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REGULAR ARTICLE

The effects of a green monetary policy on firms financing cost

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Abstract
The monetary policy operations of a central bank (CB) involve allocation decisions when purchasing assets and taking collateral. A green monetary policy aims to steer or tilt the allocation of assets and collateral toward low-carbon industries, to reduce the cost of capital for these sectors in comparison to high-carbon ones. Starting from a corporate bonds purchase program (e.g., CSPP) that follows a carbon-neutral monetary policy, we analyze how a shift in the CB portfolio allocation toward bonds issued by low-carbon companies can favor green firms in the market. Relying on optimal portfolio theory, we study how the CB might include the risk related to the environmental sustainability of firms in its balance sheet. In addition, we analyze the interactions between the neutral or green CB re-balancing policy and the evolutionary choice (i.e., by means of exponential replicator dynamics) of a population of firms that can decide to be green or not according to bonds borrowing cost.

Keywords Monetary policy · Optimal portfolio allocation · Environmental economics · Interacting agents · Evolutionary dynamics

JEL Classification E52 · E58 · G11 · C61 · C73 · Q50

1 Introduction

The core operations of a central bank (CB) include conducting monetary policy operations, managing foreign exchange reserves, and operating large value payment systems. These core operations, for which we use the shorthand of monetary policy operations, involve allocation decisions when purchasing assets and taking collateral, through the so-called ’eligibility criteria’.

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The major CBs accept private sector papers (corporate bonds, bank bonds, and bank loans) for asset purchases and collateral, and this credit policy practice has been further intensified under quantitative easing after the global financial crisis. As for the European Central Bank (ECB), the largest items on the Eurosystem balance sheet are securities holdings under the Asset Purchases Program (APP), which was launched in October 2014, and loans to EU credit institutions as part of monetary policy operations. Since then, several Asset Purchase Programs (APPs) have been introduced, allowing the ECB to buy government bonds (PSPP), asset-backed securities (ABSPP) and covered bonds (CBPP3). On March 2016, the ECB announced its intention to start buying corporate bonds directly through the implementation of the corporate sector purchase program (CSPP) as an additional component of the APP (ECB 2016).

Figure 1 shows the ECB net APP purchases, by program.[1] In August 2022, the ECB corporate bond holdings from the CSPP and other collateral monetary policy operations were €344,558 mil, while the overall APP holdings were €3,262,730 mil.[2] Thus, around 10.5% of ECB balance sheet is private corporate bonds and, as long as reinvestments in these assets will continue, this amount is expected to remain stable in the next few years (ECB 2022a).

Analogously, the Bank of England (BoE) decided on a number of non-standard monetary policy measures, including the Corporate Bond Purchase Scheme (CBPS or the Scheme), which was launched in August 2016 and further expanded in 2020 (BoE 2021a). The Federal Reserve (FED), as well, established the Secondary Market Corporate Credit Facility (SMCCF) on March 23, 2020, to support credit to employers by providing liquidity to the market for outstanding corporate bonds (FED 2021).

Following these measures, a consistent part of the securities held in the CB portfolios has become bonds of private companies.

Moreover, in recent years, it has been widely recognized that climate change is one of the main sources of structural change impacting the financial system (NGFS 2019) so that (i) its impact is of far-reaching magnitude. i.e.,: climate change affects all agents in the economy, in all sectors and geographic areas with potentially non-linear dynamics; (ii) it has a predictable nature, i.e: while the quantification of impact, time horizon, and future pathway are uncertain, there is a high degree of certainty that some combination of physical and transitional risks (ECB 2021) will materialize in the future; (iii) it has a large degree of irreversibility; (iv) it depends on short-term actions: the magnitude and nature of future impacts will be determined by actions taken today. Additionally, climate risks can affect the transmission of monetary policy through financial markets and the banking sector, particularly through asset stranding and sudden repricing of climate-related financial risks. If the financial system is weakened, the transmission of monetary policy may be impaired. For these reasons, some CBs have started greening monetary policy operations to

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[1] On 9 June 2022 the ECB Governing Council decided to discontinue net asset purchases under the APP as of 1 July 2022. Reinvestments of the principal payments from maturing securities purchased under the programs will continue, in full, for an extended period of time and as long as necessary to maintain ample liquidity conditions and an appropriate monetary policy stance (ECB 2022a).

[2] At amortized cost, in EURO millions, at month-end.

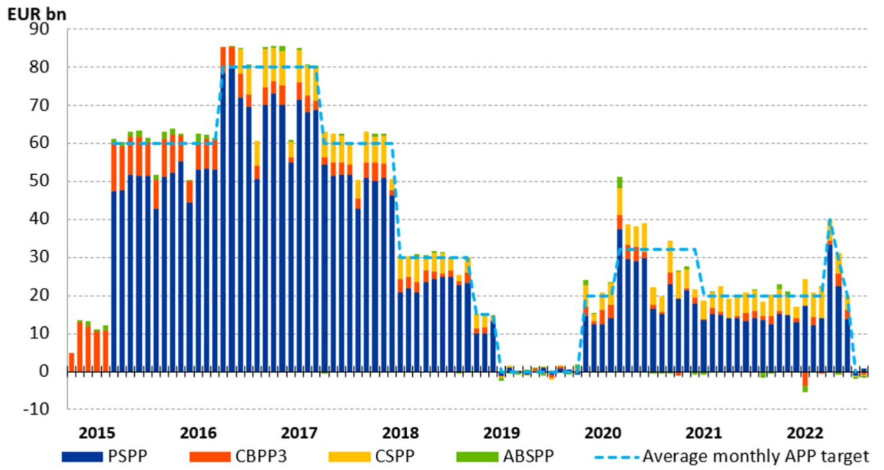
reduce the financial risk related to climate change and to promote a green transition of industries and firms (Schnabel 2023).

The aim of this paper is to shed light on the mechanisms through which a CB can implement a green monetary policy to steer or tilt the allocation of assets and collateral toward low-carbon industries, and reduce the cost of capital for these sectors in comparison to high-carbon ones. Starting from a corporate bonds purchase program that follows a carbon-neutral monetary policy, we analyze how a shift in the CB portfolio allocation toward bonds issued by low-carbon companies can favor green firms in the market. By means of a *'green monetary policy'* the CB internalizes externalities and public failures deriving from climate change through the inclusion of climate-related risks in the portfolio assessment. The CB operates according to a market efficiency principle so that the optimal portfolio choice encompasses three objectives: maximizing returns, containing risks, and reducing firms' environmental footprint. Finally, we analyze the interactions between the neutral or green CB re-balancing policy and the evolutionary choice (i.e., by means of exponential replicator dynamics) of a population of firms that can decide to be either green or not according to bonds borrowing cost.

Our model supports three main findings. First, green and non-green bond riskiness is a key factor that impacts borrowing costs where financial risk and environmental risk form substitutes. In this context, the issuing of green bonds by companies and the implementation of a CB green monetary policy that targets their acquisition results in a reduction of borrowing costs for this typology of bonds and leads to a significant increase in firms' investment in green technologies. Second, modeling an industrial sector, we found several scenarios characterized by a strong path dependency. If a large share of firms employs non-green technology, no investment in green technology occurs in the long run, even if the green investment equilibrium is Pareto efficient for the industry. We define this situation as a *technology trap*. We demonstrate that a green monetary policy can help, in different situations, to exit this technology trap. Third, the firms' sensitivity to profit differentials in investment decisions and the market structure (i.e., the degree of competitiveness) can play a crucial role in the evolution of the industry equilibria, leading, in some cases, to periodic (or even chaotic) behavior of firms' investment decisions. In scenarios characterized by periodic or chaotic behavior of investment decisions, the *green monetary policy* can not only increase the share of firms employing the green manufacturing technology but also help to stabilize the investment decisions, i.e., reducing the share of firms that switches from one manufacturing technology to the other in the sector up to the point where only one equilibrium is reached in the long-run.

Our findings are in line with recent empirical evidence according to which green monetary policy and the issuing of green bonds can support the adoption of green technology (Karpf and Mandel 2018). Indeed, it has been argued that renewable energies are more competitive when interest rates are low, even if the effects of interest rate changes are not symmetric across economic sectors (Schnabel 2023).

The paper is organized as follows. Section 2 provides the institutional background and a short literature review on the issue of greening the monetary policy of central banks. Section 3 first analyzes a *'neutral monetary policy'* based on modern



Note: The average monthly APP targets were first set by the ECB Governing Council at the beginning of the PSPP in March 2015. The additional envelope of €120 billion decided by the Governing Council on 12 March 2020 has been linearised for illustration in this chart, while it will be implemented in full according to the established principles

Fig. 1 ECB APP net purchases, by program *Source*: ECB (2022a)

portfolio theory (3.1), and then a *’green monetary policy’* by introducing a further CB objective based on the carbon intensity of firms (3.2). The section concludes with a numerical example of the results (3.3). Section 4 studies the interactions between the monetary policy strategy undertaken by the CB and the investment decision of a population of firms based on bond borrowing costs. Section 5 concludes.

2 Literature review and institutional background

Market neutrality has generally been the CB guiding principle of asset purchase programs[3]: the monetary authority buys a proportion of the market portfolio of available corporate and bank bonds (usually investment-grade bonds) to reduce price distortions from their eligible asset purchases.[4] However, this strategy might imply a carbon bias because capital-intensive companies and sectors tend to be more carbon-intensive (Papoutsi et al. 2021).

The existence of climate externalities requires a reconsideration of market neutrality. In the presence of market failures, adhering to the market neutrality principle may reinforce pre-existing inefficiencies that give rise to a suboptimal allocation

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[3] In the ECB case, the operationalisation of this principle entails the monetary authority purchases securities in proportion to their relative market capitalisation (Coeure 2015).

[4] For example, the Bank of England’s Corporate Bond Purchase Scheme (CBPS) follows a principle similar to market neutrality. The CBPS is conducted with the objective of minimizing the impact of asset purchases on the relative borrowing costs across sectors. The principle is implemented via sector key targets, with the potential for deviations (BoE 2021b).

of resources. If the market misprices the risks associated with climate change, thus underestimating the social costs of investment, adhering to the market neutrality principle may instead support a market structure that hampers an efficient allocation of resources. In view of such market failures, a market efficiency principle would explicitly recognize that a supposedly 'neutral' market allocation may be suboptimal in the presence of externalities. Indeed, market failures may drive a wedge between market prices on the one hand and efficient asset values that internalize the externalities on the other (Schnabel 2021).

