Assessing the Dual Mandates of Sustainability-Linked Monetary Policy

Ammu George Jingong Huang Taojun Xie*

June 6, 2022

Abstract

Central banks are now playing their part in promoting environmental sustainability. We incorporate a sustainability-linked monetary policy (SLMP), comprising an interest rate and a collateral constraint responding to carbon emission activity, into a two-agent New Keynesian model featuring direct lending. Our simulations find that shocks from supply and demand sides result in opposing effects on carbon emissions. In either case, the SLMP enhances social welfare and promotes environmental sustainability. We also find distributional effects on the welfare at the social optimum: In the presence of both demand and supply shocks, the entrepreneurs gain when a sustainability-linked interest rate is implemented, whereas the savers gain when a sustainability-linked collateral constraint is implemented.

Keywords: Sustainability, Monetary policy, New Keynesian model, Environmental policy, Central bank, Green finance

JEL Codes: E32, E50, Q58

*George and Xie: Asia Competitiveness Institute, Lee Kuan Yew School of Public Policy, National University of Singapore. 469C Bukit Timah Road, Singapore 259772. Huang: School of Economics & CSET, University of Nottingham at Ningbo China. 199 Taikang East Road, Yinzhou District, Ningbo, Zhejiang Province, China 315000. Huang: Corresponding author, Email: Jingong.Huang@nottingham.edu.cn. Declarations of interest: none. Financial disclosure: none.

1 Introduction

In recent years, environmental sustainability has received growing attention from policymakers (Dikau and Volz, 2021; Muller, 2021; Annicchiarico et al., 2021). There is a growing debate on whether central banks and financial institutions should step in to address risks associated with climate change and support the development of green finance. On the one hand, there are opposing voices towards the central banks' involvements in greening the economy, arguing that green monetary policies can potentially violate central bank neutrality. On the other hand, supporters contend that climate risks are intrinsically related to economic activities and financial stability, thus playing an important role in shaping central banks' traditional mandate of moderating business cycles. Therefore, designing monetary policies without taking into account the potential implications of climate risks are inefficient. Based on these considerations, a group of Central Banks and Supervisors voluntarily launched the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) to accelerate the scaling up of green finance and develop recommendations for central banks to deal with climate change. Although there is no consensus on the best practice for central banks to manage environmental risks, most policy makers believe that climate risks should not be ignored in the monetary policy design (Dikau and Volz (2021)). Given the complex interaction between climate risks and monetary conduction, it is necessary to have a careful assessment of proposals to incorporate environmental sustainability into monetary policies.

Central banks that are active in promoting environmental sustainability usually roll out a version of the so-called sustainability-linked monetary policy (SLMP) framework, which uses either interest rate or loan-to-value ratio as an instrument to target emission activities (MAS, 2021; LMA, 2019; DBS, 2021; BOJ, 2021; Mizuho, 2021). These monetary policy tools aim to influence the liquidity provided to the producers in order to encourage greener productions. However, the welfare implications of such policies remain unclear. This paper aims to shed light on this issue.

Specifically, we introduce a toolkit for the SLMP to a New Keynesian dynamic stochastic general equilibrium (DSGE) model. The toolkit comprises a Taylor-type interest rate rule and a time-varying loan-to-value ratio (LTVR) limit. Depending on the environmental policy and the central bank's choice, either the interest rate rule or the LTVR can respond to carbon emissions. Our model features two types of households: savers and entrepreneurs. The former save and provide loans to the latter who use these loans for consumption and investment. There are two types of capitals: (1) dirty capital produces air pollution; and (2) clean capital does not. Firms use both types of capitals for production and endogenously choose the abatement effort to reduce carbon emissions.

We evaluate the welfare performance of the sustainability-linked monetary policies using households' discounted lifetime utility as a measurement. In general, economic agents are in favor of a stable macroeconomic environment, as it reduces uncertainty when households and firms plan their future consumption and investments. As shown by Woodford (2003), this lower uncertainty translates into higher welfare for the agents. Therefore, central banks can potentially influence the social welfare by fine-tuning their policy parameters to reduce uncertainty. The focus of this paper is thus placed on searching the optimal policy response coefficients, that maximize the social welfare, and investigating whether the SLMP improves welfare compared to the traditional monetary policy without targeting environmental sustainability.

Through the examination of various environmental-monetary policy combinations, we find that regardless of environmental policies, the SLMP with the optimal response coefficients is always able to enhance welfare and promote environmental sustainability under both the supply and demand shocks, compared to a benchmark case without the SLMP. There are, however, differences of welfare performance between the two instruments of the SLMP. The sustainability-linked interest rate tends to outperform the sustainability-linked LTVR under the consumption preference shock, while the reverse is true under the productivity shock. We also find that there exists a range of parameter values that enable the SLMP to deliver Pareto improvements for all agents' welfare. Lastly, we simulate the impulse response functions of our model to study the dynamics of the economy. An interesting finding emerges from our analysis: depending on the nature of shocks, carbon emissions can be either pro-cyclical or counter-cyclical, rendering the relationship between output and carbon emissions ambiguous.

In the remainder of this paper, we provide a brief literature review in Section 2. Section 3 describes our model in detail. We then discuss the welfare analysis and equilibrium dynamics in Sections 4 and 5 respectively, followed by the conclusion in Section 6.

2 Related Literature

Our study contributes to several strands of literature. One strand of literature identifies the non-negligible implications of climate-related risks for monetary policies. While acknowledging that maintaining environmental sustainability is not a mainstream mandate for central banks, the survey conducted by Dikau and Volz (2021) shows that 70 out of 135 central banks have a 'direct' or 'indirect' sustainability mandate. Dikau and Volz (2021) argue that climate-related risks should be incorporated into macro-financial policy frameworks because these risks are directly related to central banks' traditional responsibilities. Supporting this finding, Economides and Xepapadeas (2018) find that climate change has non-trivial implications for the conduct of monetary policy.

Our paper is closely related to the strand of literature aiming to incorporate a climate module into an economic model. Nordhaus (1993) develops the Dynamic Integrated Climate-Economy Model (DICE) to study the dynamics of carbon emissions and climate-change impacts and the economic costs of policies to curb emissions. The key features of this framework were later adopted by Heutel (2012) to study the optimal environmental policies in response to economic fluctuations caused by persistent productivity shocks. A large literature then emerges, focusing on the implications of climate risks on business cycles in different versions of New Keynesian models (Annicchiarico and Di Dio, 2015, 2017; Annicchiarico et al., 2021). Annicchiarico et al. (2022) provide a comprehensive survey of studies on the relationship between business cycles and the design and effects of environmental policies.

