults and non-Performing Loans (NPL)

The financial risk of investment is represented via two channels in EIRIN: part of the companies within a given sector can default on their loans, while some other loans can become non-performing, i.e. the borrowers have stopped paying the agreed instalments or interest.[4]

First, as a novelty to previous versions of the model, and advancing on SFC research in general, we

[4]The definition used by the European Central Bank is that loans are classified as non-performing when the delay exceeds 90 days. Given that we use simulation periods of six months, we consider that the borrowers stop paying in the same period where the loans are classified as NPL.

include a mechanism for within-sector defaults. The ratio of defaulting firms in a sector i is given by

$$\text{Def}_i \sim \text{Beta}\left(a, a(1/\text{PD}_i - 1)\right) . \tag{20}$$

The value Def_i is also interpreted as the share of the debt affected by defaults. Moreover, we operate with the following assumptions:

- Given that the assets of the sector are divided between liquidity, productive capital, and inventory, we assume that the firms defaulting hold assets in the same proportions as the sector as a whole.
- The defaults happen due to *insolvency*, and not illiquidity. This means that defaults happen because the cumulated value of the assets of defaulting firms reaches the value of their total debt.
- When a firm defaults, it can sell a share of its capital at a *fire sales discount* to other firms in the same sector. Nonetheless, this discount is assumed not to affect the medium-term price of capital. The remaining share gets *stranded* and is completely written off.
- The bank recovers part of the defaulted firms' liquidation value, which is their cash and the proceeds from the sale of their capital.

The net effect of defaults is that the equity of banks decreases because the loss they incur on their loan book (total of the defaulted debt) is larger than the decrease of their liabilities (the liquidity recovered that the sector was holding before). The effect on the equity of the real economy sector itself is non-negative. Indeed, even in the case where all assets are recovered by the bank or get stranded, the total value lost cannot exceed that of the debt written off due to the insolvency characterization.

Second, we compute NPL ratios on a sector-level basis, based on sector-level accounting variables and macroeconomic factors identified in the literature [50]:

$$\text{NPL}(t) = \beta_0 + \beta_1 \times \text{NPL}(t-1) + \beta_2 \times \Delta\text{GDP}(t-1) + \beta_3 \times \Delta\text{UN}(t-1) \tag{21}$$

where ΔGDP is the real GDP growth, ΔUN is the change in unemployment, and $\beta_0, \beta_1, \beta_2, \beta_3$ are coefficients. Therefore, the computation of the NPL ratio is completely endogenous in the model, as no predictor variable is part of the scenario.

A sector i pays interests with rate $\kappa_i(t)$ at t on its total loans $L_i(t-1)$ of the previous period. Taking into account the NPL ratio, the total interests paid is:[5]

$$\text{ID}_i(t) = \kappa_i(t) \times L_i(t-1) \times (1 - \text{NPL}(t)) \tag{22}$$

The interests paid on debt are subtracted from the operating earnings of i and added to that of the banking sector. Similarly, the repayment of the debt is reduced:

$$\Delta^- L_i(t) = \chi_i \times L_i(t-1) \times (1 - \text{NPL}(t)) \tag{23}$$

where χ_i is the (constant) repayment rate of i, inversely proportional to the typical loan length of the sector. In effect, the NPLs create a delay in repayment, which corresponds to additional credit granted by the bank to the sector. Thus, while it is at the advantage of the real economy and reduces the immediate profits of the bank, the added leverage also motivates higher interest rates, acting as a compensating mechanism.

[5] Note that, the unpaid interest should normally start in the previous period, because of the 90 days limit used to define the NPL. This can be neglected provided that variations in the NPL ratio are small.

3.6 Macroeconomic calibration

The calibration of the model relies on the adjustment of the same key variables as in [28]. The data used for the calibration is mostly obtained from the Barbados Statistical Service, the World Trade Organization, and the World Bank.[6] The calibration is split in two groups, which rely on two separate set of parameters and benchmark values:

- Parameters that can be calibrated on real data, e.g. taxes or markups;
- "Free" parameters that cannot be observed directly, but are set such that other endogenously produced values match observed data: GDP growth, inflation, relative value added of the sectors, imports and exports to GDP, with breakdown by sector/products, unemployment rate and sector employment share, shares of energy use and carbon emissions of the sectors, etc.

In Table 1 we present the outcomes of this second-step calibration by comparing the model's outcomes with observed data over a time span of 10 years. A notable difference compared to previous studies [28, 29] is that Barbados is very dependent on its trading partners due to its size. Thus, it has both very high imports and exports relative to the size of its economy.

[6] See respective websites: `https://stats.gov.bb`, `https://stats.wto.org`, and `https://data.worldbank.org`.

		Simulation values		Real values	
		Mean	Standard dev.	Mean	Standard dev.
Key indicators	Inflation (percent)	1.34	0.05	2.31	2.00
	Real GDP growth (percent)	0.11	0.26	-1.46	5.27
	Share of unemployment (percent of total workforce)	8.19	3.11	9.59	1.65
National accounts (percent of GDP)	Government revenues from taxes	24.26	0.04	24.85	2.01
	Net remittances received	2.48	0.00	2.65	0.37
	Revenues from tourism	17.86	0.02	16.42	0.71
	Total exports	35.56	0.11	36.88	3.63
	Total government expenditures	30.32	1.97	32.57	2.61
	Total government revenues	25.86	0.88	27.86	2.22
	Total imports	40.98	0.26	43.23	5.50
Exports breakdown (percent of total exports)	Share of goods in exports	19.53	0.08	18.93	2.59
	Share of mining commodities in exports	6.83	0.37	6.61	1.67
	Share of services in exports	73.64	0.29	74.46	2.55
Value added (percent of GDP)	Consumption goods sector	14.79	0.01	6.36	0.30
	Energy sector	6.59	0.05	2.90	0.08
	Intermediary goods producers	4.80	0.58	8.82	0.60
	Oil and mining sector	3.38	0.13	0.30	0.06
	Service sector	69.30	0.26	81.62	0.88
Financial indicators	Deposit rate of the central bank (percent)	-0.62	0.04	0.92	1.06
	Lending rate from the commercial bank (percent)	4.38	0.04	8.17	0.24
Share of employees (percent of total employees)	Consumption goods sector	8.18	0.07	16.10	0.41
	Service sector	61.24	0.32	78.03	0.26
	Upstream sectors	6.27	0.43	5.88	0.32
Investment and credit	Firms' total credit (percent of GDP)	16.77	0.03	81.66	1.70
	Total investments (percent of GDP)	6.31	0.73	16.04	1.03
Energy	Share of renewable (percent of total energy consumption)	6.31	0.19	4.12	1.00

Table 1: Calibration table.
"Real values" come from real data time series, with observations from 2013 to 2020 where available. Note that, in some instances, the data obtained on some sectors does not correspond exactly to the sectoral breakdown of the EIRIN model. Thus, we do not try to get a perfect match between all of them, but rather to have dynamics that are generally in line with the country. In the case of the growth variable, we also do not focus on reaching the same value in so far as the data sample includes the first year of the COVID-19 pandemic, which skews the distribution. Moreover, the calibration is generally intended to have stable dynamics, to better study the effect of shocks later on, which explains why the standard deviation of variables in the model is generally lower than the historical ones.
Source: authors' computations.

4 Climate risk scenarios: definition and integration

In this section, we describe the scenarios designed to model the transition risk, the spillover effects, and the physical risk impact related to the same set of scenarios.

4.1 NGFS scenarios and domestic low-carbon transition

We use 3 scenarios produced in 2021 by the NGFS [58], and represented in Figure 3. The narratives of these respective scenarios is the following:

- *Current policies*: assumes that only currently implemented policies are preserved. Emissions grow until 2080 leading to about 3°C of warming and severe physical risks. It is the "hot house world" or "business-as-usual" scenario.
- *Below 2°C*: gradually increases the stringency of climate policies, with an immediate start, giving a 67% chance of limiting global warming to below 2°C.
- *Net-zero 2050*: ambitious scenario that limits global warming to 1.5°C by the end of the century (with a 50% chance) through stringent climate policies introduced immediately and innovation.

Several models are employed to project these scenarios. We use the output of the REMIND-MAgPIE 2.1-4.2 [32], which has the advantage of a better geographical downscaling. In particular, results are available for the region of Latin America and Caribbean countries.