Corporate bond holdings expose CBs to different types of financial risk that might be related to climate change: extreme weather events such as wildfires or floods can hit companies' or their customers' premises and destroy their warehouses, manufacturing plants, data centers and supply chains implying "physical risk" (Alogoskoufis et al. 2021). In addition, so-called transition risks result from societal and economic shifts toward a low-carbon and more climate-friendly production model. Such shifts could mean that some sectors of the economy face significant transformations in asset values or higher costs of doing business that alter the value of investments held by banks and insurance companies (Gourdel et al. 2022).[5] For these reasons, some CBs have started to *greener* monetary policy operations to reduce the financial risk related to climate change and to promote a green transition of industries and firms.

On November 5 2021, the Bank of England considered the climate impact of the issuers of bonds within the framework of the CBPS: "with this approach we will incentivize firms to take decisive actions that support an orderly transition to net zero. Purchases will then be tilted or skewed within sectors toward the debt of eligible firms that are performing relatively strongly in support of net zero, and responding most to the incentives we are setting, and away from those who are not" (BoE 2021a, b).

As announced in July 2022, also the Eurosystem aims to gradually decarbonize its corporate bond holdings on a path aligned with the goals of the Paris Agreement. To that end, the ECB will tilt its purchases toward issuers with a better climate performance by reinvesting the sizeable redemptions expected over the coming years. The overall volume of corporate bond purchases will, however, continue to be determined solely by monetary policy considerations and the role played by such purchases in achieving the ECB's inflation target (ECB 2022b). The ECB has also announced that when government and corporate bonds come to maturity in the context of its QE program, new bonds will be bought in the market to keep the money stock (money base) unchanged. This creates a 'window of opportunities' for the ECB. It could replace the old bonds with new 'environmental bonds' over time to establish a well-diversified portfolio that also includes the value and the risk profile of climate change and carbon transition effects (De Grauwe 2019).

Therefore, the objective of a green monetary policy is to steer or tilt the allocation of assets and collateral toward low-carbon sectors and firms. This could reduce the cost of capital for those companies and sectors in comparison to high-emission industries. The allocation policy must be designed and executed so that it does not

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[5] In this respect, an increasing number of works have tried to price physical and transition risks in the financial market, see e.g., Blasberg et al. (2021); Livieri et al. (2023).

interfere with the effective implementation of monetary policy and the transmission mechanism. Price stability is and should remain the top priority for central banks.

In this paper, we fix the dimension of the corporate bonds purchase program (i.e., the overall CB demand of private bonds), and focus on the composition of the CB balance sheet between two typologies of corporate bonds: green and non-green bonds. We study how steering the CB eligibility criteria toward low-carbon bonds issued by environmentally friendly companies and following the market efficiency principle, can help the financing condition, favoring green companies in the market.

3 The model

Equation (1) shows the total amount of corporate bonds in an economy eligible for a CB purchase program (B_T), given by green corporate bonds B_G issued by companies to finance environmentally sustainable projects, and non-green/conventional corporate bonds B_N issued by firms for investment that are not related to emission or pollution abatement technologies[6]:

$$B_T = B_G + B_N \tag{1}$$

We define the share of green bonds $x = \frac{B_G}{B_T}$, and the complementary share of non-green bonds $1 - x = \frac{B_N}{B_T}$ in the economy.

For simplicity, we assume that the CB can identify the type of bond without ambiguity. While the assumption does not alter the conclusions of the paper, it avoids dealing with various criteria that are often different for each type of institution and/or asset purchase program under consideration, since no international standard has been established yet (OECD 2017 and, see for a taxonomy, Commission 2020).[7]

If green and conventional bonds were perfect substitutes for banks, production and investment in both sectors would not be affected (Ferrari and Landi 2021) after the CB tilts the portfolio composition toward green bonds and keeps the total assets constant. However, green and non-green bonds signal two different types of use of the financial resources and hence, are imperfect substitutes both for the issuing firms and for investors (Flammer 2021; Zerbib 2019; Gianfrate and Peri 2019). We, therefore, model both types using two distinct supply functions. The aggregate supply of corporate green bonds in the market negatively depends on green bond yield: $B_G(\mu_G)$. Indeed, when the interest rate on this specific category of bonds (μ_G) increases, the firms' relative supply of bonds decreases because it becomes more

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[6] The bond and issuer eligibility conditions set forth by the European Central Bank can be found in ECB (2016), Zaghini (2019).

[7] The Eurosystem has developed a climate scoring methodology to assess the climate performance of eligible issuers that is based on three sub-scores: (i) backward-looking climate metrics, in the form of (disclosed) past GHG emissions and emission intensities (normalized by revenue); (ii) forward-looking climate metrics, such as whether the issuer has credible and ambitious decarbonization targets in place; and (iii) the quality of climate disclosures, such as their completeness and their verification by third parties. These metrics are based on publicly available data as well as other relevant information and methodologies, such as science-based targets, etc. ECB (2022c).

costly for companies to finance sustainable-friendly projects through the issuance of green bonds. The aggregate supply function is modeled by means of the unitary isoelastic function given by Eq. (2a). Similarly, the green bond supply in terms of share $x(\mu_G)$ is given by Eq. (2b), and the inverse supply function $\mu_G(x)$ is (2c):

$$B_G(\mu_G) = \frac{\alpha}{\mu_G} \Leftrightarrow \tag{2a}$$

$$x(\mu_G) = \frac{\alpha}{\mu_G B_T} \Leftrightarrow \tag{2b}$$

$$\mu_G(x) = \frac{\alpha}{x B_T} \tag{2c}$$

Analogously, the aggregate supply of corporate non-green bonds in the market negatively depends on non-green bond yield: $B_N(\mu_N)$. This aggregate supply function is unitary isoelastic, and given by Eq. (3a). The equivalent non-green bonds supply in terms of share $1 - x(\mu_N)$ is Eq. (3b), as well as the inverse supply function $\mu_N(1 - x)$ is (3c):

$$B_N(\mu_N) = \frac{\beta}{\mu_N} \Leftrightarrow \tag{3a}$$

$$1 - x(\mu_N) = \frac{\beta}{\mu_N B_T} \Leftrightarrow \tag{3b}$$

$$\mu_N(1 - x) = \frac{\beta}{(1 - x) B_T} \tag{3c}$$

By definition, the total amount of corporate bonds in the economy, as well as the yield on bonds, must be positive ($B_T, \mu_G, \mu_N > 0$). It follows from Eqs. (2c) and (3c) that also $\alpha, \beta > 0$. The parameters α and β are scaling factors of the aggregate supplies of green and non-green bonds respectively, a proxy of the relative market size of the two types of bonds considered.

3.1 Neutral monetary policy

The total volume of corporate bonds purchased by the CB through a large-scale purchase program is only determined by monetary policy considerations, i.e., inflation targeting (Bacchiocchi and Giombini 2021). We assume that the representative CB is the only corporate bonds investor in the economy and acquires the total amount of eligible bonds in the economy.[8] Therefore, we focus only on the relative composition (i.e green or non-green) of purchase program B_T and study the impact of a CB

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[8] This holds without loss of generality when there are no spillovers between the CB and other corporate bonds investors.

strategy that includes environmental considerations (i.e., *green monetary policy*), to analyze the occurrence of portfolio re-balance and its effect on the cost of bonds for firms.

Based on modern portfolio theory (Bodie et al. 2021), the CB considers the average expected yields of green μ_G and non-green bonds μ_N, their average volatility (i.e.,, the standard deviation of their returns), given respectively by $\sigma_G, \sigma_N > 0$, and the covariance between the two types of corporate bonds $\sigma_{G,N}$.[9] The covariance $\sigma_{G,N}$ is related to the correlation coefficient $r_{G,N} = \frac{\sigma_{G,N}}{\sigma_G\,\sigma_N}$, which, to be economically meaningful, must range between -1 (i.e., perfect negative correlation) and $+1$ (i.e., perfect positive correlation). Thus, we impose that:

$$-1 \leq \frac{\sigma_{G,N}}{\sigma_G\,\sigma_N} \leq 1 \tag{4}$$

According to the capital asset pricing model (CAPM), the CB portfolio's expected yield $\mu_P(x)$ is a convex combination of the individual yields, where the weights are the share of green bonds $x \in (0, 1)$ and non-green bonds $1 - x$ (i.e., the complementary part) in the CB portfolio/market:

$$\mu_P(x) = x\,\mu_G + (1-x)\,\mu_N \tag{5}$$

Substituting the inverse supply functions of green (2c) and non-green bonds (3c) into Eq. (5), and defining the CB portfolio's expected variance $\sigma_P^2(x)$, based on the volatility (i.e., standard deviation) $\sigma_i > 0, i = G, N$, and the covariance $\sigma_{G,N}$ of the individual type of onds, we obtain:

$$\begin{cases} \mu_P(x) = \frac{\alpha}{B_T} + \frac{\beta}{B_T} \\ \sigma_P^2(x) = x^2\,\sigma_G^2 + (1-x)^2\,\sigma_N^2 + 2\,x\,(1-x)\,\sigma_{G,N} \end{cases} \tag{6}$$

The system of equations in (6) determines a tuple of points, i.e., the expected yield and expected variance of the portfolio, in relation to share x. It describes the mean-variance trade-off that the CB faces for all the possible combinations/allocations of green (x) and non-green ($1 - x$) bonds.[10] Consequently, corporate bonds come in a variety of risk-reward levels depending on the issuing company's creditworthiness. While the CB prefers assets that have the highest expected return, it also seeks to minimize uncertainty about corporate bonds' future return. We assume that the CB chooses the combination of green and non-green bonds with the optimal risk-reward level and thus, the portfolio allocation that offers the maximum return-to-risk ratio, i.e., the optimal portfolio x^* in the CAPM. The CB risk-averse preference function in a *neutral monetary policy* setup can be formalized as a capital allocation line defined by the following (7):

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[9] To use standard deviations, we assume that returns are normally distributed and that the CB, as an investor, has access to sufficient information to evaluate these variables.