Another strand of literature examines how both conventional and unconventional monetary policies can influence climate-related risks. Chen et al. (2021) introduce a climate-augmented Taylor rule which allows the central bank to target the emissions in addition to the traditional inflation target. The authors find such a policy deliver higher welfare under a preference shock. Wang et al. (2021) argue that it is important for the Chinese authorities to weigh on the borrowing constraints in framing the monetary policies. Through a theoretical framework of the central bank's asset purchases, Papoutsi et al. (2021) find that such an unconventional monetary policy affects the climate. Papoutsi et al. (2021) support their theoretical argument with empirical results that shows European Central Bank's corporate bond portfolio tilted towards brown sectors. Another closely related work by Ferrari and Nispi Landi (2020) uses a DSGE model to find that the imperfect substitutability between green and brown bonds is necessary if the central bank wishes to expand the non-polluting sector by temporarily issuing green bonds. The welfare gains of such green bonds are positive but small, and their effect in reducing the pollution stock is also limited. Compared to the previous studies, our paper is one of the first to include both the interest rate and borrowing constraints as policy instruments for the central bank, allowing a direct comparison of their respective welfare impact on the economy.

Our paper is also related to the literature investigating the coordination between monetary and environmental policies. Chan (2020) shows that environmental, fiscal, and monetary policies should be time-varying to stabilize carbon emissions. Annicchiarico and Di Dio (2017) study the mix of monetary and environmental policies. They find that the policy outcomes depend on the availability of policy instruments, the extent of distortions, and their interactions. Our paper has a distinct focus. We aim to examine whether introducing sustainability-linked lending can simultaneously enhance welfare and manage pollution.

3 A sustainability-linked monetary policy framework

Our model features direct lending and a production sector with environmental externalities. There are two types of agents in the economy, savers and entrepreneurs. Savers lend their savings directly to entrepreneurs, who then use the borrowed funds to finance consumption and production. This direct lending channel follows Iacoviello and Neri (2010). It facilitates our evaluations of quantity-based policies through which the central bank intervenes the provision of loans. The profits from production are distributed back to the savers as dividends. Firms use both dirty capital and clean capital to produce output. Clean capital input does not emit carbon dioxide. By contrast, dirty capital input emits carbon dioxide, leading to a negative externality on the environment. Such externalities were first incorporated by Nordhaus (1993) into the DICE (Dynamic Integrated Climate-Economy) model, then adopted by Heutel (2012) and Annicchiarico and Di Dio (2015) respectively. Firms also make decisions on abatement efforts to reduce emissions.

There are two policy options for the environmental agency. The environmental agency can choose to maintain a constant carbon tax (hereafter CC) and allow firms to derive their desired level of emissions. Alternatively, the environmental agency can decide to fix the emission quota through a cap-and-trade policy (hereafter CT), where firms trade the emission permits at market prices. The central bank cooperates with the environmental agency to adopt a version of the SLMP to either influence the entrepreneurs' financing costs or alter the availability of loans.

Savers The economy has a population of unit mass, among which ω are entrepreneurs and $1-\omega$ are savers. A typical saver derives utility from consumption and disutility from labor supply. Her objective is to maximize the lifetime utility:

$$\mathbb{E}_t \sum_{t=0}^{\infty} \beta_s^t u\left(c_{st}, n_{st}\right), \tag{1}$$

where

$$u\left(c_{st}, n_{st}\right) = z_t(1-\upsilon)\log\left[c_{st} - \upsilon c_{st-1}\right] - \mu_n \frac{{n_{st}}^{1+\varphi}}{1+\varphi}. \tag{2}$$

c_{st} is the saver's consumption, n_{st} is the labor supply, β_s is the discount factor of the saver, z_t is a shock to the consumption preference, common across all agents, υ is the degree of internal habit persistence, φ is the inverse of the Frisch elasticity and μ_n is the weight of labor in the saver's utility. Note that we introduce internal habit preferences that make consumption endogenously persistent,which helps improve the business cycle properties of the model (Fuhrer, 2000; Boldrin et al., 2001; Christiano et al., 2005). The budget constraint for the saver in each period is given by:

$$c_{st} + b_{st} = \frac{i_{t-1}}{\pi_t} b_{st-1} + w_t n_{st} + d_t - \tau_t, \tag{3}$$

where b_{st} denotes savings in period t, w_t is the real wage, τ_t is the lump-sum tax collected by the government and d_t captures the dividends from the firms. The savings from the previous period earn a gross nominal interest at the rate i_{t-1}. π_t is the change in general price level between periods $t-1$ and t, i.e $\pi_t \equiv p_t/p_{t-1}$. The first-order conditions for savers are:

$$n_{st} : u_{n_s,t} = -u_{c_s,t} w_t, \tag{4}$$

$$b_{st} : u_{c_s,t} = \beta_s \mathbb{E}_t u_{c_s,t+1} \frac{i_t}{\pi_{t+1}}, \tag{5}$$

where $u_{x,t}$ is the derivative of the period utility function with respect to variable x.

Entrepreneurs Similar to the saver, a representative entrepreneur seeks to maximize her lifetime utility:

$$\mathbb{E}_t \sum_{t=0}^{\infty} \beta_e^t u\left(c_{et}, n_{et}\right), \tag{6}$$

where

$$u\left(c_{et}, n_{et}\right) = z_t(1-\upsilon)\log\left[c_{et} - \upsilon c_{et-1}\right] - \mu_n \frac{{n_{et}}^{1+\varphi}}{1+\varphi}. \tag{7}$$

c_{et} and n_{et} are the consumption and labor supply, and β_e is the discount factor for the entrepreneur. We follow Iacoviello and Neri (2010) to assume that $\beta_s > \beta_e$. The budget constraint for the entrepreneur in period t is:

$$c_{et} + \frac{i_{t-1}}{\pi_t} b_{et-1} + I_{ct} + I_{dt} = b_{et} + w_t n_{et} + r_{ct} k_{ct-1} + r_{dt} k_{dt-1}, \tag{8}$$