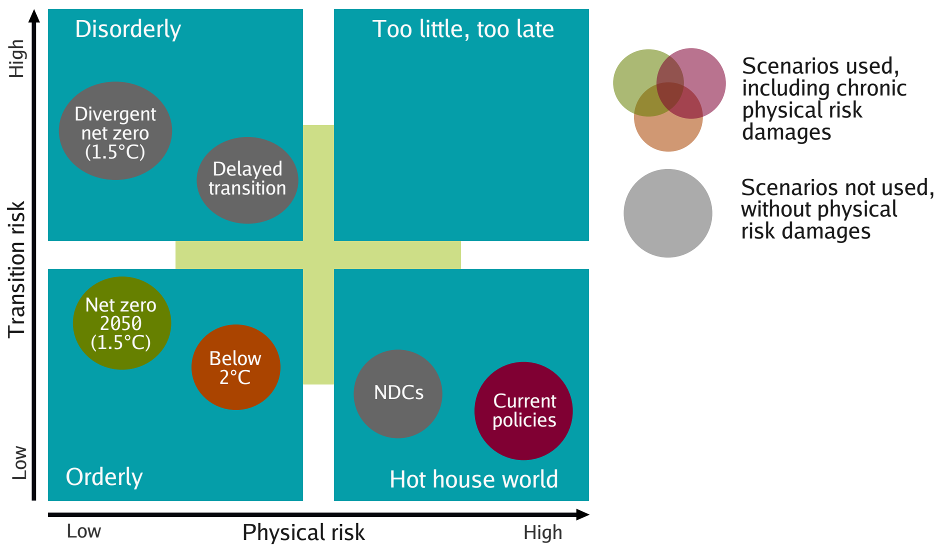


FIGURE 3: Estimated risk positioning of the NGFS scenarios.
Three scenarios are not employed as they have not been used with the REMIND-MAgPIE 2.1-4.2 and therefore do not have the same richness with regard to available series. NDCs stands for "Nationally Determined Contributions", i.e. the non-binding plans of countries within the Paris Agreement framework. Source: NGFS [58] and authors.

The key feature of climate policies is an *increase in carbon price*, represented in Figure 4. Model-wise, it comes as a rate $\theta^{\text{GHG}}(t)$ such that the revenues generated by a sector i at t are given by $\text{Em}_i(t) \times \theta^{\text{GHG}}(t)$ where Em_i denotes the total carbon emissions of i and covers roughly scope 1 and 2 emissions. We operate under a neutral revenue-recycling assumption, i.e. the revenues from the carbon tax are re-injected in the general budget of the government. The carbon tax comes for companies as an additional cost to what was presented in section 3, and is taken into account in their pricing.

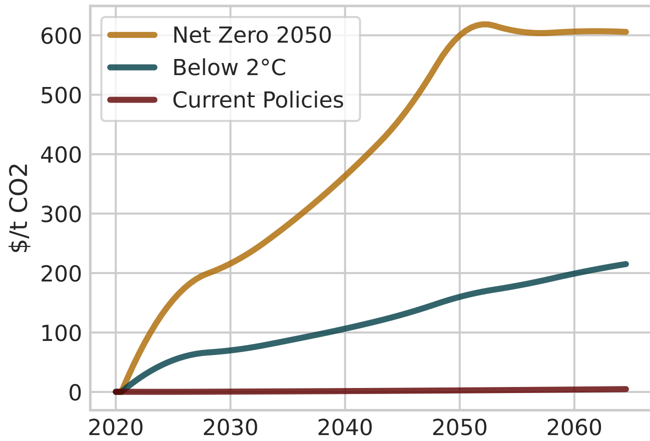


FIGURE 4: Carbon price path from NGFS scenarios, generated by the model REMIND-MAgPIE 2.1-4.2. The geographic scope of the output used is Latin America and Caribbean countries. Values are interpolated from a five-year to a six-month period.
Source: NGFS [58].

The paths for the carbon price vary substantially between scenarios. First, Net Zero 2050 exhibits a very sharp increase until the beginning of the 2050s (also the end of our simulation horizon), and a plateau at a high value after. The increase is more moderate for the Below 2°C scenario, with a value in 2050 less than a third of that of Net Zero 2050, and a continued increase later. For Current Policies, the change in carbon prices is negligible in comparison to the previous two.

The enforcement of a carbon price is not the sole policy used within the model, even if it is the most important one when measured by total revenues. In addition to it, *secondary policy channels are implemented* in the same way as in Gourdel et al. [28].

The first other policy integrated is the aggressiveness of investments from the green energy sector. A parameter governs the share of the energy market that renewable energy producers aim to expand to in each period. In transition scenarios (Net Zero 2050 and Below 2°C), this parameter is set higher than in the calibration baseline, meaning that investment in renewables will be higher. These investments are taken from the cash reserves of the green energy sector, meaning that they are covered by a mix of revenues from energy sales and credit.

A second related policy is a rebate on green energy by the government, in practice subsidizing renewables. This is implemented as a price discount for green energy producers to buy capital, which will help to boost its production capacity. This policy intervenes in a context where energy is sold at a unique price that is determined by considering the production costs from both producers [see details in 28]. The direct effect is to transfer costs to the government. It makes the green energy sector more profitable, in turn increasing its capacity to invest.

The last type of policy implemented is the requirement of a minimum green capital ratio. This policy intervenes in the context where sectors that produce consumption goods (Fk) and provide services (Fl) can choose between green and high-carbon productive capital. At the beginning of the transition especially, green capital alternatives such as green hydrogen are still more expensive. For these two firms, the key step when making investment decisions is the calculation of the NPV associated with the purchases of green and high-carbon capital. At the point of introducing stringent climate policies, we generally start observing a higher NPV for green capital. However, the government could impose environmental requirements prior to that change in profitability. This is modelled through a parameter that determines the minimum ratio of green capital that Fk and Fl must acquire in their capital investment, and at the same time the ratio in the government's own capital purchases. This parameter is then gradually raised in the two transition scenarios, although to a limited extent, such that from the private sector the profitability switch remains the most important driver.

4.2 Transition spillover risk: shock on revenues from tourism

A key challenge for Barbados is the potential of a decrease in the revenues from tourism, given the importance of the industry, as was highlighted in section 2. The top 3 countries of origin of tourists in Barbados are the UK, the US, and Canada, followed by EU countries. The three of them would be expected to introduce climate policies that would affect the aviation sector in some form if they want to achieve their climate transition. On the global scale, ambitious low-carbon transition policies are expected to reduce the emission from air travel. Therefore, the IEA models this change in its World Energy Outlook. We use the paths that it provides, represented in Figure 5. Values are interpolated with original data from 2020 excluded, so that the decrease coming from the COVID-19 crisis is not considered, in order to focus on the dynamics of expected climate shocks only.

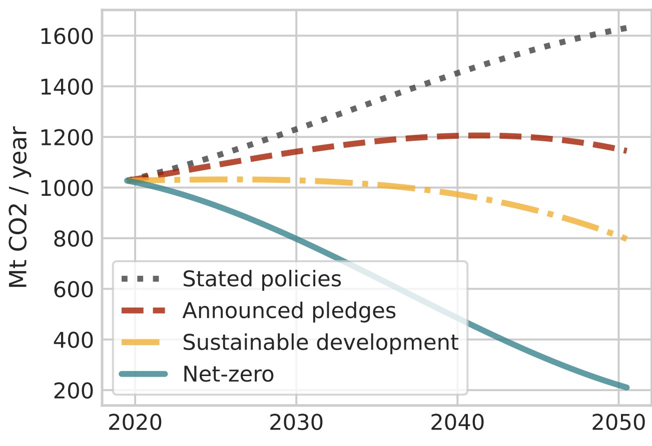


Figure 5: Evolution of total **GHG emissions of the aviation sector**, from the World Energy outlook.
Source: IEA [34].

The paths of Figure 5 are used such that the deviation in GHG emissions (relative to the level in 2020) is directly used as a deviation in revenues from tourism, relative to a baseline scenario with no tourism shock. In doing so, we do not consider the assumed efficiency improvements that are also envisaged by the World Energy Outlook scenario, thus shocks may be conservative to an extent. Nevertheless, this is counter-balanced by the following three aspects:

- We assume that expenses linked to tourism increase with the GDP of the local economy.
- Tourism could be more compressible than other segments of long-distance aviation use.

World Energy Outlook	NGFS
Stated policies	∅
Announced pledges	Current policies
Sustainable development	Below 2°C
Net zero	Net zero

TABLE 2: Matching of World Energy Outlook and NGFS scenarios.

- Developing countries would be the most likely to increase their air travel capacities, and they are not the ones that send the most tourists to Barbados.

A key difference when compared to the transition spillover risk of Gourdel et al. [29] is that the shock in some scenarios would be positive, i.e. aviation emissions are expected to increase in both the stated policies scenario and the announced-pledges scenario. In comparison, [29] considers shocks that all entail a net reduction of exports. Given that we want to focus on downside spillover risk, we exclude the stated-policies scenario, which features a significant increase in air travel. The rest of the link to the scenarios of NGFS, that governs their integration within the simulations, is given by Table 2. The rationale for the matching is that the implementation by Western economies of more stringent carbon prices (present in the NGFS scenarios) would be transmitted to a significant extent to consumers. This would deter consumers from visiting far-off countries such as Barbados, in line with the emission reduction paths of the IEA. The transmission and eventual effects of the transition spillover risk are shown in Figure 6, including indirect impacts that will be part of our analysis. Note that Table 2 follows the relative order of both scenario sets, but the match of policies on both sides is not necessarily perfect. For instance, from Figure 5, the Sustainable development scenario leads only to a minor decrease in emissions at the end of the period, compared to the carbon price path of the Below 2°C scenario. This means that the combined scenario may be interpreted as one where domestic transition policies are more stringent than the ones applied by other countries.

4.3 Physical risk damages

The integration of physical risk damages comes through two separate dimensions:

(i) A chronic impact that is sourced from NGFS scenarios.

(ii) Acute climate impacts, which are calculated as a stochastic impact based on past hurricanes in the Caribbean, modelled with CLIMADA.