[10] The efficient frontier is the set of portfolios which satisfy the condition that no other portfolio exists with a higher expected return but with the same standard deviation of return (i.e.,, the risk).

$$\mu_P(x) = r_F + S_P\, \sigma_P(x) \tag{7}$$

The CB maximizes the portfolio return $\mu_P(x)$ for a given portfolio risk $\sigma_P(x)$, where S_P is the Sharpe ratio or reward-to-risk ratio (Sharpe 1971), and $r_F \geq 0$ is the equivalent risk-free asset (i.e., the yield associated to a risk-free asset, for example a short-term U.S. treasury bond). Equation (7) shows the trade-off between the expected portfolio return $\mu_P(x)$ and its volatility $\sigma_P(x)$ and thus defines the risk-aversion preference of the CB. The CB is willing to hold a riskier portfolio if and only if it guarantees a higher average return reflected in S_P. Therefore, the CB maximizes the reward-to-risk ratio S_P given the constraints in (6) by determining the share x that maximizes the Sharpe ratio of a portfolio that is on the envelope of the Markowitz bullet (Markowitz 1952)[11]:

$$\begin{gathered}\max_x \quad S_P = \frac{\mu_P(x) - r_F}{\sigma_P(x)} \quad \text{s.t.} \\ \text{constraints in (6)}\end{gathered} \tag{8}$$

Note that $\mu_P(x) \geq r_F$ in (8) requires that:

$$\frac{\alpha + \beta}{B_T} \geq r_F \tag{9}$$

From the Sharpe ratio condition (8), it is also required that $\sigma_P^2(x) > 0$ in (6). It must therefore hold that:

$$\sigma_{G,N} > -\frac{x\sigma_G^2}{2(1-x)} - \frac{(1-x)\sigma_N^2}{2x} \tag{10}$$

The problem in (8) can be reduced to solving the unconstrained maximization problem

$$\max_x \quad \frac{\frac{\alpha}{B_T} + \frac{\beta}{B_T} - r_F}{\sqrt{x_G^2\, \sigma_G^2 + (1-x)^2\, \sigma_N^2 + 2\,x\,(1-x)\,\sigma_{G,N}}} \tag{11}$$

The solutions to problem (11) returns the optimal shares of green and non-green corporate bonds in the CB portfolio and in the market, and is given by:

$$x^* = \frac{\sigma_N^2 - \sigma_{G,N}}{\sigma_G^2 + \sigma_N^2 - 2\,\sigma_{G,N}} \tag{12a}$$

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[11] Graphically, the slope of the optimal set, the maximum Sharpe ratio, is such that it is tangent to the portfolio efficient frontier (Sharpe 1971).

$$1 - x^* = \frac{\sigma_G^2 - \sigma_{G,N}}{\sigma_G^2 + \sigma_N^2 - 2\,\sigma_{G,N}} \tag{12b}$$

From condition (4) and using (12a), (12b) $\in (0, 1)$, it must hold:

$$\sigma_N^2 > \sigma_{G,N} \tag{13a}$$

$$\sigma_G^2 > \sigma_{G,N} \tag{13b}$$

In the following, we define the derivatives of the optimal shares (12a), (12b) with respect to the model parameters:

$$\frac{\partial x^*}{\partial \sigma_N^2} = \frac{\sigma_G^2 - \sigma_{G,N}}{\left(\sigma_G^2 - 2\sigma_{G,N} + \sigma_N^2\right)^2} > 0 \tag{14a}$$

$$\frac{\partial x^*}{\partial \sigma_G^2} = \frac{\sigma_{G,N} - \sigma_N^2}{\left(\sigma_G^2 - 2\sigma_{G,N} + \sigma_N^2\right)^2} < 0 \tag{14b}$$

$$\frac{\partial x^*}{\partial \sigma_{G,N}} = \frac{\sigma_N^2 - \sigma_G^2}{\left(\sigma_G^2 - 2\sigma_{G,N} + \sigma_N^2\right)^2} \gtreqless 0 \tag{14c}$$

$$\frac{\partial^2 x^*}{\partial \sigma_N^2 \partial \sigma_G^2} = \frac{\sigma_N^2 - \sigma_G^2}{(\sigma_G^2 - 2\sigma_{G,N} + \sigma_N^2)^3} \gtreqless 0 \tag{14d}$$

$$\frac{\partial^2 x^*}{\partial \sigma_G^2 \partial \sigma_{G,N}} = \frac{2\sigma_{G,N} + \sigma_G^2 - 3\sigma_N^2}{(\sigma_G^2 - 2\sigma_{G,N} + \sigma_N^2)^3} \gtreqless 0 \tag{14e}$$

$$\frac{\partial^2 x^*}{\partial \sigma_N^2 \partial \sigma_{G,N}} = -\frac{2\sigma_{G,N} - 3\sigma_G^2 + \sigma_N^2}{(\sigma_G^2 - 2\sigma_{G,N} + \sigma_N^2)^3} \gtreqless 0 \tag{14f}$$

As expected, an increase of the variance (i.e., financial risk) reduces the optimal share of the correspondent corporate bond in the CB portfolio, while the effect of the covariance on x^* can be positive, negative or null, depending on the difference of the two variances.

Given the optimal shares, it is possible to retrieve the optimal amount of green B_G^* and non-green bonds B_N^* in the market:

$$B_G^* = x^* B_T \tag{15a}$$

$$B_N^* = (1 - x)^* B_T \tag{15b}$$

Substituting the optimal portfolio amount of green and non-green bonds into the aggregate inverse supply functions (2c) and (3c), provides the equilibrium bonds yields μ_G^* and μ_N^*:

$$\mu_G^* = \frac{\alpha}{B_G^*} = \frac{\alpha\,(\sigma_G^2 + \sigma_N^2 - 2\,\sigma_{G,N})}{B_T\,(\sigma_N^2 - \sigma_{G,N})} \tag{16a}$$

$$\mu_N^* = \frac{\beta}{B_N^*} = \frac{\beta\,(\sigma_G^2 + \sigma_N^2 - 2\,\sigma_{G,N})}{B_T\,(\sigma_G^2 - \sigma_{G,N})} \tag{16b}$$

These bond yields represent the cost of capital for each type of firms issuing the bond. Given Eqs. (16a), (16b), the monetary authority can reduce the yield/cost of capital for green companies and increase the yield/cost of capital for non-green firms by altering the composition x^* of its balance sheet without modifying the latter's total dimension (B_T).

3.2 Green monetary policy

The existence of climate externalities, and physical and transition risks related to climate change question market neutrality, as it could reinforce pre-existing inefficiencies that give rise to erroneous prices and suboptimal resources allocation. The objective of the *green monetary policy* is to internalize such externalities and risks to obtain an efficient allocation of financial resources that take into consideration climate related issues.

In other words, the CB desires to re-balance its portfolio to reduce the cost of capital for firms that invest in sustainable/green projects, while fixing, at the same time, the overall dimension of the balance sheet B_T.

By increasing the relative share x^* of green bonds, the CB reduces the borrowing cost for environmentally sustainable firms while rendering it more costly for companies to finance non-green investment projects. This *green monetary policy* should encourage firms to invest and shift to environmentally sustainable production. We model the green monetary policy by introducing a steering/tilting factor (Schoenmaker 2021) that governs the CB's portfolio:

$$p = \frac{C_N}{C_G} \tag{17}$$

where C_i, with $i = G, N$ is a synthetic indicator of the environmental footprint of the i-type issuer, e.g., the average carbon emissions and/or other environmental measures. Note that the average environmental footprint indicator of non-green issuers C_N is greater than the same indicator for green issuers C_G. This is consistent with studies such as Fatica et al. (2021), where green bonds issued by non-financial corporations are associated with a reduction in firm-level carbon emissions induced by climate-friendly investment projects.

Since the tilting factor p in Eq. (17) is the ratio between the two footprint indicators, it always exceeds 1. Moreover, this ratio defines the extent of the greening monetary policy and accounts for the additional risks (physical, transition) related to the carbon footprint of firms that issue corporate bonds to finance non-sustainable investments. Since these projects are not green, they: (1) contribute more to adverse climatic events and natural disasters that bring direct and indirect physical assets damages (e.g., business disruption, system failures, disruption of transportation facilities and telecommunications infrastructure, etc.), (2) are more vulnerable to an increasing legal and regulatory environmental-friendly framework where compliance risk as well as litigation, and liability costs associated with climate-sensitive investments, undermine business profitability, (3) become target of economic policies that demand a reduction in the use of fossil fuels and carbon emissions (e.g., carbon tax) (Alogoskoufis et al. 2021; ECB/ESRB 2021).

The climate-related risks become relevant and are internalized via the CB corporate bond purchase program. As they affect the variance of the corresponding bonds (σ_N^2), we define a modified variance $\hat{\sigma}_N^2$ that beside the financial risk, considers these climate-related risks:

$$\hat{\sigma}_N^2 = p\,\sigma_N^2 \tag{18}$$

Given that the tilting/steering factor $p > 1$, the overall risk of non-green corporate bonds increases,[12] In this way, the CB internalizes the externalities and public failures through the inclusion of climate-related risks in the portfolio assessment. Therefore, following the market efficiency principle, the optimal portfolio choice in a *green monetary policy* setting encompasses three objectives: maximizing returns, containing risk/volatility, and reducing firms' environmental footprint, are defined equivalently to Eqs. (6) and (8) and given by:

$$\max_x s_P = \frac{\mu_P(x) - r_F}{\sigma_P(x)} \quad \text{s.t.} \qquad \begin{cases} \mu_P(x) &= \frac{\alpha}{B_T} + \frac{\beta}{B_T} \\ \sigma_P^2(x) &= x^2\,\sigma_G^2 + (1-x)^2\,\hat{\sigma}_N^2 + 2\,x\,(1-x)\,\sigma_{G,N} \end{cases} \tag{19}$$

and the corresponding solutions in (12a) and (12b) with the substitution of $\hat{\sigma}_N^2$ in Eq. (18).