where b_{et} is the amount of funds borrowed by the entrepreneur, k_{ct-1} and k_{dt-1} are the end-of-period stock of clean and dirty capital inputs respectively, I_{ct} is the investment in clean capital, I_{dt} is the investment in dirty capital, r_{ct} and r_{dt} are the rental costs of the respective capital inputs. The amount of borrowing is subject to the following collateral constraint:

$$b_{et} \leq \kappa_t \, \mathbb{E}_t \frac{\pi_{t+1} k_t}{i_t}, \tag{9}$$

where $k_t \equiv \left[\gamma^{1/\zeta} k_{dt}^{1-1/\zeta} + (1-\gamma)^{1/\zeta} \left(A_c k_{ct}\right)^{1-1/\zeta}\right]^{\frac{\zeta}{\zeta-1}}$ is a composite of clean and dirty capital used for production with A_c denoting the productive efficiency of clean capital relative to dirty capital. Note that this setup is a departure from the framework in Acemoglu et al. (2012) who model the final good production function with clean and dirty intermediate goods. We assume that the clean and dirty capital inputs are imperfect substitutes. κ_t is a time-varying factor which the social planner uses to limit the amount of loans available to the entrepreneur. It is also referred to as the loan-to-value ratio (LTVR) limit. The evolution of the two types of capital stocks follows:

$$k_{dt} = (1-\delta)k_{dt-1} + \Lambda\left(\frac{I_{dt}}{k_{dt-1}}\right)k_{dt-1}, \tag{10}$$

$$k_{ct} = (1-\delta)k_{ct-1} + \Lambda\left(\frac{I_{ct}}{k_{ct-1}}\right)k_{ct-1}, \tag{11}$$

where δ is the depreciation rate of capital. The adjustment costs of capital, following Jermann (1998), are defined as $\Lambda\left(\frac{I_{dt}}{k_{dt-1}}\right) = \frac{\alpha_1}{1-\zeta^{cost}}\left(\frac{I_{dt}}{k_{dt-1}}\right)^{1-\frac{1}{\zeta^{cost}}} + \alpha_2$ and $\Lambda\left(\frac{I_{ct}}{k_{ct-1}}\right) = \frac{\alpha_1}{1-\zeta^{cost}}\left(\frac{I_{ct}}{k_{ct-1}}\right)^{1-\frac{1}{\zeta^{cost}}} + \alpha_2$. The entrepreneur maximizes Eq. (6) subject to Eqs. (8) to (11). The first-order conditions for entrepreneurs are:

$$n_{et} : u_{n_e,t} = -u_{c_e,t}w_t, \tag{12}$$

$$b_{et} : \lambda_{bt} - \beta_e \mathbb{E}_t u_{c_e,t+1}\frac{i_t}{\pi_{t+1}} = -u_{c_e,t}, \tag{13}$$

$$k_{dt} : \begin{array}{l} \frac{\lambda_{et}}{\Lambda'\left(\frac{I_{dt+1}}{k_{dt}}\right)} - \beta_e \mathbb{E}_t \lambda_{et+1}\left[r_{dt+1} + \frac{1-\delta+\Lambda\left(\frac{I_{dt+1}}{k_{dt}}\right)}{\Lambda'\left(\frac{I_{dt+1}}{k_{dt}}\right)} - \frac{I_{dt+1}}{k_{dt}}\right] \\ = \gamma^{1/\zeta}\left(\frac{k_{dt}}{k_t}\right)^{-1/\zeta}\kappa_t\lambda_{bt}\mathbb{E}_t\frac{\pi_{t+1}}{i_t} \end{array}, \tag{14}$$

$$k_{ct} : \begin{array}{l} \frac{\lambda_{et}}{\Lambda'\left(\frac{I_{ct+1}}{k_{ct}}\right)} - \beta_e \mathbb{E}_t \lambda_{et+1}\left[r_{ct+1} + \frac{1-\delta+\Lambda\left(\frac{I_{ct+1}}{k_{ct}}\right)}{\Lambda'\left(\frac{I_{ct+1}}{k_{ct}}\right)} - \frac{I_{ct+1}}{k_{ct}}\right] \\ = (1-\gamma)^{1/\zeta}\left(\frac{A_L k_{ct}}{k_t}\right)^{-1/\zeta}\kappa_t\lambda_{bt}\mathbb{E}_t\frac{\pi_{t+1}}{i_t} \end{array}, \tag{15}$$

where λ_{bt} is the Lagrangian multiplier of the collateral constraint.

Firms We extend the production sector in Annicchiarico and Di Dio (2015) to distinguish between the clean and dirty capital inputs. A firm producing variety j chooses labor n_{jt}, clean capital k_{cjt-1}, dirty capital k_{djt-1} and the abatement effort v_{jt}, to maximize its profits, taking into account costs of production factors, tax τ_{xt} on carbon emission x_{jt}, and the cost of emission abatement $\mathcal{C}_{Ajt}$:

$$\max_{n_{jt}, k_{cjt-1}, k_{djt-1}, v_{jt}} y_{jt} - w_t n_{jt} - r_{ct}k_{cjt-1} - r_{dt}k_{djt-1} - \tau_{xt}x_{jt} - \mathcal{C}_{Ajt}$$

For each variety j, the production function, carbon emissions, and abatement cost are respectively given by:

$$
\begin{aligned}
y_{jt} &= A_t \left[1 - \Gamma\left(m_t\right)\right] n_{jt}^{1-\alpha} k_{jt-1}^{\alpha}, \\
x_{jt} &= \left[1 - v_{jt}\right] \phi_d k_{djt-1}, \\
\mathcal{C}_{Ajt} &= \phi_1 {v_{jt}}^{\phi_2} k_{djt-1},
\end{aligned}
$$

where k_{jt-1} is the composite capital input for variety j as defined before. A_t is the total factor productivity common to all firms, $\Gamma\left(m_t\right)$ is the damage function of global carbon emissions stock m_t, which is assumed to take the form as follows:

$$
\Gamma\left(m_t\right) = \gamma_0 + \gamma_1 m_t + \gamma_2 m_t^2. \tag{16}
$$