Both impacts are expressed as a ratio of productive capital destroyed in a simulation period. So, the final ratio of capital lost is the sum of these two components. This means that we combine a baseline scenario of chronic risk and a scenario of random acute risk added on top to represent the occurrence of hurricanes. The rationale for the transmission of this impact in EIRIN is given by Figure 7.

For shock *(i)*, the physical risk trajectory is represented in Figure 8. In EIRIN, the GDP is a fully endogenous outcome variable. Hence, exogenous GDP impacts cannot be used as an input in the EIRIN model. Instead, the physical risk shocks are interpreted as cumulative impacts on capital stocks.[7]

Regarding the *acute shocks* modeling of *(ii)*, the acute impact of past hurricanes on the capital of the

[7] The application of disaster risk modeling (e.g. those in [22]) can provide a more accurate estimation of disaster impacts on productive capital stock at the disaggregated sector and geographical level.

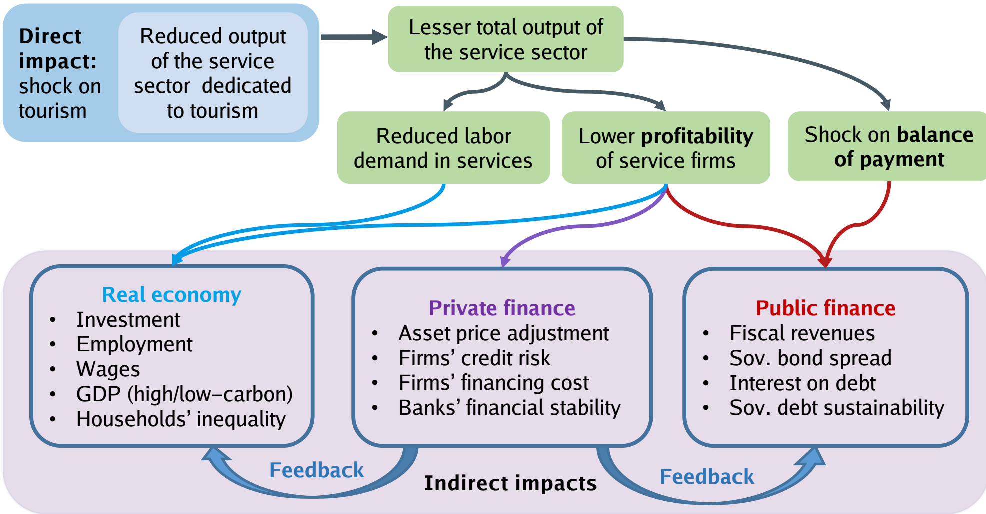


FIGURE 6: Transmission channels of tourism **transition spillover risk** in EIRIN. Source: authors.

country is modelled with CLIMADA [1, 7]. To begin, we create an augmented data set of hurricanes based on the ones observed in the Caribbean basin. The consequences of each hurricane are assessed at a granular geographical level, using a damage function. We can then derive their total damages across the country. For the purpose of visualization we also average across time in different areas in Figure 9. The details for this part of the calibration are provided in appendix A.

From the data available, we estimate the likelihood of a hurricane to occur by simulation period. Let $\mathcal{H}_t$ denote the event of a hurricane happening in a time period t. We are interested in the value $\mathbb{P}(\mathcal{H}_t = 1 \mid \mathcal{S})$, i.e. the probability that a hurricane happens in t given a scenario $\mathcal{S}$. A baseline value $p_{\mathcal{H}}$ is measured from the data, where we observed that significant hurricanes affecting Barbados were registered for 36% of the years from 2000 to 2021.[8] We use it in combination with NGFS data, so that

$$\mathbb{P}(\mathcal{H}_t = 1 \mid \mathcal{S}) = p_{\mathcal{H}} + (1 - p_{\mathcal{H}}) \times f_{\mathcal{H}}(\mathcal{S}, t) \tag{24}$$

where $f_{\mathcal{H}}$ is a function increasing in the physical risk severity of the scenario.

Finally, we calibrate a damage distribution from the data, to calculate the impact of a hurricane impacting Barbados when one occurs. To integrate the damages incurred from hurricanes in a period t, we model the damages as a random variable $\mathcal{D}_t^{\mathcal{S}}$ such that

$$\mathcal{D}_t^{\mathcal{S}} \mid \{\mathcal{H}_t = 1\} \sim \text{Beta}(\alpha(\mathcal{S}, t), \beta(\mathcal{S}, t)) \,. \tag{25}$$

These damages are usually expressed as the share of capital destroyed over total stocks, so that $\mathcal{D}_t^{\mathcal{S}} \in [0, 1]$, which justifies the use of a Beta distribution. The baseline shape parameters α_0 and β_0 that apply at the beginning of the simulation are directly inferred from the augmented data set of hurricanes, using the method of moments. We then determine the parameter functions $f_{\mathcal{H}}, \alpha, \beta$ using these baseline values. That is, we want to spell out the dependency of acute physical risk on scenario variables.

[8] To account for the fact that the simulation period used is six months, we calibrate $p_{\mathcal{H}}$ as half this value.

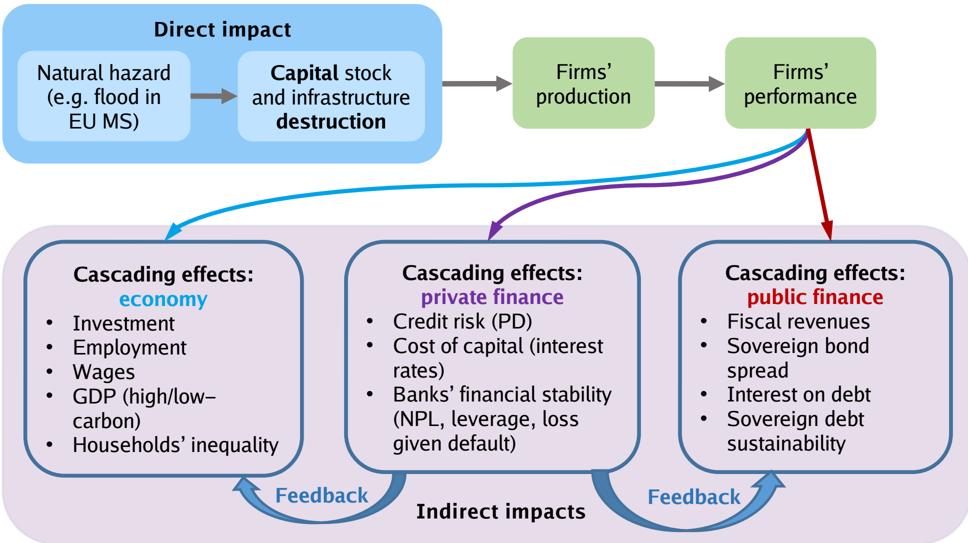


FIGURE 7: Transmission channels of climate **physical risk** in EIRIN.
Source: Gourdel et al. [28].

To ensure consistency across scenarios, we determine the parametrization under the constraint that the average total damages from hurricanes evolve proportionally to the value of chronic damages.[9] It means that, on average, the acute risk will evolve similarly to what is presented in Figure 8. Denoting chronic physical damages for scenario $\mathcal{S}$ at time t by $C_t^{\mathcal{S}}$, the constraint formally translates into

$$\forall(\mathcal{S},t), \quad \frac{\mathbb{E}[\mathcal{D}_t^{\mathcal{S}}]}{\mathbb{E}[\mathcal{D}_0]} = \frac{C_t^{\mathcal{S}}}{C_0} \,. \tag{26}$$

For simplicity, we assume that β is constant, i.e. $\forall(\mathcal{S},t), \beta(\mathcal{S},t) = \beta_0$. Then, we have

$$\begin{aligned}\mathbb{E}[\mathcal{D}_t^{\mathcal{S}}] &= \mathbb{P}(\mathcal{H}_t = 1 \mid \mathcal{S}) \times \mathbb{E}[\mathcal{D}_t^{\mathcal{S}} \mid \{\mathcal{H}_t = 1\}] \\ &= (p_{\mathcal{H}} + (1 - p_{\mathcal{H}}) \times f_{\mathcal{H}}(\mathcal{S},t)) \times \frac{\alpha(\mathcal{S},t)}{\alpha(\mathcal{S},t) + \beta_0} \,.\end{aligned}$$

We then make the assumption that the frequency at the start of the simulations is the historical one, i.e. $\forall\mathcal{S}, f(\mathcal{S},0) = 0$. This choice is not completely obvious in so far as we would expect the probability of hurricanes in the early 2020s to be higher than the average of the previous 20 years due to the change in climate already observed. However, in the case of Barbados we do not observe a clear trend at the end of the period. Moreover, the year with the most damages observed is 2004. Therefore, this assumption appears generally reasonable. Then, we get

$$\forall\mathcal{S}, \quad \mathbb{E}[\mathcal{D}_0^{\mathcal{S}}] = \frac{p_{\mathcal{H}}\alpha_0}{\alpha_0 + \beta_0} \,. \tag{27}$$

[9]Alternatively we could parametrize the model to depend on the own GHG emissions of Barbados. However, given the relatively small size of the Barbadian economy, internal emission dynamics are not likely to be determinant for the scale of climate damages.