Since

$$\frac{\partial x^*}{\partial p} = \frac{\sigma_N^2\left(\sigma_G^2 - \sigma_{G,N}\right)}{\left(\sigma_G^2 + p\,\sigma_N^2 - 2\,\sigma_{G,N}\right)^2} > 0 \tag{20}$$

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[12] Note that the case of *neutral monetary policy* is obviously the special case in which $p = 1$.

from condition (13b), the CB optimal portfolio contains a higher share of green bonds x^* and a lower share of non-green bonds $1 - x^*$. The optimal amount of the two types of bonds B_G^* and B_N^* is given by Eqs. (15a) and (15b), the bonds yields μ_G^* and μ_N^* are given by (16a) and (16b) after substituting $\hat{\sigma}_N^2$ into (18):

$$\mu_G^* = \frac{\alpha}{B_G^*} = \frac{\alpha\,(\sigma_G^2 + \hat{\sigma}_N^2 - 2\,\sigma_{G,N})}{B_T\,(\hat{\sigma}_N^2 - \sigma_{G,N})} \tag{21a}$$

$$\mu_N^* = \frac{\beta}{B_N^*} = \frac{\beta\,(\sigma_G^2 + \hat{\sigma}_N^2 - 2\,\sigma_{G,N})}{B_T\,(\sigma_G^2 - \sigma_{G,N})} \tag{21b}$$

The CB lowers the financing costs for environmentally sustainable firms and tightens the financing conditions of non-green companies, i.e., increasing the so-called green premium or *greenium* (Agliardi and Agliardi 2021; Caramichael and Rapp 2022), since

$$\begin{aligned} \frac{\partial \mu_G^*}{\partial p} &= \frac{\alpha\,\sigma_N^2\left(\sigma_{G,N} - \sigma_G^2\right)}{B_T\left(\sigma_{G,N} - p\,\sigma_N^2\right)^2} < 0 \\ \frac{\partial \mu_N^*}{\partial p} &= -\frac{\beta\,\sigma_N^2}{B_T\left(\sigma_{G,N} - \sigma_G^2\right)} > 0 \end{aligned} \tag{22}$$

A short numerical example shows the impact of a *green monetary policy* CSPP undertaken by a representative CB. Assume that a volume of eligible corporate bonds equal to $B_T = 140,000$ millions EUR or USD is acquired by the central bank through the CSPP. Let the scaling factors of the aggregate bonds supply be $\alpha = 2300$ for green bonds, and $\beta = 4000$ for non-green bonds. Furthermore, the CB can observe the yield trends to assess the financial risk related to these assets. Let the volatility, given by the standard deviation, of green bonds $\sigma_G = 0.20$ is higher than that of non-green bonds $\sigma_N = 0.15$, and covariance between the two types of bonds is $\sigma_{G,N} = -0.002$, corresponding to a moderate negative correlation coefficient $r_{G,N} = -0.067$. The risk-free asset has a yield of $r_F = 0.02$. The assumptions satisfy conditions (4), (9), (10), (13), and Table 1 compares the optimal shares, amounts and yields of green and non-green bonds for a *neutral monetary policy* ($p = 1$) and for a *green monetary policy* ($p = 1.1$).

Table 1 shows that if the tilting factor $p > 1$, that is, as long as the CB accounts for the additional risks related to the carbon footprint of firms that issue corporate bonds to finance non-sustainable investment, the financing conditions of green firms improve, *ceteris paribus*.

4 Green monetary policy and firm investment choice

In this section, we consider the interaction between monetary policies, i.e., neutral or green, and the investment choice of firms in a given sector.

The investment survey of the European Investment Bank (EIB) in Fig. 2 shows that an increasing number of firms is investing in green/climate-related measures (EIB 2022).[13]

Furthermore, Europe has also become a world leader in the issuance of green bonds. In late 2021, the volumes issued by companies as well as national and subnational governments in the EU-27 reached €497 bn compared to a bond volume of non-European issuers at roughly €558 bn (Fatica and Panzica 2021).

Building on this evidence and similar to Pindyck (1998, 1991), we model the potential impact of a CSPP program on a population of firms which invests capital $C(t)$ in each period t. The population of firms belongs to an industry with two technologies of production: a green technology G and a non-green technology N. Consequently, the firms in the sector can invest capital $C(t)$ at every period t (e.g., every year) in either green/climate-related technology $G(t)$ (i.e., 'green investment') or in non-green technology $N(t)$ (i.e., 'non-green investment'). The share of green investment in the industry is $0 \leq y(t) = \frac{G(t)}{C(t)} \leq 1$ and the complementary share of non-green investment is $1 - y(t) = \frac{N(t)}{C(t)}$, assuming that the background growth rate of bond capital $r(t)$ is independent of the technology investment choice $i = G(t), N(t)$ at each time t.

We assume that firms make investment choices under limited information: firms do not know exactly what the return on investment of each technology will be and/or are not able to compute the optimal alternative following traditional profit maximization rules. In this case, the decision cannot be based on expected return on investment as in a perfect information setting. Instead, firms imitate the investment behavior of other firms. More specifically, each company in the industry simply observes a small subset of other firms and replicates the investment strategy of the most successful ones.[14]

Similar to Shaffer (1991), and Calcagnini et al. (2022), we assume that the firm investment in technology $i(t)$ earns a marginal return $MR_i(t)$:

$$MR_G(t) = a_G - b_G\, y(t) \tag{23a}$$

$$MR_N(t) = a_N - b_N\, [1 - y(t)] \tag{23b}$$

where the parameters $a_G, a_N, b_G, b_N > 0$ depend on the characteristics of the manufacturing technology $i = G(t), N(t)$ of the sector and are assumed to be constant over time.[15] The total earnings $E_i(t)$ from a given technology investment in/adoption of $i(t)$ are the integral of (23a),(23b) with respect to the correspondent share of investment, i.e.,:

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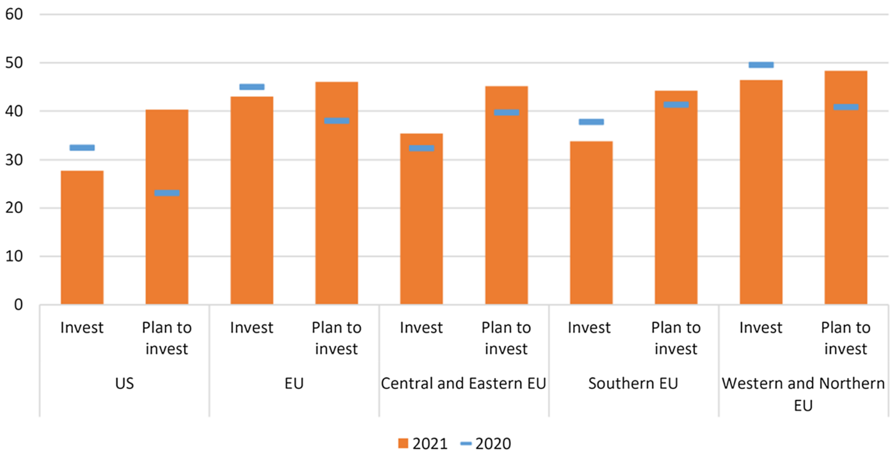
[13] The share of firms investing in climate measures in 2021 is marginally below the share in 2020, which is likely the result of the repercussions the COVID-19 pandemic had on firms' investment plans. Overall, the share of EU firms investing in climate-related measures is significantly higher than in the United States, with companies in Western and Northern Europe leading the trend (EIB 2022).

[14] The presence of information asymmetry and uncertainty of returns makes it difficult for firms to evaluate and forecast the profitability of an investment in a specific technology. The assumption, therefore, acknowledges that the strategy to simply compare the returns/ profits of competitors, which had already invested in this technology, and to imitate their initiatives is less resource and time intensive.

[15] For this reason we refer to them as *structural parameters.*

Table 1 Comparison between neutral and green monetary policy

Type of mon. pol. (p)	x^* (%)	$1-x^*$ (%)	B_G^*	B_N^*	μ_G^* (%)	μ_N^* (%)
Neutral $(p=1)$	36.8	63.2	51, 579	88, 421	4.46	4.52
Green $(p=1.1)$	40.9	59.1	54, 473	85, 527	4.22	4.68



Source: EIBIS 2021, EIBIS 2020

Note: The base is all firms (data not shown for those who said do not know/refused to answer)

Question: Has your company already invested to tackle the impacts of weather events and reduce carbon emissions?

Fig. 2 Firms (in %) investing or planning to invest in climate-related measures

$$E_G(t) = a_G\, y(t) - \frac{b_G}{2}\, y(t)^2 \tag{24a}$$

$$E_N(t) = a_N\, [1 - y(t)] - \frac{b_N}{2}\, [1 - y(t)]^2 \tag{24b}$$

Given the large number of firms in the economy and the relatively low (compared to the aggregate bonds supplies in the market of Eqs. 2a, 3a) supply of bonds of each firm, we can safely assume they are price-takers in the bonds markets. It follows that, at each time t, firms can issue either a green bond at a constant interest rate μ_G^* to finance investment in the green technology G, or they can issue a non-green/conventional bond at a constant interest rate μ_N^* to finance investment in the non-green technology N.[16] The cost of the two alternative types of bonds is determined by the portfolio optimization problem of the monetary authority in relation to its

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[16] Here we do not consider the phenomenon of green-washing, in which some firms issue green bonds to bear a lower financing cost, but they employ the proceeds in non-green investment.

policy and defined by (21). For the sake of simplicity and to ensure equivalence of the two firms' investment opportunities, both types of bonds are assumed to have the same maturity (e.g., one year). This does not alter by any means the conclusion. As a result, the borrowing cost of a firm is given by the principal amount to be reimbursed at maturity (i.e., after a year), which coincides with the value of the investment, and the (fixed) interest rate μ_G^* or μ_N^* on this debt,[17]

$$C_G(t) = y(t)\,(\mu_G^* + 1) \tag{25a}$$

$$C_N(t) = [1 - y(t)]\,(\mu_N^* + 1) \tag{25b}$$

Considering both the total earnings from the investment (24a), (24b) and the corporate bond cost (25a), (25b), we define the firms' return on green investment $\pi_G(y)$ as a function of the share of green investment in the industry at time t, and the firms' return on non-green investment $\pi_N(1-y)$ as a function of the share of non-green investment at time t,[18]

$$\pi_G(y) = a_G\, y - \frac{b_G}{2}\, y^2 - (\mu_G^* + 1)\, y \tag{26a}$$

$$\pi_N(1-y) = a_N\,(1-y) - \frac{b_N}{2}\,(1-y)^2 - (\mu_N^* + 1)\,(1-y) \tag{26b}$$

The CB corporate bonds purchase program can follow the *neutral monetary policy* or the *green monetary policy* framework. The type of program undertaken by the CB affects the relative bonds' cost μ_G^* and μ_N^* [see Eqs. (21a),(21b)], and therefore, the firms' decision to invest in environmental-friendly technology.