Note that emissions arise only from dirty capital. The optimality conditions for the firm are:

$$
n_{jt} : (1-\alpha) \frac{y_{jt}}{n_{jt}} = \frac{w_t}{mc_{jt}}, \tag{17}
$$

$$
k_{djt-1} : \alpha\, \gamma^{1/\zeta} \frac{y_{jt}}{k_{jt-1}} \left(\frac{k_{djt-1}}{k_{jt-1}}\right)^{-1/\zeta} = \frac{\tilde{r}_{djt}}{mc_{jt}}, \tag{18}
$$

$$
k_{cjt-1} : \alpha\ (1-\gamma)^{1/\zeta}\ \frac{y_{jt}}{k_{jt-1}} \left(\frac{k_{cjt-1}}{k_{jt-1}}\right)^{-1/\zeta} = \frac{r_{ct}}{mc_{jt}}, \tag{19}
$$

$$
v_{jt} : \tau_{xt}\phi_d = \phi_1\phi_2 v_{jt}^{\phi_2 - 1}, \tag{20}
$$

where mc_{jt} is the marginal cost and $\tilde{r}_{djt} \equiv r_{dt} + \tau_{xt}\phi_d\left[1 - v_{jt}\right] + \phi_1 v_{jt}^{\phi_2}$ is the rental cost of high emission capital, taking into account the cost of abatement. Among the four optimality conditions, the first three are standard, which ensures that the marginal products of production factors equal the corresponding marginal costs. The last one is specific to our setup, which requires the marginal cost of reducing emissions is equal to the marginal benefit. Notice that the benefit of reducing emissions arises from the the deduction of tax payments. Therefore, without environmental regulation, there will be no incentive for firms to engage in the pollution abatement. Taken together, the optimality conditions imply that all firms employ the same share of labor and capital (clean and dirty). Hence, all firms face similar marginal cost given by:

$$
mc_t = \frac{1}{\alpha^\alpha (1-\alpha)^\alpha} \frac{1}{A_t(1-\Gamma\left(m_t\right))} w_t^{1-\alpha} \left\{ \left[\gamma^{1/\zeta} \cdot \tilde{r}_{dt}^{1-1/\zeta} + (1-\gamma)^{1/\zeta} \cdot \left(\frac{r_{ct}}{A_c}\right)^{1-1/\zeta} \right]^{\frac{\zeta}{\zeta-1}} \right\}^{\alpha} \tag{21}
$$

Consistent with conventional New Keynesian literature, we assume that in each period, a $(1-\theta)$

fraction of firms is able to re-optimize prices. The optimal price is such that:

$$\tilde{\pi}_t = \frac{\epsilon}{\epsilon - 1} \frac{\sum_{l=0}^{\infty} \theta^l \mathbb{E}_t \mathcal{Q}_{t,t+l} \left(\frac{p_t}{p_{t+l}}\right)^{-\epsilon} y_{t+l} mc_{t+l|t}}{\sum_{l=0}^{\infty} \theta^l \mathbb{E}_t \mathcal{Q}_{t,t+l} \left(\frac{p_t}{p_{t+l}}\right)^{1-\epsilon} y_{t+l}}, \tag{22}$$

where $\tilde{\pi}_t = \tilde{p}_t / p_t$ is the optimal price relative to the general price level. ϵ is the elasticity of substitution between goods of different varieties. $\mathcal{Q}_{t,t+l}$ is the dynamic discount factor. Lastly, the gross inflation rate $\pi_t = p_t / p_{t-1}$ is pinned down by:

$$1 = \theta \pi_t^{\epsilon - 1} + (1 - \theta) \tilde{\pi}_t^{1-\epsilon}. \tag{23}$$

Retailers There is a continuum of output variety j populating the unit interval. The retailers aggregate the output variety into a CES composite with elasticity $\epsilon > 1$ for final consumption:

$$y_t = \left(\int_0^1 y_{jt}^{\frac{\epsilon - 1}{\epsilon}} dj \right)^{\frac{\epsilon}{\epsilon - 1}}$$

Government The government uses a lump sum tax to maintain a balanced budget. It purchases goods and collects an emission tax from the entrepreneurs and a lump sum tax from the savers:

$$\omega \tau_{xt} x_t + (1 - \omega) \tau_t = g_t, \tag{24}$$

where government purchases of goods is a fraction s_g of steady-state output, $g_t = s_g \overline{y}$.

Equilibrium Aggregating the production of all varieties, we obtain the total output

$$y_t = A_t \left[1 - \Gamma(m_t)\right] n_t^{1-\alpha} k_{t-1}^{\alpha} s_t^{-1}, \tag{25}$$

where $s_t = \int_0^1 \left(\frac{p_{jt}}{p_t}\right)^{\epsilon} dj$ is the price dispersion with the law of motion $s_t = (1 - \theta) \tilde{\pi}_t^{-\epsilon} + \theta \pi_t^{\epsilon} s_{t-1}$. The market for consumption goods clears when production equals the total demand:

$$\omega\, y_t = c_t + \omega \left[c_{et} + I_{ct} + I_{dt} + \phi_1 v_t^{\phi_2} k_{dt-1} \right] + g_t, \tag{26}$$

where $c_t = \omega c_{et} + (1 - \omega) c_{st}$.

The loan market clears when savings are equal to borrowings

$$\omega\, b_{et} = (1 - \omega)\, b_{st}. \tag{27}$$

At a rate of ξ, the global emission stock decays on its own, but is also accumulated as new emissions are produced:

$$m_t = (1-\xi)\, m_{t-1} + x_t + x_t^*, \tag{28}$$

where x_t is the overall emission produced by the firms, and x_t^* is the emission from the rest of the world.

Environmental policy The environmental agency has the option of adopting CC or CT. For the former, the environmental agency levies taxes on emissions at a constant rate τ_x. For the latter, x_{jt} is fixed, i.e. $x_{jt} = x$.