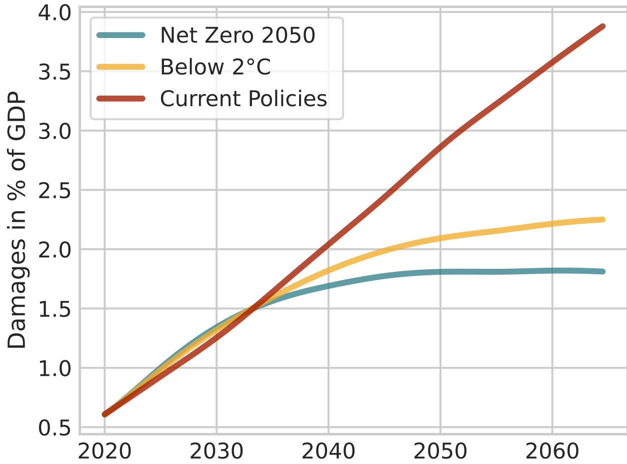


FIGURE 8: Chronic physical risk paths of the different scenarios.
The x axis displays the simulation time and the y axis gives the percentage of GDP lost to physical damages in each period, used as an input in the model. Source: NGFS [58].

Thus, equations 26 and 27 fully determine the values $\mathbb{E}[\mathcal{D}_t^S]$, given C_t^S. There remains one degree of liberty in the general determination of the model, i.e. between α and $f_{\mathcal{H}}$. Therefore, we make the additional assumption that the increase in expected damages is equally shared by the increase in frequency and the increase in conditional impact. That means we have

$$\frac{\mathbb{P}(\mathcal{H}_t = 1 \mid \mathcal{S})}{\mathbb{P}(\mathcal{H}_0 = 1)} = \frac{\mathbb{E}[\mathcal{D}_t^S \mid \{\mathcal{H}_t = 1\}]}{\mathbb{E}[\mathcal{D}_0 \mid \{\mathcal{H}_0 = 1\}]} = \sqrt{\frac{C_t^S}{C_0}}\,. \tag{28}$$

This results in the following definitions:

$$f_{\mathcal{H}}(\mathcal{S}, t) := \frac{p_{\mathcal{H}}}{1 - p_{\mathcal{H}}}\left(\sqrt{\frac{C_t^S}{C_0}} - 1\right), \quad \text{and} \quad \alpha(\mathcal{S}, t) := \frac{\beta_0\sqrt{C_t^S/C_0}}{(\alpha_0 + \beta_0)/\alpha_0 - \sqrt{C_t^S/C_0}}\,. \tag{29}$$

The outcome of this is represented in Figure 10. The fact that both plots are the same, if not for the scale, is a direct result of the assumption made in equation 28, with likelihood and impact both having the same contribution to the increase of risk.[10]

4.4 The trade-off of free-riding scenarios

As an extension of the scenarios discussed above, we also consider the configuration of a *free-riding* policy. These cases model situations where Barbados does not implement significant climate mitigation policies, but other countries do. This reflects a country-level individualistic attitude, trying to have the "best of both world" (a view we will challenge below). Therefore, these cases are defined by the

[10]Note that a more general form would have been possible, with an asymmetry between both. This would mean replacing $\sqrt{C_t^S/C_0}$ by $(C_t^S/C_0)^\eta$ in the determination of $f_{\mathcal{H}}$, and by $(C_t^S/C_0)^{1-\eta}$ in the determination of α, with $\eta \in [0,1]$. However, in the absence of specific data on that aspect, choosing $\eta = 1/2$ appears as the most neutral assumption.

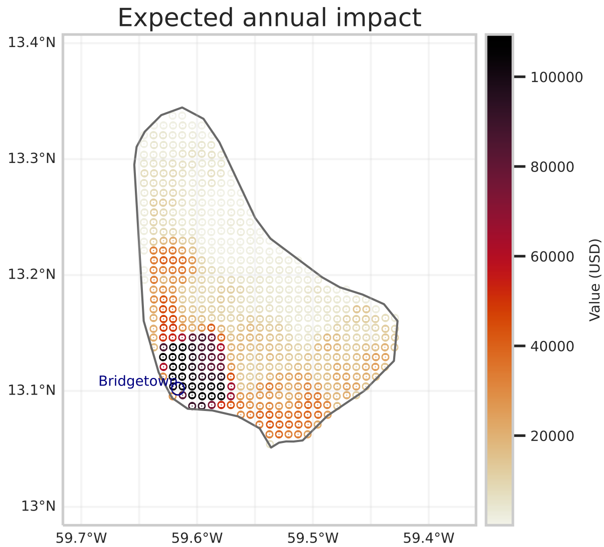
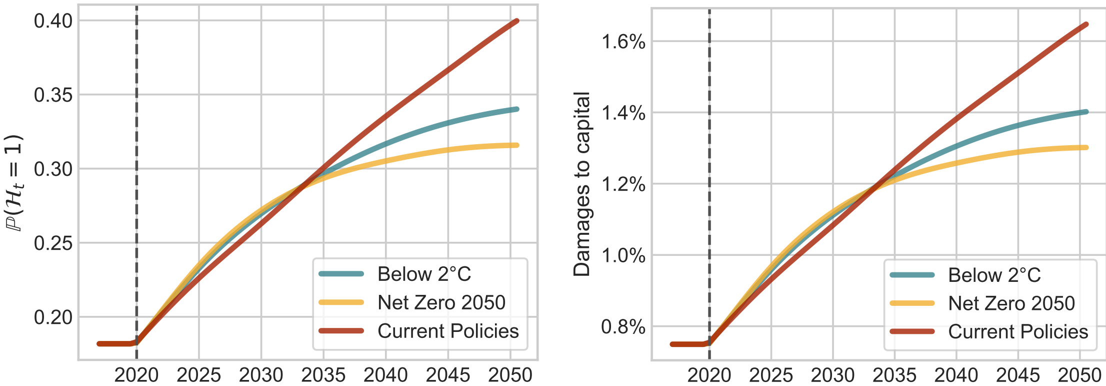


FIGURE 9: Visualization of the expected annual damages by area in Barbados. Based on our data, impacts are unsurprisingly concentrated on the South-Western facade of the island which is also where productive capital is and where urban density is highest.
Sources: World Bank, Eberenz et al. [24], Center for International Earth Science Information Network - CIESIN - Columbia University [17], Emanuel [25] and authors' computations.

combination of

- no significant mitigation policy in the Barbadian economy (domestic variables follow the Current Policies scenario);
- more ambitious policies are implemented by the rest of the world, such that physical risk follows the Below 2°C or the Net-Zero 2050 scenarios.

Within this general definition, we can differentiate situations where the flight reduction policies are implemented, and others where they are not (in case the rest of the world can reach the temperature targets even with sustained air travel). From the global perspective, free-riding is obviously detrimental since too many countries adopting this strategy would stall the transition altogether. While a dedicated strand of the literature has been interested in the problem of free-riding at large and theoretical solutions [e.g. 31, 42, 60], the actual trade-offs and incentives at the country-level are not necessarily understood. In fact, the quantification of transition spillover risk would be a pre-requisite for such an evaluation for many countries. We summarize below the advantages and drawbacks that can emerge from a free-riding policy conduct. We focus on the economic impacts and leave aside reputational incentives or further political considerations.



(A) Hurricane likelihood

(B) Conditional damages

FIGURE 10: Evolution of the acute physical risk components in the different scenarios. The left-hand plot represents the likelihood $\mathbb{P}(\mathcal{H}_t = 1 \mid \mathcal{S})$ of a hurricane happening. The right-hand plot represents the value $\mathbb{E}[\mathcal{D}_t^{\mathcal{S}} \mid \{\mathcal{H}_t = 1\}]$, which crucially depends on the value $\alpha(\mathcal{S}, t)$, and is almost proportional to it as the constant β_0 is much larger with the distribution used here. It is expressed as the percentage of the capital that would be lost by an average hurricane. Both calculations of $f_{\mathcal{H}}$ and α are based on equation (29). Source: authors' computations.

Free-riding advantages

- No burden on public finances from climate change mitigation investment.
- Benefits from reduced physical risk accrue, provided that domestic GHG emissions are not enough to put the global low-carbon transition at risk.
- Lesser dependence on international partnership, foreign firms and technology transfers that would be necessary to transition to green capital.

Free-riding drawbacks

- Legacy energy production from fossil fuel becoming more expensive than renewable alternatives.
- Maintains a high-level of oil imports, negatively affecting the balance of payment.
- Potentially larger exposure to transition spillover risk.
- Risk of direct trade restrictions or carbon tax border adjustment mechanism.

Thus, the consequences of a free-riding policy approach are not straightforward to assess, as both sides could be economically significant. In fact, Mercure et al. [53] provide one of the broadest assessment of the climate policy incentives and conclude that free-riding is in general a losing choice. They find in particular that all fossil fuel importers (which includes Barbados) are better off decarbonizing. While [53] identifies the benefits of the low-carbon transition as a deterrent for free-riding, it employs a small set of global scenarios and it does not exactly quantify the induced economic difference when singular countries opt out of transition efforts. Thus, we have an interest in

1) assessing the relative important of the advantages and drawbacks highlighted above in the case of Barbados, with the dynamics of the EIRIN model;

2) better isolating the contribution of climate physical risk as it is a key difference going from the complete Current Policies scenario to one of the free-riding scenarios;

3) introducing spillover transition risk and reflect on how it is likely to shift the policy trade-off that already exists given other components highlighted.