The decision of the firms to invest in the green technology $y \in [0,1]$ is assumed to evolve in discrete time, according to an exponential replicator dynamics R, as in Cabrales and Sobel (1992):

$$y(t+1) = f(y(t)) = (1-\eta)\,y(t) + \eta\,\frac{y(t)}{y(t) + (1-y(t))\,e^{-\gamma\, g(y(t))}} \tag{27}$$

The dynamic model (27) describes the time evolution of the green investment share by introducing adaptive adjustments based on a direct comparison of the expected firm's return on investment:

$$g(y(t)) = \pi_G(y(t)) - \pi_N(1 - y(t)) \tag{28}$$

According to (27) and (28), the share of green investment y increases (decreases) in period $t+1$ when a firm's return on green investment is higher (lower) than the return on non-green investment during period t (each year).

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[17] Since the maturity of green and non-green corporate bonds is the same, it is sufficient to compare firm' borrowing cost in only one period of time, typically a year.

[18] For sake of brevity we omit t in Eqs. (26a), (26b).

The parameter $\gamma > 0$ represents the firms' sensitivity to profit differentials and captures the intensity of choice, i.e.,: it expresses the firms' ability and propensity to switch to the alternative manufacturing technology as a profit gain is observed in the current time period. The γ parameter is related to the visibility of profit differentials as well as the adjustment costs and the irreversibility of investment[19]; indeed, switching technology might be very expensive. Thus, the larger the adjustment costs, the lower the value of γ and firms' ability to switch technology of production, *ceteris paribus*.[20]

Equation (27) also captures the level of inertia as a consequence of the degree of competitiveness between firms, measured by the parameter $0 \leq \eta \leq 1$. For $\eta \to 0$, the firms of the industry have the highest degree of inertia. In this case, investment choices do not change over time, since $y(t+1) = y(t) = y(0)$; while for $\eta \to 1$, no anchoring exists, since a firm's survival critically depends on quickly adopting the most profitable technology of production, i.e., $y(t) \to 1$ if $g(y) > 0$ and $y(t) \to 0$ if $g(y) < 0$. Industries with higher degrees of market concentration and larger numbers of older firms are, therefore, expected to show lower levels of η compared to highly competitive and emerging markets in which mainly small startups compete.

4.1 Analysis

Since $y(0) \in [0;1]$ then $y(t) \in [0;1]$ for each $t \geq 0$, as it follows from the inequality $0 \leq \frac{y}{y+(1-y)\,e^{-\gamma\, g(y)}} \leq 1$. Additionally, it is straightforward to see that two pure fixed points exist at $y^* = 0$ and $y^* = 1$ (i.e., *pure equilibria*), where "all firms invest in non-green technology N" and "all firms invest in green technology G", respectively. The interior fixed points (i.e., *mixed equilibria*) are then given by the solution to $g(y^*) = 0$ in (28). Solving for $\pi_G = \pi_N$ with respect to y, we obtain the position of the interior fixed points at[21]:

$$y^*_{1,2} = \frac{c \pm \sqrt{c^2 - 4d\left(1 - a_N + \frac{b_N}{2} + \mu^*_N\right)}}{2d} \tag{29a}$$

$$\text{where } c = 2 - a_G - a_N + b_N + \mu^*_G + \mu^*_N \tag{29b}$$

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[19] It is determined by whether once installed, capital has little or no value unless used in production (Bertola 1998), its industry or firm-specificity (Pindyck 1991), and as a consequence its intangibility, the difficulty of re-employment, market imperfections (Calcagnini et al. 2019).

[20] In the model, a period might be considered one year.

[21] Since (26a) and (26b) are second degree polynomials, only none, one or two interior fixed points exist.

$$d = \frac{1}{2}\left(b_N - b_G\right) \tag{29c}$$

and μ_G^* and μ_N^* are given by (21a) and (21b), respectively.

The two interior fixed points exist if and only if $0 < y_{1,2}^* < 1$ and the discriminant $\Delta = c^2 - 4d\left(1 - a_N + \frac{b_N}{2} + \mu_N^*\right) > 0$.

The asymptotic stability of the fixed points in discrete time is given by condition $-1 < R'(y^*) < 1$, where $R'(y^*)$ is the derivative of (27) at fixed point y^*.[22] The derivatives $R'(y^*)$ at each of the four fixed points are:

$$R'(0) = 1 - \eta\left(1 - e^{\gamma\left(1 - a_N + \frac{b_N}{2} + \mu_N^*\right)}\right) \tag{30a}$$

$$R'(1) = 1 - \eta\left(1 - e^{\gamma\left(1 - a_G + \frac{b_G}{2} + \mu_G^*\right)}\right) \tag{30b}$$

$$R'(y_1^*) = 1 - \frac{\gamma\eta r(r - c)(c - 2d - r)}{4d^2} \tag{30c}$$

$$R'(y_2^*) = 1 - \frac{\gamma\eta r(r + c)(c - 2d + r)}{4d^2} \tag{30d}$$

with $r = \sqrt{\left(b_G - b_N\right)\left(2 - 2a_N + b_N + \mu_N\right) + c^2}$ and μ_G^* and μ_N^* are given by (21a) and (21b), respectively.

Given the complexity of the derivatives, we cannot derive analytical conditions in terms of the model parameters. We, therefore, numerically explore the dynamical proprieties of the system (27) when parameters change to infer relevant economic implications. In particular, we will define four scenarios with at least one internal equilibrium for different values of the *structural parameters* that define the characteristic of the manufacturing technology $i = G(t), N(t)$ of the industry: a_G, a_N, b_G, b_N .[23] We take the parameter values in Table 1 as a benchmark case for a *neutral monetary policy* setting and investigate how a change in p influences the share of green and non-green investment in the industry.

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[22] The stability condition includes both an upper and a lower threshold for the slope of the non-linear function R at the equilibrium point, and the two limiting values -1 and $+1$ constitute two different conditions of non-hyperbolicity of the fixed point. When the condition of non-hyperbolicity $R'(y^*) = 1$ is crossed, as parameters vary, potentially three bifurcations can occur: fold, transcritical (or stability exchange) and pitchfork bifurcation. The bifurcation occurring at $R'(y^*) = -1$ is denoted as flip, at which the fixed point changes its oscillatory stability (i.e., convergence through damped oscillations) into oscillatory instability (i.e., trajectories starting close to y^* exhibit oscillatory expansion).

[23] We will ignore those scenarios in which only *pure equilibria* exist, i.e., the industry invests fully in green or non-green technology because a technology is (always) more profitable than the other, independently from the sector starting conditions.

4.2 Unstable internal equilibrium and path dependency

We start with the easiest scenario in which one internal unstable fixed point exists at $y_1^* = 0.569$ ($R'(y_1^*) = 7.30$). The pure equilibria at $y^* = 0$, ($R'(0) = 0.40$) and $y^* = 1$ ($R'(1) = 0.40$) are stable. The time series plot in Fig. 3a shows that the interior equilibrium is a separatrix and defines the basins of attraction of the two attracting pure equilibria.[24] Starting from the initial condition (i.c) $y_o = 0.56$ at which 56% of the investment in the industry is in green technology and the remaining 44% is in the conventional non-green technology, the time series shown in red and given by (27), converges to $y^* = 0$. All the firms of the sector eventually invest in non-green technology in the long-run. This holds for all $y_o < y_1^*$ as highlighted by the arrows in the phase plot of Fig. 3b. For all $y_o > y_1^*$ (such as $y_o = 0.57$ of the blue time series in Fig. 3a), R converges to $y^* = 1$, i.e., all the companies invest in green technology after a certain period of time t.

In the former case, in Fig. 4a, profits from green investment are $\pi_G = 0$, while the all non-green investment generates an equilibrium profit $\pi_N = 0.046$. Figure 4b shows the latter case in which the all green investment leads to a profit of $\pi_G = 0.055$ at equilibrium, and non-green profits are $\pi_N = 0$ in the long-run.

This scenario is characterized by a strong path dependency: if a large share of firms employed non-green technology, no investment in green technology occurs in the long-run, while if a critical share of the firms already invested in green technology, eventually the entire firm population will adopt the latter technology. Furthermore, note that the all non-green investment equilibrium is Pareto inefficient in terms of profits compared to the all green investment equilibrium (i.e., $0.046 < 0.055$). This constitutes a *technology trap*, where all the firms in the sector are stuck with a sub-optimal choice.

CSPP monetary policy can be used to help the industry leave a *technology trap*. This is demonstrated by the bifurcation diagram for the parameter p in Fig. 5.[25] In the previous scenario, the CB ran a neutral monetary policy (i.e., $p = 1$). By increasing p, the monetary authority moves toward a green monetary policy and reduces the cost of corporate green bonds. Consequently, increasing p shifts the internal equilibrium and increases the basin of attraction of the all green investment. At $y_o = 0.56$, a value of $p = 1.04$ now leads to a convergence toward the all green investment equilibrium. For higher p values, lower initial conditions converge to the same equilibrium.

4.3 Stable internal equilibrium and transition to deterministic chaos

We consider the case with only one internal equilibrium $y_1^* = 0.763$, which is stable ($R'(y_1^*) = 0.47$). The two pure equilibria are unstable ($R'(0) = 12.60, R'(1) = 2.45$).

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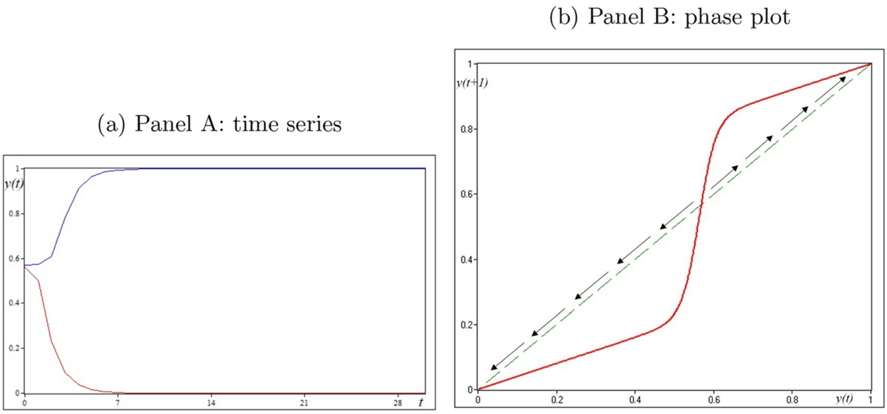
[24] All the time series plots hereinafter are computed over a time span of 30 periods.