Monetary policy The central bank's toolkit comprises an interest rate and a LTVR limit. The SLMP introduces new mechanisms for funds available to entrepreneurs to adapt to environmental conditions. Funds provision changes via either a price or a quantity channel. For the price channel, the interest rate increases with emissions, reflecting higher costs (prices) of funding for firms. Consequently, higher emissions result in a higher interest rate, which depresses firm borrowing. We name this interest rate a *sustainability-linked interest rate* (SLI). For the quantity channel, the availability of funds, adjusted via the LTVR in the collateral constraint Eq. (9), is lower as emissions increase. Therefore, higher emissions lead to a tighter collateral constraint, which again reduces the supply of funds. We name this LTVR a *sustainability-linked constraint* (SLC). Formally, we specify the SLI and SLC in the following two equations:

$$\text{SLI}: \quad i_t = {i_{t-1}}^{\rho_i} \times \left\{ i \times \pi_t^{\phi_\pi} \times \left[\hat{x}_t^{\phi_x^i \cdot \mathbf{1}_{\text{CC}} \cdot \mathbf{1}_{\text{SLI}}} \times \hat{\tau}_{xt}^{\phi_{\tau_x}^i \cdot (1-\mathbf{1}_{\text{CC}}) \cdot \mathbf{1}_{\text{SLI}}} \right]^{\mathbf{1}_{\text{SL}}} \right\}^{1-\rho_i} \exp(\varepsilon_t^m) \tag{29}$$

$$\text{SLC}: \quad \kappa_t = {\kappa_{t-1}}^{\rho_\kappa} \times \left\{ \kappa \times \left[\hat{x}_t^{-\phi_x^\kappa \cdot \mathbf{1}_{\text{CC}} \cdot (1-\mathbf{1}_{\text{SLI}})} \times \hat{\tau}_{xt}^{-\phi_{\tau_x}^\kappa \cdot (1-\mathbf{1}_{\text{CC}}) \cdot (1-\mathbf{1}_{\text{SLI}})} \right]^{\mathbf{1}_{\text{SL}}} \right\}^{1-\rho_\kappa} \tag{30}$$

where $\hat{x}_t \equiv x_t / x_{t-1}$ is the rate of change in carbon emission, and $\hat{\tau}_{xt} \equiv \tau_{xt}/\tau_{xt-1}$ is the rate of change in the price of emission permits. ρ_i and ρ_κ are the respective smoothing parameters for the interest rate and the LTVR. ϕ_π is central bank's response coefficient to inflation. ϕ_x^i (ϕ_x^κ) and $\phi_{\tau_x}^i$ ($\phi_{\tau_x}^\kappa$) are the response coefficients to carbon emission growth and changes in the price of emission permits respectively when the central bank adopts SLI (SLC). Larger values of these coefficients imply that the borrowing cost changes more aggressively to every percentage point change of the target variables.

Notice that the SLMP targets either carbon emission growth $\hat{x}_t$ or the price change of emission permits $\hat{\tau}_{xt}$ in the above setup, contingent on the environmental agency's policies. Specifically, the SLMP complements a constant carbon tax by targeting carbon emission growth. Alternatively, if the environmental agency adopts a cap-and-trade policy, the SLMP then targets the price change of emission permits.

The $\mathbf{1}$'s in the SLI and SLC are "switches" for specific policy regimes. $\mathbf{1}_{\text{SL}}$ is the indicator for the adoption of the SLMP by the central bank. $\mathbf{1}_{\text{CC}}$ and $\mathbf{1}_{\text{SLI}}$ are indicator variables as the environmental agency imposes a constant carbon tax and the central bank adopts the SLI, respectively. By switching the values of $\mathbf{1}$'s between 0 and 1, we formulate the policy regimes as follows:

1. CC: The environmental agency adopts CC while the central bank does not target emissions, i.e. $\mathbf{1}_{\text{SL}} = 0$. The monetary policy is one of inflation-targeting as in Annicchiarico and Di Dio (2015).

2. CC+SLI: The environmental agency adopts CC and the central bank uses the <u>interest rate</u> to target carbon emission growth, i.e. $\mathbf{1}_{\text{CC}} = 1$, $\mathbf{1}_{\text{SL}} = 1$ and $\mathbf{1}_{\text{SLI}} = 1$. The LTVR is constant and equal to κ.

3. CC+SLC: The environmental agency adopts CC and the central bank uses the <u>LTVR</u> to target carbon emission growth, i.e. $\mathbf{1}_{\text{CC}} = 1$, $\mathbf{1}_{\text{SL}} = 1$ and $\mathbf{1}_{\text{SLI}} = 0$. The LTVR is lower when carbon emission is higher.

4. CT: The environmental agency adopts CT while the central bank does not target emissions, i.e. $\mathbf{1}_{\text{SL}} = 0$. The monetary policy is the same as in CC, targeting only the inflation.

5. CT+SLI: The environmental agency adopts CT and the central bank uses the <u>interest rate</u> to target the price change of emission permits, i.e. $\mathbf{1}_{\text{CC}} = 0$, $\mathbf{1}_{\text{SL}} = 1$ and $\mathbf{1}_{\text{SLI}} = 1$. The collateral constraint is constant and equal to κ.

6. CT+SLC: The environmental agency adopts CT and the central bank uses the <u>LTVR</u> to target the price change of emission permits, i.e. $\mathbf{1}_{\text{CC}} = 0$, $\mathbf{1}_{\text{SL}} = 1$ and $\mathbf{1}_{\text{SLI}} = 0$. The LTVR is lower when the price of emission permits is higher.

The common feature among regimes 2, 3, 5 and 6 is that they all exert counter-cyclical forces on emissions. They discourage borrowing when emissions are high and vice versa. The SLC is analogous to a macro-prudential policy. Campiglio (2016) provides rationales for the central bank to introduce macro-prudential measures to complement carbon taxes.

Exogenous variables The exogenous variables are g_t, A_t, and z_t. We keep g_t at the steady-state value. In this paper, we consider productivity shock A_t and consumption preference shock z_t. We