5 Results

In this section we present the results of the simulations run with EIRIN on macroeconomic and public finance indicators. We analyze the impacts of climate risk (transition and physical jointly) for each scenario, and we present the differentiating impact of transition spillover risk within each scenario.

Due to the stochastic nature of the acute physical risk presented in 4.3, the results presented in this section are obtained after averaging across a set of simulations for each scenario. That means, each point is a Monte Carlo estimation. This aspect is also new compared to previous works using EIRIN [54, 28, 29], which were all deterministic in that regard.

The direct impacts considered in this study involve two main dimensions:

(a) A domestic dimension: the application of climate policies together with physical risk.

(b) An external dimension, the evolution of tourism.

Both dimensions are investigated in the context of three NGFS scenarios: Below 2°C, Net Zero 2050 and Current Policies (see section 4.1). Each is characterized by different transmission channels through which the shocks propagate into the Barbadian economy, with cascading effects on GHG emissions, macroeconomic indicators, and public finance (indirect impacts).

We compare the main simulations to a counterfactual with no shock on tourism. That is, on one hand we have the *(a + b)* scenario where both channels operate, i.e. assuming that the demand for tourism is shocked due to climate policies implementation elsewhere. It is indicated as "with spillover" in the charts. On the other hand, the counterfactual is a scenario *(a)* only, with no shock on tourism. It is represented by a dashed line "No spillover". Thus, we can identify the scope of changes attributable to spillover risk. In several figures (bar charts), we represent directly the difference *(a + b) - (a)* in order to single out the effect of the spillover risk conditioned on a certain scenario.

5.1 Climate variables: physical risk and GHG emissions

First, we examine the details of the physical risk materialization, described in 4.3. Figure 11 focuses on the 2040s decade, where the difference in physical risk between the scenarios is clearer. However, due to the general climate inertia, this difference within the simulation horizon is still relatively small compared to what is expected after 2050, as per Figure 8. These considerations are reflected in Figure 11, where, focusing first on the chronic risk (markers **X**), we see that the gaps between scenario are in the sense expected, but limited in size.

We further find that the acute physical risk (markers • and ⧫) is less important than the chronic one. This is a direct consequence of the calibration, where the initial magnitudes of chronic and acute were calibrated separately based on different sources. The only link made between the two is that of proportional evolution, which is also visible in the plot, as the ratios between the ⧫ markers are similar to those between the **X** ones. Overall, both shocks are of moderate magnitude, in line with NGFS scenarios [58], which predict high impacts mostly after 2050 in the Current Policies scenario.

We then examine the other side of the economy-climate interaction: green house gas (GHG) emissions are represented in Figure 12, with their evolution over the three NGFS scenarios considered. Two main results can be highlighted here:

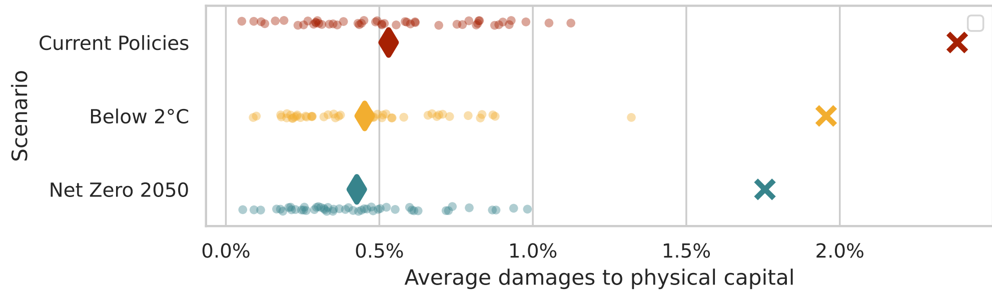


FIGURE 11: Physical damages in the 2040-2050 decade, with chronic and acute impacts represented separately. Markers **X** are the mean chronic impacts over the decade, i.e. the average over time of the ratio of capital that is lost to climate damages in every six-month simulation period. Markers • represent, for one Monte Carlo simulation, the average over time of the acute physical risk destruction ratio. Markers ♦ are the average across Monte Carlo simulations of their mean acute physical risk.
Source: authors' computations.

1. the GHG emissions are smaller for Net Zero 2050 and Below 2°C with respect to the Current Policies scenario, mainly driven by the transition to renewable in the energy sector;
2. transition spillover effects tend to decrease the overall levels of emissions (for the two transition scenarios), because it reduces the overall economic activity. However, this effect is quantitatively smaller than the first point.

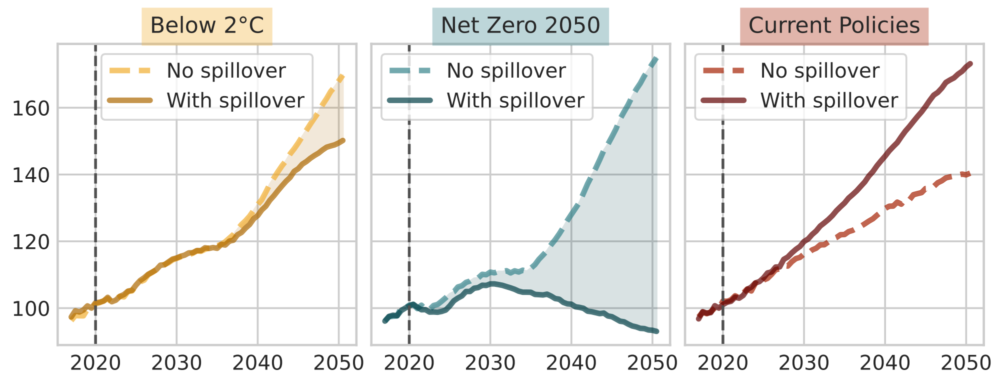


FIGURE 12: Total **GHG emissions** from the domestic economy, indexed at 100 at the starting time of the scenarios.
Source: authors' computations.

More details are provided in Figure 13, which shows the breakdown of emissions by sector. This allows us to observe that the transition pathways are successful in bringing down the GHG emissions of all sectors except for that of the green capital producer. This last case is explained by the higher demand for green capital, hence larger emissions from the producer's own operations. The central feature of green capital, relative to brown capital, is to reduce the quantity of raw material and energy required in use. Thus, the increase in green capital production is key in reducing the emissions of the consumption sector (aggregating consumption goods and services in this figure).

On the other hand, the difference induced by the tourism shock is moderate for most sectors. In particular, to the contrary of [29] where spillover damages affected directly a polluting sector, the effect of the tourism shock is smaller with regard to GHG emissions, because its most direct effect is on the service sector, which is not carbon-intensive. The exception is capital producers, with a large decrease in emissions when including spillovers in the Net Zero 2050 scenario. Nevertheless, these results do not integrate the lower emissions on the side of origin countries, i.e. the reduction given in Figure 5, which we consider as a GHG reduction for other countries.

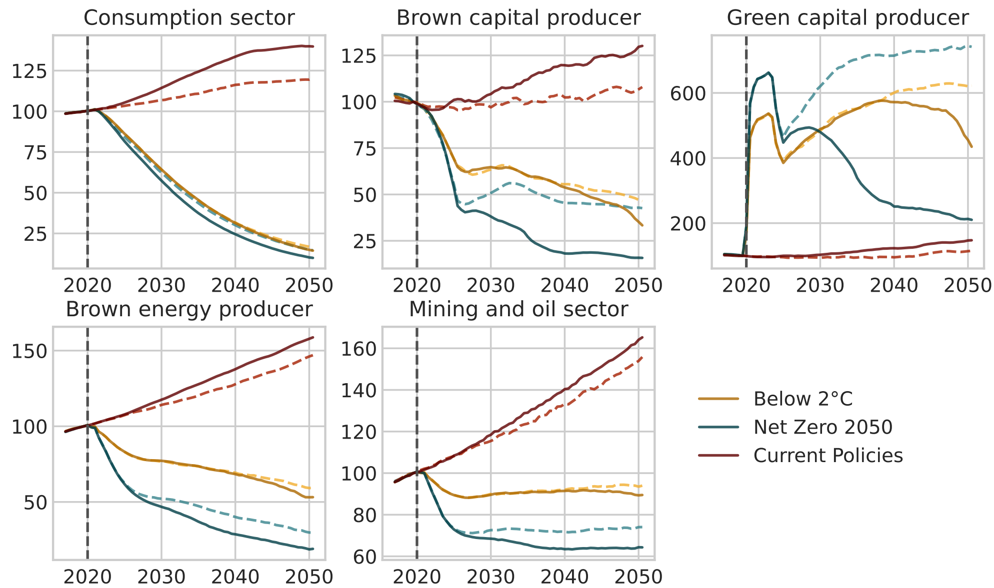


FIGURE 13: Sector-level **breakdown of GHG emissions** under different scenarios, with dashed lines representing the counterfactual with no spillover risk. “Consumption sector” aggregates both the consumption goods producers and the service sector.
Source: authors’ computations.