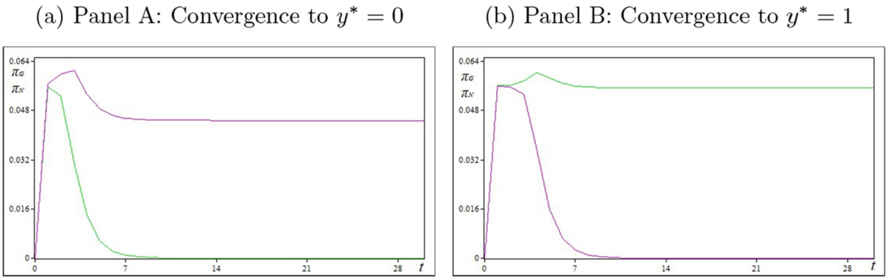
[25] In dynamical systems, a bifurcation diagram shows the values visited or approached asymptotically (fixed points, periodic orbits, or chaotic attractors) of a system as a function of a bifurcation parameter in the system.



(a) Panel A: time series

(b) Panel B: phase plot

Fig. 3 Scenario of unstable internal equilibrium $y_1^* = 0.569$. Parameters: $a_G = 1.2, a_N = 1.24, b_G = 0.2, b_N = 0.3, \eta = 0.6, \gamma = 50, \alpha = 2300, \beta = 4000, BT = 140000, \sigma_G = 0.2, \sigma_N = 0.15, \sigma_{G,N} = -0.002, p = 1, r_F = 0.02$. In panel A, for the red time series the initial condition (y_o) is 0.56, for the blue time series $y_o = 0.57$



(a) Panel A: Convergence to $y^* = 0$

(b) Panel B: Convergence to $y^* = 1$

Fig. 4 Profits' evolution. Parameters: same parameters of Fig. 3. In panel A $y_o = 0.56$, in panel B $y_o = 0.57$. The green curve represents green profit π_G, the pink curve non-green profit π_N

Figure 6 highlights the evolution (6a) of the green investment share starting from $y_o = 0.2$. The firm population converges to $y_1^* = 0.76$ (i.e., 76% green technology, 24% non-green technology adoption in the sector). In this case, y_1^* is the unique global attractor of the system and is reached for every $0 < y_o < 1$ (Fig. 6b).

Figure 7 presents the bifurcation diagrams for the standard deviations of green bonds (Fig. 7a), non-green bonds (Fig. 7b), and the covariance between the two typology of bonds (Fig. 7c).[26] An increase in the average financial risk of green bonds σ_G translates into a lower share of these assets in the CB portfolio, and it leads to a rise in the cost of borrowing for these firms. Consequently, the share of green investment gradually falls at the equilibrium (Fig. 7a). The opposite holds for an increase in average financial risk of non-green bonds σ_N as shown in Fig. 7b. The

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[26] The range of variation of the parameters in this Figure and in all the subsequent bifurcation diagrams is subject to conditions in Eqs. (4), (9), (10), (13).

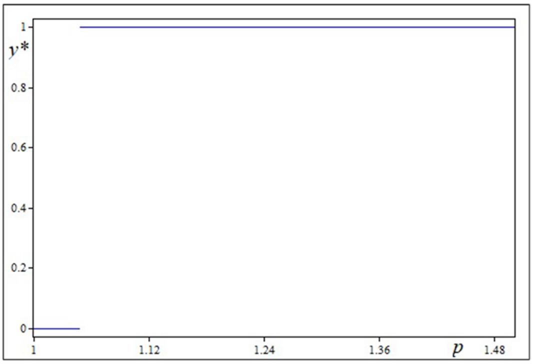
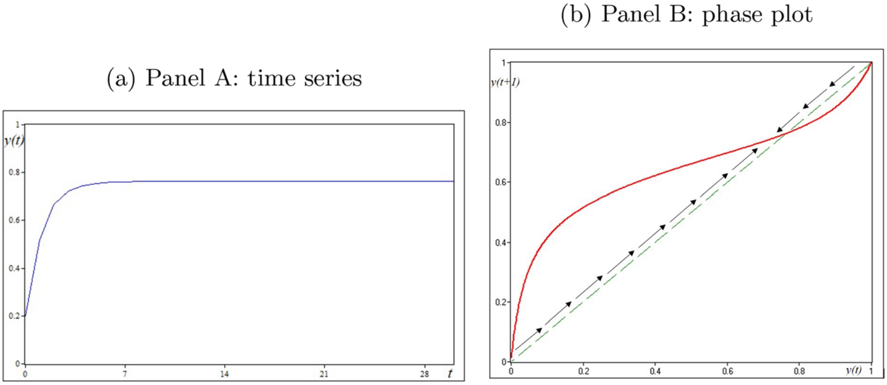


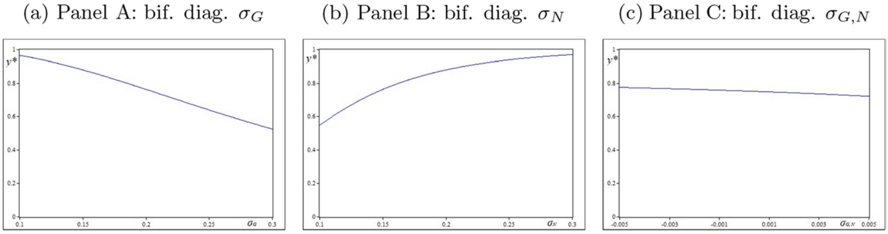
Fig. 5 Bifurcation diagram for p. Parameters: same parameters of Fig. 3 and $y_o = 0.56$



(a) Panel A: time series

(b) Panel B: phase plot

Fig. 6 Scenario of unique stable equilibrium $y_1^* = 0.76$. Parameters: $a_G = 1.22, a_N = 1.16, b_G = 0.4, b_N = 0.35, \eta = 0.6, \gamma = 50, \alpha = 2300, \beta = 4000, BT = 140000, \sigma_G = 0.2, \sigma_N = 0.15, \sigma_{G,N} = -0.002, p = 1, p = 1, r_F = 0.02$ and $y_o = 0.2$

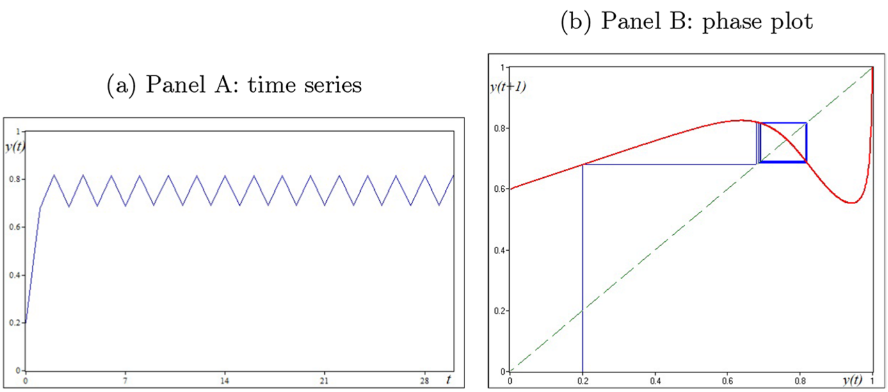


(a) Panel A: bif. diag. σ_G

(b) Panel B: bif. diag. σ_N

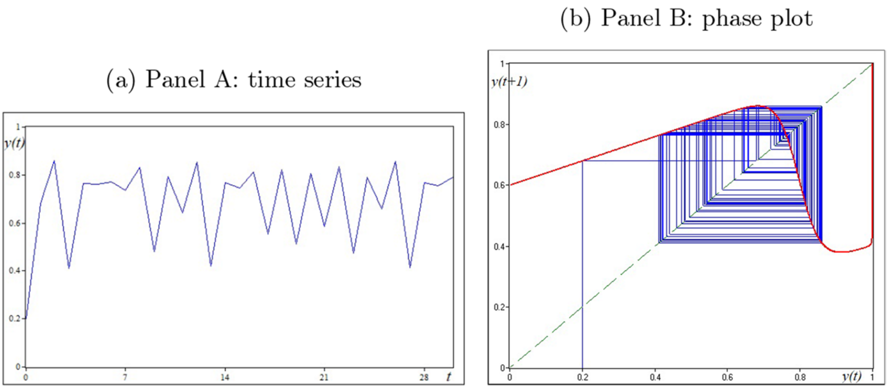
(c) Panel C: bif. diag. $\sigma_{G,N}$

Fig. 7 Bifurcation diagrams for variances. Parameters: same parameters and y_o of Fig. 6


(a) Panel A: time series

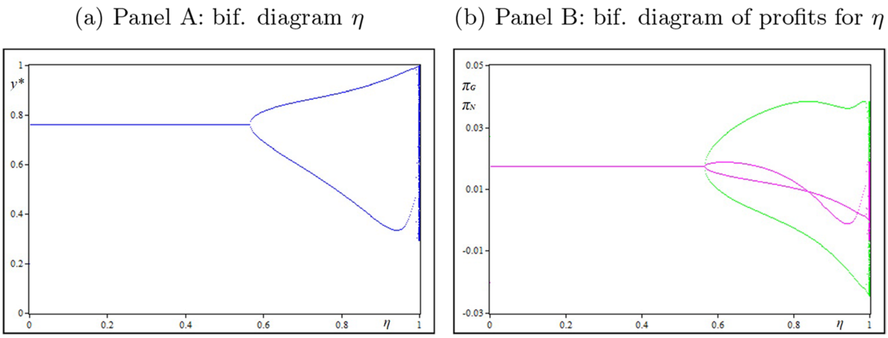
(b) Panel B: phase plot

Fig. 8 Convergence toward a cycle-2 period. Parameters: same parameters and y_o of Fig. 6, except for $\gamma = 200$


(a) Panel A: time series

(b) Panel B: phase plot

Fig. 9 Convergence toward a deterministic chaos region. Parameters: same parameters and y_o of Fig. 6, except for $\gamma = 400$


(a) Panel A: bif. diagram η

(b) Panel B: bif. diagram of profits for η

Fig. 10 Bifurcation diagrams for η. Parameters: same parameters and y_o of Fig. 8. In panel B, the green curve represents green profit π_G, the pink curve non-green profit π_N

share of green investment rises and the share of non-green investment falls. Lastly, increasing the covariance $\sigma_{G,N}$ from a negative correlation to a positive correlation slightly decreases the share of green investment at the equilibrium (Fig. 7c).