Table 1: Model parameters

Parameter	Description	Value	Source
β_s	Saver discount factor	0.99	Annicchiarico and Di Dio (2015)
μ_n	Weight of labor in utility function	19.8413	
φ	Inverse of labor supply elasticity	1	
ϵ	Elasticity of substitution between goods	6	
θ	Fraction of firms with prices unchanged	0.75	
α	Share of composite capital in production function	1/3	
γ_0	Damage function coefficient	1.3950e-3	
γ_1	Damage function coefficient	-6.6722e-6	
γ_2	Damage function coefficient	1.4647e-8	
δ	Capital depreciation	0.028	
ϕ_1	Abatement cost function coefficient	0.1850	
ϕ_2	Abatement cost function coefficient	2.8	
ξ	Rate of pollution decay	1-0.9979	
s_g	Government purchases coefficient	0.1022	
β_e	Entrepreneur discount factor	0.975	Iacoviello and Neri (2010)
υ	Habit persistence	0.85	Ravn et al. (2010)
ζ^{cost}	Elasticity of capital investment rate	0.4	Jermann (1998)
ω	Entrepreneur population share	0.5	Quint and Rabanal (2013)
γ	Dirty capital coefficient in composite capital function	0.5	Papageorgiou et al. (2017)
ζ	Elasticity of substitution between clean and dirty capital	10	Papageorgiou et al. (2017)
ϕ_d	Emissions per unit of dirty capital	0.45/9	Authors' estimate

assume that A_t and z_t follows an autoregressive process. Hence, we have

$$\ln(A_t) = \rho_a \ln(A_{t-1}) + (1-\rho_a)\ln(\overline{A}) + \varepsilon_t^a, \quad \varepsilon_t^a \sim N(0, \sigma_{\boldsymbol{a}}^2) \tag{31}$$

$$\ln(z_t) = \rho_z \ln(z_{t-1}) + (1-\rho_z)\ln(\overline{z}) + \varepsilon_t^z, \quad \varepsilon_t^z \sim N(0, \sigma_z^2) \tag{32}$$

Parameter calibration Table 1 reports the parameter values used for simulations and welfare analysis. The top panel reports the parameter values obtained from Annicchiarico and Di Dio (2015), who calibrates their model to the United States. The bottom panel of Table 1 reports the additional parameters stemming from our extensions to the benchmark model.

The steady-state values of key variables in our model follow Annicchiarico and Di Dio (2015). The steady-state government purchases-to-GDP ratio $\frac{\overline{g}}{\overline{y}}$ equals 10.22%. The inflation is equal to zero ($\overline{\pi} = \overline{\tilde{\pi}} = 1$). Carbon emission growth and price change of emission permits are also equal to zero ($\overline{\tilde{x}} = \overline{\tilde{\tau}_x} = 1$). The total factor productivity $\overline{A}$ equals 1.248. The clean capital productive efficiency A_c equals 1.1. We calibrate ϕ_d to obtain the steady-state pollution stock $\overline{x}$ to equal 0.22. The global emission stock $\overline{m}$ is 800 in a no policy case, which is the same as the no-policy steady-state value in Annicchiarico and Di Dio (2015). Finally, we calibrate α_1 and α_2 to obtain zero capital adjustment costs in the steady-state. Hence, we have $\alpha_1 = \delta^{\frac{1}{\zeta^{cost}}}$ and $\alpha_2 = \frac{\delta}{1-\zeta^{cost}}$.

Estimation We use Bayesian estimation to pin down: (1) the persistence and standard deviations of the three shocks analyzed in our paper: productivity shock, preference shock and monetary shock; and (2) the interest rate smoothing coefficient and the inflation response coefficient. The estimation methodology follows Herbst and Schorfheide (2015) with the implementation in Dynare 4.6.4. With three exogenous shocks in the model, the estimation process requires three data series to construct observables. To this end, we use the United States quarterly macroeconomic time-series on GDP, consumption and fed fund rate. The Great Moderation period in the United States constitutes our data sample's period. Hence, the period extends from 1984Q1 to 2008Q4, before the great financial crisis. Using a one-sided HP filter with $\lambda = 1600$ on the GDP and consumption data, we secure the observables on output, y_t^{obs} and consumption, c_t^{obs}. In the case of interest rate, the deviation of the time series from the sample average constitutes the interest rate observable, i_t^{obs} (Pfeifer, 2021)[1].

Table 2 reports the priors used for the Bayesian estimation of the parameters. We use past literature to set the priors. The prior distribution of all the persistence coefficients corresponding to interest rate, ρ_i, and shocks, ρ_a and ρ_z, is set as beta distribution with a mean of 0.1 (Smets and Wouters, 2007). The inflation feedback coefficient, ϕ_π, has a prior gamma distribution with a mean of 1.5. Finally, the standard deviation of all the exogenous shocks follows an inverse gamma distribution with mean 0.1 (Hommes et al., 2019). Table 2 also shows the posterior mean and the highest posterior density (HPD) interval of the parameters from Metropolis-Hastings Algorithm with 400,000 replications. Productivity shock is the most persistent, with the posterior mean of AR(1) coefficient at 0.9614. Among the three shocks under purview, the posterior standard deviation of the consumption preference shock is relatively high at 6.13%.

Table 2: Estimated coefficients in CC regime.

Symbol	Description	Prior (p_1, p_2)	Posterior estimation		
			Mean	2.5%	97.5%
ρ_a	AR(1) productivity shock	$\mathbb{B}(0.5, 0.2)$	0.9614	0.9309	0.9896
ρ_z	AR(1) consumption preference shock	$\mathbb{B}(0.5, 0.2)$	0.6141	0.5304	0.6972
σ_a	SD productivity shock	$\mathbb{IG}(0.1, 2)$	0.0041	0.0034	0.0049
σ_z	SD consumption preference shock	$\mathbb{IG}(0.1, 2)$	0.0613	0.0540	0.0683
σ_m	SD monetary policy shock	$\mathbb{IG}(0.1, 2)$	0.0024	0.0020	0.0027
ρ_i	Interest rate smoothing	$\mathbb{B}(0.5, 0.2)$	0.4908	0.9309	0.9896
ϕ_π	Inflation feedback	$\mathbb{G}(1.5, 0.25)$	1.4628	1.2965	1.6179

SD is the acronym for standard deviation. $\mathbb{B}$ ≡Beta distribution, $\mathbb{IG}$ ≡ inverse gamma distribution, $\mathbb{G}$ ≡ gamma distribution. p_1 ≡ mean and p_2 ≡ standard deviation. The estimation results are obtained from Meltropolis-Hastings Algorithm with 400,000 replications.

[1] Appendix A provides more details on the data and sources used in the estimation process.