The other key factor that drives down the GHG emissions of the two transition scenarios relative to the baseline is the increase of renewable energy in the energy mix. This is represented in Figure 14, where we observe a sharp increase of the renewable energy share under the Net Zero 2050 scenario, reaching more than 70% of the total energy mix by 2050, and a slower increase under the Below 2°C scenario, close to 60% in 2050.

5.2 Macroeconomic indicators

We discuss here the results of the simulated scenarios on key macroeconomic indicators. Figure 15 shows the real GDP at different points in time relative to the scenario of current policies without spillover risk, which is where the highest GDP is achieved. We first note that Net Zero 2050 and Below 2°C show higher real GDP than Current Policies in the absence of spillover. This result is first driven by the difference in physical risk damages, which are hurting the Barbadian economy more in the Current Policies scenario. The implied shock to productive capital generally leads to a lower economic output, in line with the outcome of Gourdel et al. [28] on euro area countries. The other driver of this first result is the economic stimulus from larger investments in green capital, as part of the low-carbon transition scenarios, both by

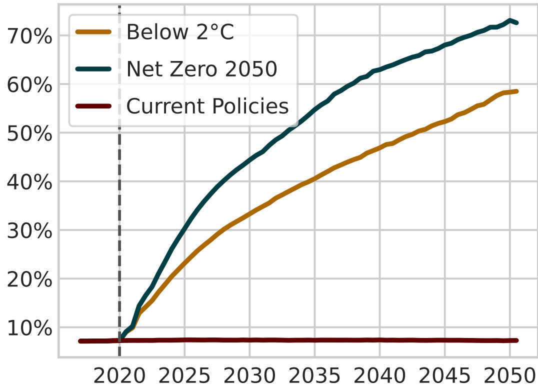


Figure 14: Share of **renewable energy** over the total produced under the different scenarios, with spillover. Source: authors' computations.

the consumption goods producers and by the green energy sector. Green investments lead to an increase in employment and, thus, in wages and households' consumption.

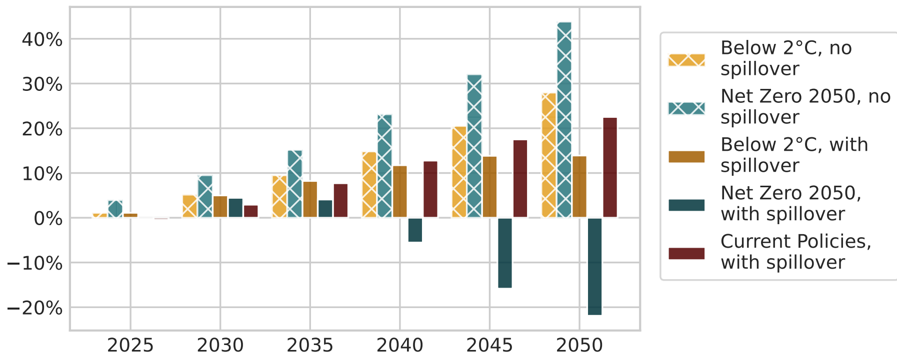


Figure 15: Real GDP, as percentage deviation from the baseline scenario of current policies without spillover. The x axis for both panels displays selected years of the simulation, and the y axis displays the percentage deviation in real GDP level relative to the reference scenario, which is NGFS current policies with no spillover risk. Source: authors' computations.

When the carbon price is high – especially in the case of the Net Zero 2050 scenario – the government's budget increases significantly, following the introduction of the policy. The added tax income is affected to the general budget of expenditures and redistribution in the same proportions as before. The only difference is represented by government's expenses linked to subsidies for green energy and green capital, which are increasing (by design) in the Net Zero 2050 and Below 2°C scenarios. However, as shown in Appendix B (Figure 24), sustainability expenses are dwarfed by the carbon tax income in the two scenarios, such that most of the additional budget can be considered as being re-injected in the general expenses. Thus, the differences observed in Figure 15 are also influenced by government's budget allocation, which contributes to foster economic growth in the short and medium term, compared to the "natural" money flow circulation.

With regard to spillover risk, Figure 15 shows that the reduction in tourism negatively affects the

Barbadian real GDP in the two NGFS transition scenarios considered, but not in the Current Policies one as the shock is reverse. Lower demand from tourism has both a direct and indirect negative impact on the Barbadian economy. Indeed, the lower touristic demand reduces the activity of the service sector, in turn decreasing its demand for labor as well as the profits reversed to the government. Then, higher unemployment and lower government's revenues negatively affect the Barbadian economy (see sectoral growth in value added in Appendix B, Figure 22). Because of this feedback effect, the difference between the spillover simulations and their no-spillover counterparts gets larger over the simulation period for all scenarios.

Furthermore, as observed in Figure 16, we find that the inflation in Barbados is contained in all scenarios, although the swift implementation of climate policies in the Net Zero 2050 scenarios has a temporary inflationary effect. It is also where spillover risk has the largest effect, causing a sustained low-inflation level from 2040 onward.

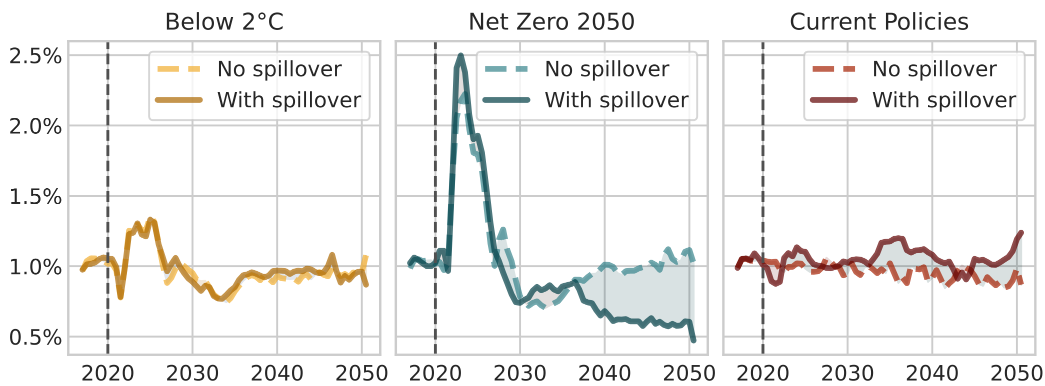


FIGURE 16: Inflation rate in the NGFS scenarios.
The x axis for both panels displays years of simulation, and the lower panel, the y axis displays the yearly inflation rate based on a representative and adaptive basket of services and consumption good.
Source: authors' computations.

5.3 Public finance indicators

In this section we show the effect of climate transition scenarios and of spillover risk on public finances, focusing on the balance of payment, and the government debt-to-GDP ratio.[11]

The difference in the balance of payments induced by the spillover risk, represented in Figure 17, is material and negative. The shock is more positive for the Current Policies scenario, in line with the series given in Figure 5, but very negative for the other two, especially the Net Zero 2050 scenario. Overall, given the importance of tourism in the initial volume of exports, the impact of the shock is very significant for the country's trade. It is important to note that we do not model any explicit policy of economic reorientation in the model. Thus, the outcome for transition scenarios is most likely a conservative one, in so far as a shock of this scale would probably trigger a policy response to dampen this shock over the three decades of our simulation.

[11] The balance of payment is measured as the difference of exports and imports for the regions of interest. Remittances are not included (and are assumed stable as a share of domestic GDP by calibration).

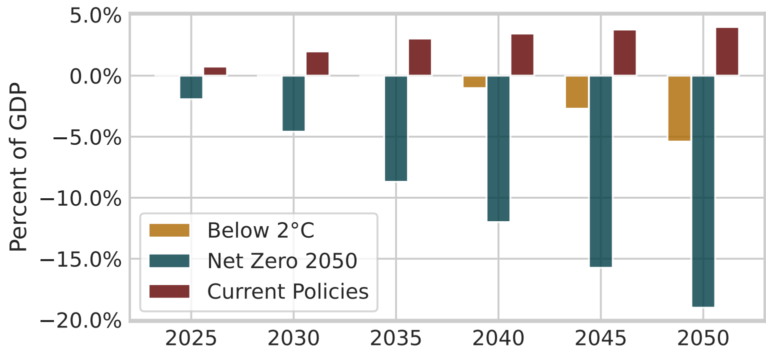


FIGURE 17: Difference in the **balance of payment** in the three scenarios when introducing spillover, measured as percentage of GDP (each scenario with spillover is compared to its no-spillover version).
Source: authors' computations.

Consistently, public debt increases the most in scenarios characterized by spillover risk (Figure 18), in particular at the end of the period. The debt added is taken on to compensate the government's deficit. While the value observed in the Net Zero 2050 scenario might be excessively pessimistic, for reasons already exposed above, this hints to the danger of such risk given that the Barbadian debt is already at a high point. This highlights the importance of considering all risk channels in the analysis of the low-carbon transition scenarios generally, as overlooking it could lead to erroneous projections.

Furthermore, we find in Figure 18 a large difference between the two shocks from the transition scenarios. Considering a broader range of possibilities, policies applied in a somewhat ambitious case could be somewhere between Below 2°C and Net Zero 2050. For countries such as Barbados – and for international institutions that advise them – it is thus important to estimate where policy pledges would place us on this spectrum, in order to best anticipate and mitigate spillover economic costs.