Note that Fig. 6 is obtained given a low sensitivity to payoff differentials in the industry: $\gamma = 50$. Starting with the same parameter values and initial condition, Fig. 8 demonstrates that an increase in the sensitivity to payoff differentials ($\gamma = 200$) following a reduction in adjustment costs due to e.g., market deregulation (credit, product, and labor markets among others) causes systemic instability, creating a cycle of period 2. The firm population periodically shifts between $y = 0.69$ and $y = 0.82$ as shown in Fig. 8a and in the phase plot of Fig. 8b.[27] In economic terms, lower adjustment costs cause a larger share of firms to switch to the alternative technology in each period.[28]

Further increasing γ to 400 leads to the creation of a region of deterministic chaos in Fig. 9b.[29] We should specify that high values of γ (e.g., $\gamma > 300$), as in this instance, are associated with cases of adjustment costs that tend to zero and full reversibility of investments. For these reasons, the scenario depicted in Fig. 9 is more hypothetical than a realistic dynamics noticeable in industries. Nonetheless, from a policy makers perspective, it is relevant to point out that such dynamics could potentially arise in a few extreme cases. In this particular example, the time evolution of the green investment share is erratic (see Fig. 9a). The economic consequence of such erratic motion is a low level of predictability regarding the proportion of each manufacturing technology adopted in the sector. Furthermore, an (almost) zero switching cost generates an even greater share of firms that change investment decisions in each period (Fig. 9a) when compared to the time series in Fig. 8a.

Starting from the scenario of the cycle-2 period in Figs. 8 and 10a plots the bifurcation diagram for various values of η, *ceteris paribus*. For low values of η, and thus low market competition, the firm population converges to a single interior equilibrium. Bifurcations occur for values of η exceeding 0.55, leading to the cycle of period 2 observed in Fig. 8 with $\eta = 0.6$. For higher values of market competition, the periodic shift between the two equilibria gradually increases in amplitude with a greater share of firms that changes investment decision in every period. Figure 10b shows the corresponding average profits for both technologies. We can see that the periodic shifts at higher η are caused by periodic shifts in the firm profits associated with each technology, rendering green investment more profitable in the current period and non-green investment more profitable in the next. At very high levels of

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[27] The phase plot shows that the point where the system (in red) intercepts the bisector is the same. However, the increase of γ warps R, lower the point derivative at the previous equilibrium to less than -1. The system undergoes a flip bifurcation.

[28] This is caused by a periodic shift in the profits associated with each technology. While not shown here, we demonstrate this in Fig. 10b for the same set of parameters.

[29] The chaotic attractor characterizes a system that is sensitive dependent on initial conditions (see e.g., Devaney 1986; Lorenz 1989; Medio and Lines 2001).

competition (for $\eta \to 1$), profits start to exhibit a chaotic behavior similar to what Fig. 9 highlights.

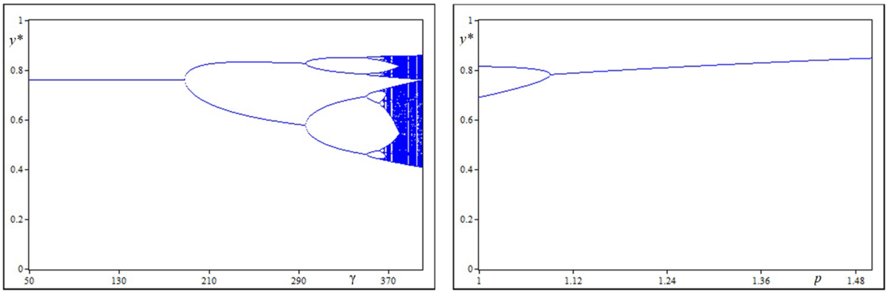
Figure 11a shows the bifurcation diagram for different rates of sensitivity γ, *ceteris paribus*. Here, we observe an effect similar to higher levels of competition. The system bifurcates as the sensitivity increases, eventually leading to chaotic behavior at $\gamma = 400$ as demonstrated in Fig. 9.

Note that a green monetary policy can stabilize investment decisions. Figure 11b shows the impact of p starting from the neutral monetary scenario of Fig. 8. Values of p exceeding 1.1 stabilize technology adoption in the industry, switching from the initial periodic behavior of the industry to a unique stable equilibrium. It follows that in scenarios characterized by periodic (or even chaotic) behavior of investment decisions, a *green monetary policy* can not only increase the share of firms employing the green manufacturing technology in the industry but also help to stabilize the investment decisions, i.e., reducing the share of firms that switches from one manufacturing technology to the other in each period up to the point where only one equilibrium is reached in the long-run.

4.4 Two internal equilibria (unstable and stable)

Figure 12 shows the case of two internal equilibria: the first $y_1^* = 0.377$ is unstable ($R'(y_1^*) = 1.25$), the second $y_2^* = 0.631$ is stable ($R'(y_2^*) = 0.75$), and correspondingly equilibrium $y^* = 0$ is stable ($R'(0) = 0.47$) and $y^* = 1$ is unstable ($R'(1) = 3.08$). Figure 12a shows two time series: the red starts from $y_o = 0.2$ and converges quite rapidly to the equilibrium of all non-green investment $y^* = 0$, whereas the blue starts from $y_o = 0.5$ and converges after a relatively longer period of time to the mixed (or internal) stable equilibrium $y_2^* = 0.63$ where 63% of the firms in the industry employ green technology. The corresponding phase plot is given in Fig. 12b, showing the path dependency of the system. A critical share of at least 37.7% of firms adopting green technology is needed to converge to the upper equilibrium. Any initial condition with fewer firms will remain trapped at the lower equilibrium at which no firm adopts a green technology. Figure 12c and d illustrate the firm profits if the population converges to the low or high stable equilibrium, respectively. The low equilibrium is Pareto inefficient and constitutes a *technology trap*.

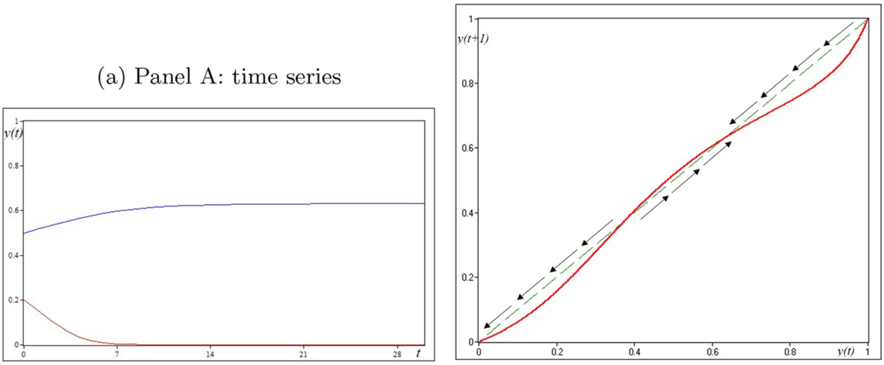
As pointed out in Schaffer (1989); Radi (2017); Radi et al. (2021) these counterintuitive results arise from the imitation process based on profit differentials and find an explanation in terms of 'spiteful' behaviors, i.e., a strategy is played just because it damages competitors more than their own firm. In this particular scenario, even if profits are greater for both types of investment at the high equilibrium (Fig. 12d), the existence of a critical share of firms adopting the non-green technology makes firms willingly to continue with the sub-optimal strategy because the profits gain obtained by green competitors moving to the high equilibrium would be greater than the profit gain potentially achievable by non-green firms, i.e., this sub-optimal strategy (Fig. 12c) damages more my competitor (green firms).



(a) Panel A: bif. diagram γ

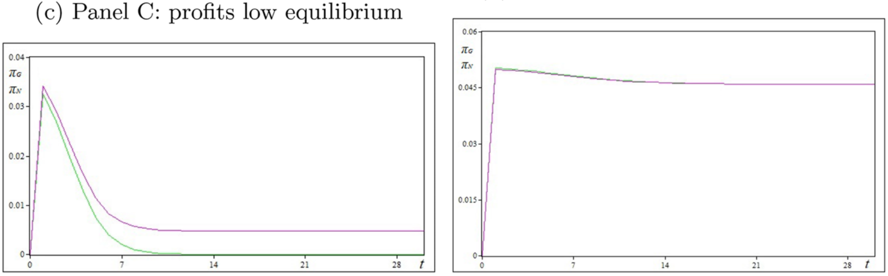
(b) Panel B: bif. diagram p

Fig. 11 Bifurcation diagrams for relevant parameters. Parameters: same parameters and y_o of Fig. 8