4 Welfare analyses

This section aims to identify potential changes in welfare should the central bank adopt the SLMP. As a social planner, the central bank's objective is to improve the welfare of the society, which is defined as the weighted sum of savers' and entrepreneurs' welfare:

$$\mathcal{W}_t = (1-\omega)\,\mathcal{W}_t^s + \omega\,\mathcal{W}_t^e, \tag{33}$$

The welfare of savers', $\mathcal{W}_t^s$, and entrepreneurs', $\mathcal{W}_t^e$, are the discounted value of their respective life-time utility evaluated at the social planner's discount factor $\tilde{\beta}$:

$$\mathcal{W}_t^s = \mathbb{E}_t \sum_{j=0}^{\infty} \tilde{\beta}^j u\left(c_{st+j}, n_{st+j}\right), \tag{34}$$

$$\mathcal{W}_t^e = \mathbb{E}_t \sum_{j=0}^{\infty} \tilde{\beta}^j u\left(c_{et+j}, n_{et+j}\right). \tag{35}$$

We explore the welfare implications of the SLMP in two steps. We first find the benchmark welfare in a simple inflation-targeting regime. This is the maximum welfare that the central bank can achieve by adjusting its reaction to inflation when setting the policy instruments. We do this by searching over a plausible range of ϕ_π in the CC or CT regime to identify a value that delivers the highest unconditional mean of $\mathcal{W}_t$. Then, as the central bank considers the additional targets pertaining to carbon emission activity, we examine how far the welfare frontier can be pushed when the policy instruments also respond to these new targets. If the additional targets are welfare-improving, we expect to see nonzero reactions in the policy instruments to carbon emission activity, coupled with changes in the reactions to inflation. If targeting the emission activity does not improve the welfare at all, the optimal coefficients in the second step will be zeros.

The distinction between savers and entrepreneurs in our model allows an analysis of Pareto optimality in welfare improvements. Our focus is on whether improving the overall social welfare in Eq. (33) implies that both the savers and entrepreneurs gain at the same time. Such an analysis provides insights into potential distributional issues as new policy regimes are introduced.

Grid search We conduct a grid search to determine the optimal response coefficients. The grid over which we search is defined as follows with increments of 0.01:

1. CC: $\rho_i \in [0, 0.9]$, $\phi_\pi \in [0, 5]$;

2. CC+SLI: $\rho_i \in [0, 0.9]$, $\phi_\pi \in [0, 5]$ and $\phi_x^i \in [0, 20]$;

3. CC+SLC: $\rho_i \in [0, 0.9]$, $\phi_\pi \in [0, 5]$, $\rho_\kappa \in [0, 0.9]$ and $\phi_x^\kappa \in [0, 70]$;

4. CT: $\rho_i \in [0, 0.9]$, $\phi_\pi \in [0, 5]$;

5. CT+SLI: $\rho_i \in [0, 0.9]$, $\phi_\pi \in [0, 5]$ and $\phi_{\tau_x}^i \in [0, 5]$;

6. CT+SLC: $\rho_i \in [0, 0.9]$, $\phi_\pi \in [0, 5]$, $\rho_\kappa \in [0, 0.9]$ and $\phi_{\tau_x}^\kappa \in [0, 5]$.

The model is solved for all combinations of parameter values in the grid. In the CC regime, for instance, with two free parameters, the model is iteratively solved for $91 \times 501 = 45,591$ times. In each iteration, Dynare 4.6.4 numerically finds the solutions at the second order. The unconditional means of welfare defined by Eqs. (33) to (35) are collected, except for when the parameters lead to indeterminacy in the model. The parameter values delivering the highest social welfare outcome in each policy regime are then reported as the optimal coefficients. The welfare effect of an SLMP regime (CC+ or CT+) tells the extent to which its highest welfare has improved upon the benchmark. For easier understanding, we use the consumption-equivalence compensation, commonly used in the literature and described below, to provide an intuitive interpretation of the simulated numbers.

Simultaneous shocks Table 3 reports the optimal coefficients and the welfare outcomes when both technology and consumption preference shocks are present. In the baseline scenario when the SLMP is not implemented, the optimal coefficients of inflation in the Taylor rule are 2.62 for CC and 2.63 for CT. Our simulations also find that smoothing the interest rate movements is not helpful in enhancing social welfare. The optimal value for ρ_i is always 0 and thus not reported.

Augmented with a target for emission activity, the optimal interest rate rule, specifically the SLI, features nonzero reactions to emission activity. The interpretation of these optimal coefficients needs to be associated with the standard deviations of emission activity implied by our model. Based on our parameterization, the standard deviation of carbon emission growth is 0.02 basis points under the CC+SLI, and the standard deviation of emission permit price growth is 0.96 basis points under CT+SLI. Given the optimal response coefficient to emissions of 7.14 under CC+SLI, every one-standard-deviation increase in carbon emissions leads to 0.14 percentage-point increase in nominal interest rate. Whereas, when the environmental policy is cap-and-trade, every one-standard-deviation increase in permit price growth leads to 0.16 percentage-point increase in nominal interest rate. Thus, despite the different scales in the optimal coefficients, the responses of the nominal interest rate to carbon emission activity are more or less equivalent across the two environmental policies. The optimal response coefficients to inflation are, however, slightly lower under the SLMP.

We also find comparable results when the central bank augments the LTVR with a target on emission activity. One key difference from the interest rate rule in the optimal LTVR is that smoothing the LTVR is useful in improving social welfare: The optimal smoothing parameter of the LTVR is 0.9. With constant carbon tax, every one-standard-deviation increment in carbon emissions leads to 0.13 percentage-point decrease in LTVR. Alternatively, when the environmental policy is cap-and-trade, every one-standard-deviation increase in the permit price leads to 0.12 percentage-point decline in the LTVR. Similar to the results with the SLI, the LTVR's optimal responses to carbon emission activity are also similar across the two environmental policies.

Upon identifying the optimal coefficients, we express the welfare effects in terms of percentages of consumption, known as the consumption-equivalence welfare gain, calculated as

$$100 \times \left(1 - \exp\left[\frac{\left(\tilde{\beta} - 1\right)\left(\mathcal{W}^{X+SLMP} - \mathcal{W}^{X}\right)}{1 - \upsilon}\right]\right), \quad X \in (CC, CT), \tag{36}$$

The consumption-equivalence welfare gain gives the percentage of consumption that an agent is willing to give up to change from a pure environmental policy regime CC or CT to one with the SLMP (through either the SLI or SLC). A positive number then implies a welfare gain, because it means that households are willing to accept some losses in consumption in a baseline regime, in exchange for a better welfare outcome in an alternative regime.