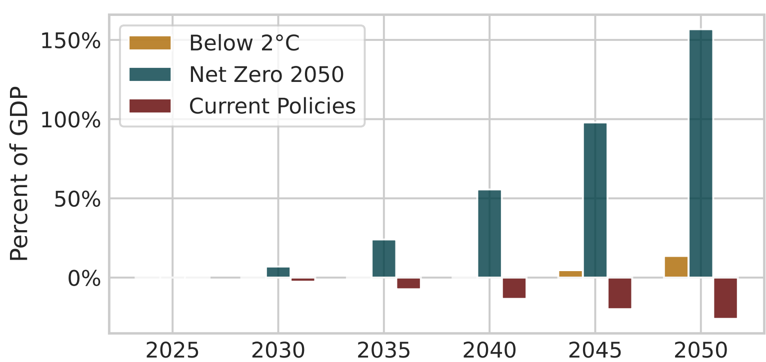


FIGURE 18: Difference in **public debt** level induced by the transition spillover shock, measured in percentage points of GDP (each scenario with spillover is compared to its no-spillover version).
Source: authors' computations.

6 Conclusion

We have developed in this paper a significant extension of previous works [29] on transition spillover risk, looking at the effect on the tourism industry that could follow the implementation of low-carbon transition policies by trading partners. This paper innovates in its uniquely broad range of climate risks that are considered, in order to best capture all challenges that Barbados will face in the coming decades. In particular, we introduce a new data-based calibration of acute shocks, deriving an impact at the national level.

We summarize in Figure 19 the key results from our simulations, using the most important dimensions of economic output and GHG emissions. For each scenario its original single country version is represented by a diamond marker, and its version with spillover effect from a change in tourism is represented by a round marker. The straight arrows represent the effect of integrating transition spillover shocks in any of these three scenarios. What we find is that spillover risk mostly affects the economic output of Barbados, with little change on the total carbon emissions of the country. The extent of the GDP change varies depending on which scenarios we consider, and might be positive if Western countries that supply tourists to Barbados do not become more ambitious in their crackdown on air travel to reach the Paris Agreement targets. In the absence of any significant evolution from tourism however, we notice that Barbados is slightly better off economically when implementing climate policies. Moreover, climate policies such as modelled here could be highly successful in reducing emissions, as exemplified by the distances between scenarios on the x axis.

As an extension of the previous, we also represent the paths that a "free-rider" policy would entail (with **X** markers on the graph). What we find is that the country is economically losing in the Net Zero 2050 scenario, because of the spillover effect, while in the Below 2°C scenario the spillover effect is less important and reduction in physical risk prevails.

A first consequence for Barbados is that the country would benefit from making its economy more robust with regard to possible decrease in tourist flows. Further motivation for this also comes from the recent experience of the COVID-19 crisis. While we did not allow it in the model, improvements with regard to transition spillover risk could also be the promotion of more long-term stays for tourists, generating more revenue for the same of lower number of arrivals. More generally, channels such as this one deserve the attention of international financial institution to help countries anticipate these developments, in particular in cases where a strong effort is needed at the same time for the adaptation to climate physical risk.

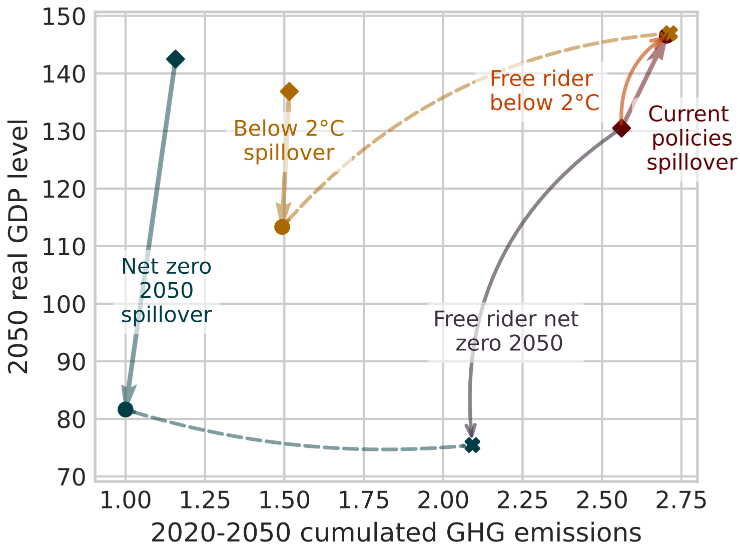


FIGURE 19: Summary of the different scenarios on the dimensions of GDP and GHG emissions.
On the x axis are indicated cumulative emissions for the period 2020-2050, rescaled to have the minimum value equal to 1. On the y axis is indicated the final GDP value, i.e. in 2050. A ♦ marker denotes results with no spillovers and a • marker denotes results with spillover (Barbados and the rest of the World following the same scenarios). An arrow from ♦ to • denotes the shift induced by the integration of spillover effect, given the same scenario. A marker **X** denotes "free rider" results, i.e. cases where the Barbadian domestic policies follow the Current Policies scenario, and the rest of the world follows a transition scenario, with spillover. An arrow from the ♦ marker of Current Policies to **X** denotes the shift induced by the spillover effect from the rest of the World (and not Barbados) adopting one of these two transition scenarios. Dash lines are linking a spillover scenario to its free-riding equivalent, i.e. the difference between both is whether Barbados implements transition policies, and the rest of the World does on both sides.
Source: authors' computations.

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A Calculation of acute physical risk with CLIMADA

This appendix provides the details of the calibration for the stochastic module that generates acute damages in the EIRIN model. The calculation of the initial parameters for the simulation of acute shocks is achieved in several steps using CLIMADA [1, 7]. It proceeds as follows:

1. We obtain a map of produced capital based on NASA's Earthdata. The data is used with the highest available resolution given the small size of the country, i.e. an arc resolution of 30 seconds.
2. The history of hurricanes in the North Atlantic basin is downloaded, with their full path and intensity [46, 45]. Hurricanes whose paths were too far from Barbados are discarded, using a cut-off of 100 nautical miles. This gives us a sample of 58 events. Their paths are represented in Figure 20.
3. For hurricanes kept, disturbances in trajectories are introduced, in order to augment the database. This function is included in CLIMADA and allows us to generate a set of plausible synthetic hurricanes on top of the observed ones. All such hurricanes are affected the same year as the original hurricane that has been disturbed. For the rest of the computations we keep only those hurricanes that affect Barbados at some point. To do so, the area covered by the hurricane at any point is determined using its radius of outermost closed isobar, which is part of the information available.
4. The impacts of all hurricanes generated is assessed by the model on the most granular scale, using the impact function from Emanuel [25]. This step allows for area-specific statistics such as presented in Figure 9. Instances where the damage to produced capital is less than 0.5 basis point are discarded, to keep only significant events for the fitting of the distribution.
5. The frequency and impact of the hurricanes informs the calculation of baseline parameters α_0 and β_0. With the method of moments, both parameters are calculated based solely on the mean and variance of the historical observations. We find $\alpha_0 = 0.4547$ and $\beta_0 = 60.2185$. The outcome is represented in Figure 21, where we plot the probability distribution function that is inferred from the data, together with vertical lines that represent the data points at hand.

Note that the measurement of the impact of acute shocks has been the object of recent research such as Bressan et al. [8] and Le Guenedal et al. [49] for granular assets. We extend this methodologies by bringing this data-driven process to use for macro-level calibration. Other recent contributions to the literature, such as Bloemendaal et al. [5], aim at modeling more precisely the changes in the frequency and intensity of the tropical cyclones.

B Additional results

In this appendix we analyze more detailed results, extending on what is presented in section 5.

To better explain the differences in growth between the different scenarios discussed in Figure 15, we represent in Figure 22 the yearly changes in value added for sectors in the economy. The consumption sector is the one that is hit most directly by the spillover shock. Therefore, the gap in growth due to the spillover is important, even if it absorbs the domestic policy shocks better than the rest of the economy, and thus presents little growth deviations in the absence of spillover. For the brown capital producer, transition policies lead to an important shrinkage in the short-run, and further decrease in output until 2050. On the contrary, the green capital producer exhibits a very high growth over the same period of time, reflecting its increased profits and higher share in the capital market production.

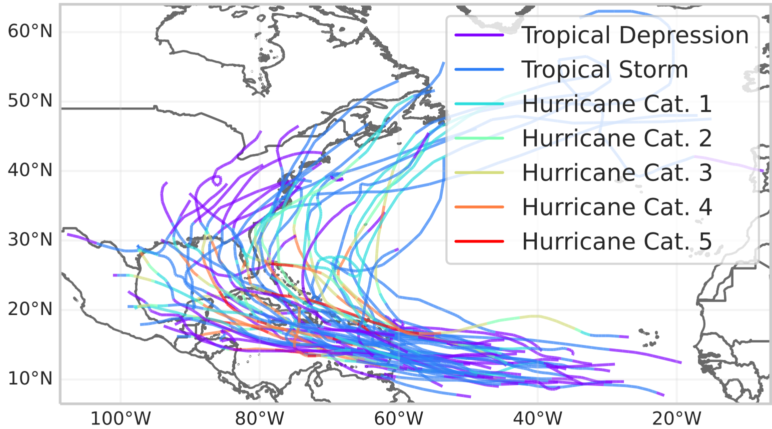

FIGURE 20: Visualization of the tracks of hurricanes retained. The legend indicates the category that these hurricanes fall in at different points of their trajectories.
Source: Knapp et al. [46, 45] and authors' computations.