(a) Panel A: time series

(b) Panel B: phase plot

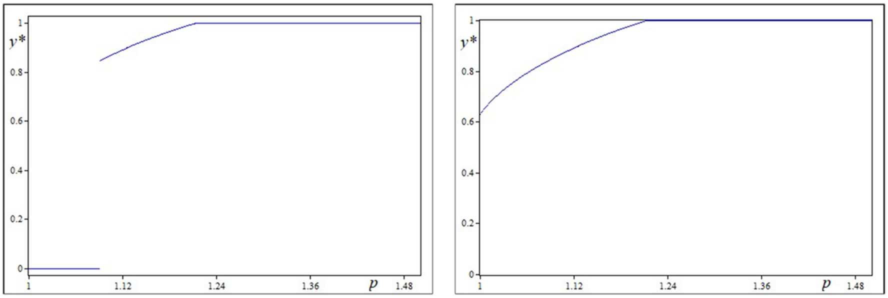


(c) Panel C: profits low equilibrium

(d) Panel D: profits high equilibrium

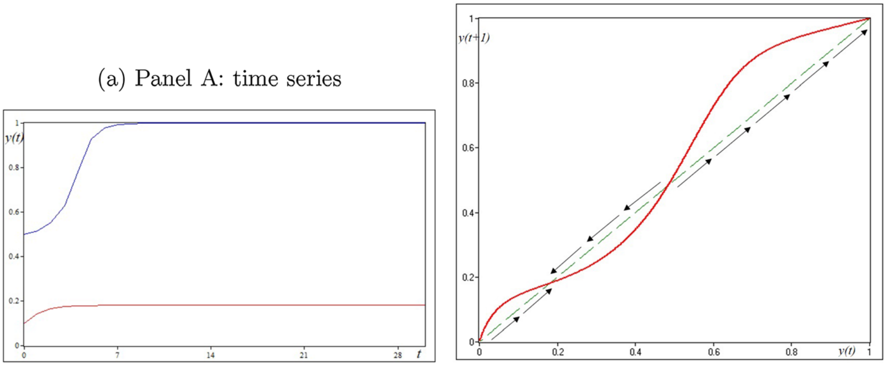
Fig. 12 Scenario of two stable equilibria $y^* = 0$, $y_2^* = 0.63$. Parameters: $a_G = 1.25, a_N = 1.24, b_G = 0.42, b_N = 0.38, \eta = 0.8, \gamma = 200, \alpha = 2300, \beta = 4000, BT = 140000, \sigma_G = 0.2, \sigma_N = 0.15, \sigma_{G,N} = -0.002, p = 1, r_F = 0.02$. In panel A, for the red time series the initial condition (y_o) is 0.2, for the blue time series $y_o = 0.5$. In panel C $y_o = 0.2$, in panel D $y_o = 0.5$. The green curve represents green profit π_G, the pink curve non-green profit π_N

A green policy by the CB can then help escape this trap as highlighted in Fig. 13. The bifurcation diagram of Fig. 13a corresponds to the case of the red time series


(a) Panel A: $y_o = 0.2$

(b) Panel B: $y_o = 0.5$

Fig. 13 Bifurcation diagram for p. Parameters: same parameters of Fig. 12


(b) Panel B: phase plot

(a) Panel A: time series

(c) Panel C: profits low equilibrium

(d) Panel D: profits high equilibrium

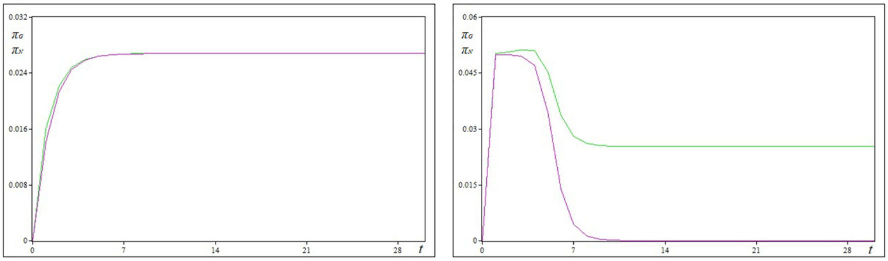


Fig. 14 Scenario of two stable equilibria $y^* = 0.18$, $y^* = 1$. Parameters: $a_G = 1.22, a_N = 1.25, b_G = 0.3, b_N = 0.42, \eta = 0.8, \gamma = 200, \alpha = 2300, \beta = 4000, BT = 140000, \sigma_G = 0.2, \sigma_N = 0.15, \sigma_{G,N} = -0.002, p = 1, r_F = 0.02$. In panel A, for the red time series the initial condition (y_o) is 0.1, for the blue time series $y_o = 0.5$. In panel C $y_o = 0.1$, in panel D $y_o = 0.5$. The green curve represents green profit π_G, the pink curve non-green profit π_N

in Fig. 12a. Indeed, for a *neutral monetary policy* ($p = 1$) the equilibrium value is $y^* = 0$. A *green monetary policy* that progressively augments p causes the firm population to escape the trap. At $p \approx 1.10$, the population shifts from the low to the high equilibrium. To a lesser extent, the beneficial effect can also be observed if the firm population has a critical number of firms, which initially adopt a green technology. However, increasing p does not lead to a shift between the equilibria, but a higher interior equilibrium value. Figure 13b shows the the situation for an initial condition of 0.5, where the industry is already on the socially optimal equilibrium. Here, moving to a *green monetary policy* ($1 < p < 1.21$) increases the initial mixed equilibrium value from $y_2^* = 0.63$ to $y^* = 1$ for $p > 1.21$.

4.5 Two internal equilibria (stable and unstable)

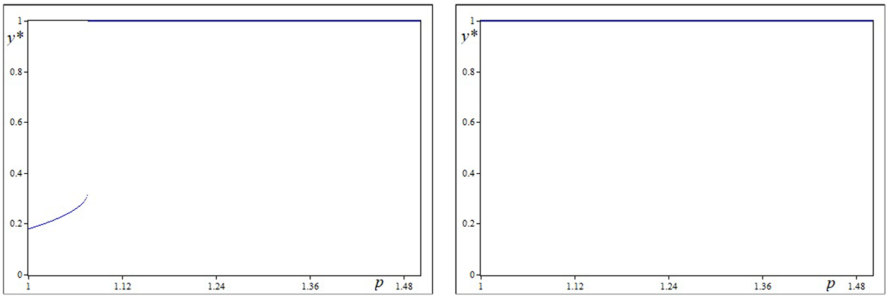
The last relevant scenario is characterized again by two internal equilibria, but with opposite stability properties: the lower interior equilibrium $y_1^* = 0.181$ is stable ($R'(y_1^*) = 0.44$), the second interior equilibrium $y_2^* = 0.480$ is unstable ($R'(y_2^*) = 1.95$), while $y^* = 0$ is unstable ($R'(0) = 3.67$) and $y^* = 1$ is stable ($R'(1) = 0.30$). The scenario is depicted in Fig. 14.

In Fig. 14a, the red time series starts from $y_o = 0.1$ and converges quite rapidly to the lower mixed equilibrium, whereas the blue starts at $y_o = 0.5$ and approaches, after a relatively long period of time, the equilibrium of all green investment $y^* = 1$. The internal unstable equilibrium $y_2^* = 0.48$ define the separatrix between the two basins of attractions, is shown in Fig. 14b. As previously stressed, the path dependence phenomenon can be better visualized from the phase plot, where for all $y_o < y_2^*$ the interior equilibrium $y_1^* = 0.18$ is reached, while for all $y_o > y_2^*$ the pure equilibrium $y^* = 1$ is attained in the long run. The possibility of having two fixed points depending on the initial state of the industry translates into different profit evolution. In Fig. 14c, the firm population converges to the lower mixed equilibrium. Profits for both technologies are equal at 0.027. In Fig. 14d, the entire population eventually only adopts the green technology. Green profits π_G converge to the same profit at 0.027. In this particular scenario, no Pareto inefficient allocation occurs and the green monetary policy of the CB does not affect profits.

However, in this scenario, *green monetary policy* CSPP is still useful to encourage the adoption of green technology. The bifurcation diagrams in Fig. 15 demonstrate the impact of p in both scenarios, respectively. While the policy does not contribute to firm payoffs in the high equilibrium scenario (Fig. 15b), increasing p beyond 1.10 helps the firm population to move from the low equilibrium to the high equilibrium (Fig. 15a).

5 Conclusion

In recent years, it has become increasingly evident that climate change is one of the main sources of structural change that impacts the financial system. While the impact and the time horizon is difficult to estimate, it is evident that a combination of physical and transitional risks will materialize in the near future that will negatively affect the stability of the financial and economic systems. Therefore, CBs have starting to consider risks related to climate change with the aim of strengthening the role of the


(a) Panel A: $y_o = 0.1$

(b) Panel B: $y_o = 0.5$

Fig. 15 Bifurcation diagram for p. Parameters: same parameters of Fig. 14

financial system to manage risk and mobilize capital for green and low-carbon investments in the broader context of environmentally sustainable development.

In this paper, we developed a model of CSPP that internalizes climate-related externalities by means of a tilting factor that governs the share of green and non-green bonds in the the CB's portfolio. We showed generally that a shift in the CB portfolio allocation toward bonds issued by low-carbon companies can favor green firms on the market. To explore the dynamics of such a shift in detail, we modeled firm investment choices using an exponential replicator dynamics and numerically explored the dynamical proprieties of the system.

We showed that green and non-green bond riskiness is a key factor that impacts borrowing costs. Financial risk and environmental risk thereby constitute substitutes. Empirical evidence shows that brown companies demonstrate lower leverage, obtain less bank credit and are charged a higher loan rate (for examples, see Ginglinger and Moreau 2019; Chang et al. 2018; Ghoul et al. 2011). Here, green monetary policy and the issuing of green bonds can support the adoption of green technology (Karpf and Mandel 2018). However, this effect is not universal and exhibits path-dependencies based on the market environment. In these cases, firms fail to adopt green technology even if such technology entails higher profits. This can explain the ambiguous empirical results regarding the performance of green bonds (Schoenmaker 2021; Zhang et al. 2022) as well as the greenium associated with them (Caramichael and Rapp 2022, see also the results of Karpf and Mandel (2018) versus Baker et al. 2018; Chava 2014). Our model also shows scenarios, in which an industry converges to a mixed equilibrium with a limited adoption of green technology. While empirical evidence is scanty (Bryan 2023; Alloway 2023), such a scenario is characterized by the lower than anticipated adoption of green technology, leading to situations of growing concern of investors and dwindling sales of these bonds. Evidence from China shows that non-heavily polluting as well as less environmentally regulated industries benefit more strongly from green bonds than older, heavily polluting industries (Zhang et al. 2022). This supports the model's result that the sensitivity to profit differentials and the market structure plays a role in the effectiveness of green bonds to encourage investment in environmentally-friendly technologies (see also

Caramichael and Rapp 2022). Similarly, the lack of transparency can obstruct the effectiveness of green bonds on firm financing (D'Arcangelo et al. 2023).

Our future research agenda aims at studying two possible extensions. Firstly, we plan to study a model that incorporates the risk of green-washing. A second extension takes into account the interaction between the green monetary CSPP and fiscal policies.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare.

Consent to publication All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

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