Looking now at the energy sector, the pattern is somewhat different, with only a short dip in growth for the brown energy producer under the two transition scenarios, and a relatively unchanged level in the Current Policies scenario. For the green energy sector, transition policies cause a high growth in output for a few years, before stabilizing for the rest of the simulation horizon. Finally, the mining and oil sector sees minor effects from the spillover shock, and it is more affected by domestic policies, whereby transition scenarios lead to a shrinkage of the sector in the 2020-2030 decade.

Next, in Figure 23 we display the changes in unemployment rates and show how it reacts to the inclusion of spillover risk in the model. Introducing spillover risks leads to an increase of the unemployment level in the Net Zero 2050 and Below 2°C scenarios, largely explained by the lower workforce needed in the service sector, which is labor-intensive.

To add to the analysis of the government balance-sheet, we then look at the impact of the different low-carbon transition measures. These measures can be decomposed in one source of income – the carbon tax – and two expenses: the subsidies to green capital and green energy. This is represented in Figure 24, with all values in percent of GDP. We find that the revenues from the carbon tax exceed by a large margin the sustainability expenses in the scenarios Below 2°C and Net Zero 2050. The expenses themselves increase slightly by design at the start of these two scenario as subsidies are reinforced. For these two scenarios, including spillover risk has the effect of increasing the importance of these different budgets relative to GDP, which presumably reflects the differences in denominator.

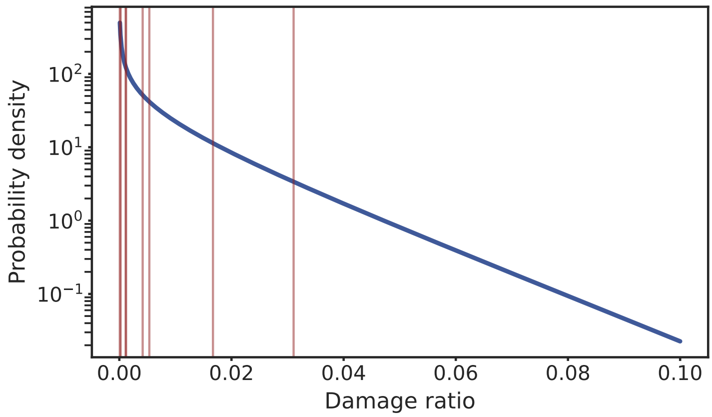

FIGURE 21: Fitted Beta distribution of acute damages given the occurrence of at least some significant hurricane. The x axis represents the damage ratio, i.e. the share of productive capital that is destructed. The y axis represents the density of the fitted Beta distribution, in log scale. Vertical lines represent the historical observations that were used in the fitting process.
Source: Knapp et al. [46, 45] and authors' computations.

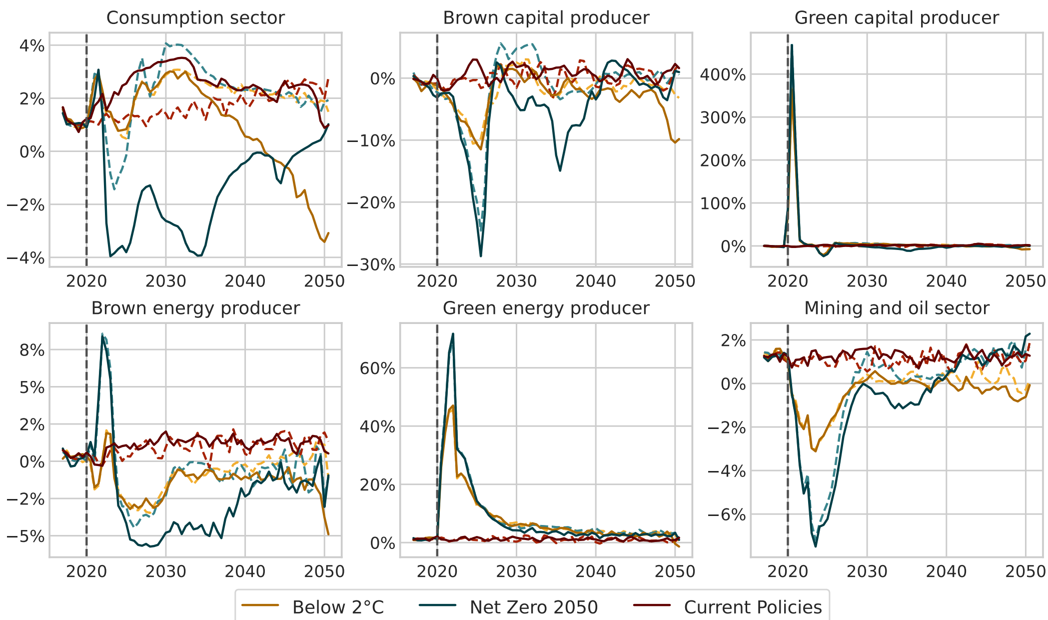

FIGURE 22: Sector breakdown of value added growth under different scenarios, year-on-year, with dashed lines representing the counterfactual with no spillover risk. "Consumption sector" aggregates both the consumption goods producers and the service sector.
Source: authors' computations.

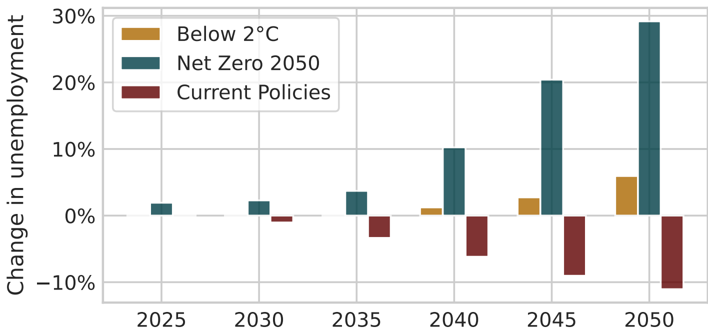

Figure 23: Difference in unemployment rate induced by the transition spillover risk for the different scenarios, in percentage points over total active population.
For each year represented, the value on the y axis represents the difference between the unemployment level with spillover, and the unemployment level without spillover.
Source: authors' computations.

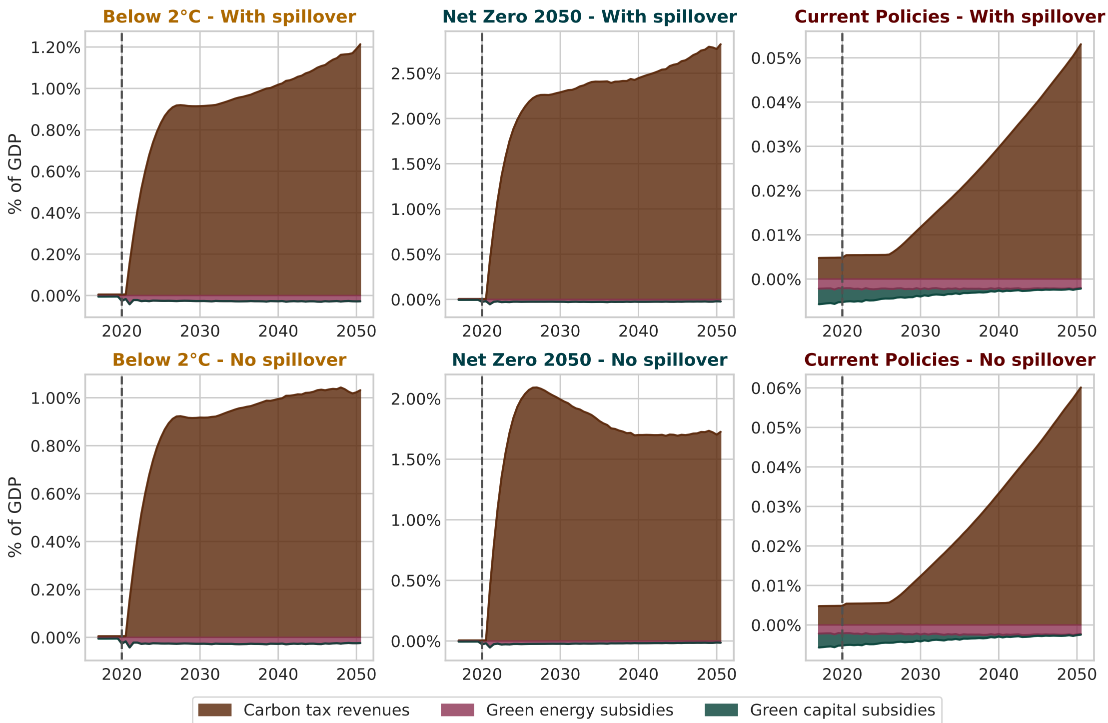

Figure 24: Revenues and expenses for the government linked to environmental sustainability.
Source: authors' computations.