Our calculations find that both the SLI and SLC deliver improvements in welfare to the society. In the context of CC, welfare gains for society amount to 0.008% and 0.016% of consumption with the implementation of SLI and SLC, respectively. As for the CT, the welfare gains for the society are 0.011% and 0.002% with SLI and SLC implementation, respectively.

There are, however, interesting re-distributions in the welfare changes between the savers and entrepreneurs. The SLI, in general, makes entrepreneurs better off at the expenses of the savers, while the SLC does the opposite. These differences across household types mean that the societal welfare gains are not Pareto optimal, as both groups of households do not enjoy welfare gains simultaneously. The non-Pareto outcomes can be attributed to the changes in the volatility of some key economic variables across the policy regimes.

We examine the volatility implications of the SLMP measured by the standard deviation of key macroeconomic variables. Table 4 reports the results when the economy simultaneously faces the productivity and consumption preference shocks. Both output and consumption are almost equally stable for SLI and SLC, but slightly less volatile than the case when only CC is implemented. However, inflation becomes more volatile when the central bank adopts the SLI than the SLC. The higher volatility in inflation results in higher uncertainty in the future value of savers' savings. At the same time, given higher inflation under a positive consumption preference shock, borrowers also repay their debts less in

Table 3: Welfare gain from SLMP.

	Response to target				Welfare gain (% consumption)		
	π_t	$\hat{x}_t$	$\hat{\tau}_{xt}$	κ_{t-1}	Society	Savers	Entrepreneurs
CC	2.62	-	-	-			
CC+SLI	2.50	7.14	-	-	0.008	-0.003	0.019
CC+SLC	2.38	66.88	-	0.90	0.016	0.053	-0.021
CT	2.63	-	-	-			
CT+SLI	2.48	-	0.17	-	0.011	-0.006	0.027
CT+SLC	2.39	-	1.27	0.90	0.002	0.043	-0.017

Welfare gain is computed using theoretical moments from second-order perturbations around the stochastic steady state in Dynare 4.6.4.

Table 4: Standard deviation of key variables.

	CC	CC+SLI	CC+SLC	CT	CT+SLI	CT+SLC
y_t	0.0292	0.0290	0.0290	0.0288	0.0287	0.0287
c_t	0.0142	0.0141	0.0142	0.0142	0.0141	0.0141
π_t	0.0010	0.0020	0.0017	0.0010	0.0021	0.0016
b_{et}	0.0815	0.0808	0.0937	0.0695	0.0693	0.0866
k_{ct}	0.0493	0.0487	0.0473	0.0598	0.0594	0.0600
k_{dt}	0.0434	0.0429	0.0414	0.0213	0.0209	0.0202

Volatility moments are derived using second-order perturbations around the stochastic steady state in Dynare 4.6.4 when the economy simultaneously faces productivity and consumption preference shocks.

real terms. Hence, we see that savers lose while entrepreneurs gain when the SLI is implemented. As for the SLC, the LTV ratio is used as the instrument to manage emissions, the borrowing funds are understandably more volatile under the SLC. The higher volatility in borrowing results in more uncertainty for the borrowers. As a result, we see in Table 3 that entrepreneurs lose in welfare while the savers gain.

Note, however, that these welfare effects are the combined results of productivity and consumption preference shocks. To explore the uneven distribution of welfare further, it is instructive to look at the individual shocks in isolation, and also to find out the variance decomposition of the shocks.

Productivity shock Panel A of Table 5 reports the results when only the productivity shock is present. The optimal coefficients are in general smaller than those reported in Table 3. Nevertheless, nonzero reactions to emission activity still prove to be welfare-improving.

The most important finding from Panel A is that regimes with the SLC deliver Pareto improvements for the society. We see that both savers and entrepreneurs enjoy higher welfare under the SLC regimes. In the context of CC, welfare gains for society amount to 0.0053% and 0.0027% of consumption with the SLC, respectively for the savers and entrepreneurs. As for the CT, the welfare gains for the society are 0.0040% and 0.0047% with the SLC, respectively. Compared to the SLI, the SLC delivers higher social

Table 5: Welfare gain from SLMP: Individual shocks.

	Response to target					Welfare gain (% consumption)		
	i_{t-1}	π_t	$\hat{x}_t$	$\hat{\tau}_{xt}$	κ_{t-1}	Society	Savers	Entrepreneurs
A. Productivity shock								
CC	0	2.20	-	-	-			
CC+SLI	0	2.20	1.15	-	-	0.0004	0.0013	-0.0013
CC+SLC	0	2.13	10.29	-	0.43	0.0046	0.0053	0.0027
CT	0	2.20	-	-	-			
CT+SLI	0	2.19	-	0.05	-	0.0005	0.0020	-0.0007
CT+SLC	0	2.13	-	0.20	0.41	0.0042	0.0040	0.0047
B. Consumption preference shock								
CC	0	3.08	-	-	-			
CC+SLI	0.30	3.91	36.73	-	-	0.0280	-0.0187	0.0746
CC+SLC	0	2.48	121.35	-	0.9	0.0222	0.0553	-0.0113
CT	0	3.11	-	-	-			
CT+SLI	0.51	5.55	-	1.20	-	0.0308	-0.0160	0.0766
CT+SLC	0	2.50	-	2.22	0.9	0.0174	0.0447	-0.0107

Welfare gain is computed using theoretical moments from second-order perturbations around the stochastic steady state in Dynare 4.6.4.

welfare gains under both environmental policies.

Our simulations around the optimal reactions to emission activity find that Pareto improvements in welfare are attainable in some cases. In Fig. 1, we show plots of the welfare gains against ϕ_x^i, ϕ_x^κ, $\phi_{\tau_x}^i$ and $\phi_{\tau_x}^\kappa$. For both types of households and the society, the welfare gains are concave functions of the response coefficients. This confirms our findings that the social welfare values are the local maximum in our search grid. Further to the results in Table 5, we can see from the figures that Pareto improvements, indicated by the welfare changes of savers and entrepreneurs simultaneously being positive, can be achieved in relatively wide ranges of the coefficients under the regimes with SLC. For instance, under CC+SLC, the welfare gains for both the savers and entrepreneurs are positive when $\phi_x^\kappa \in [1.99, 15.18]$. Also, despite that the optimal coefficients do not deliver Pareto improvements under the regimes with SLI, we can still see from Fig. 1c that the welfare of both types of households improves simultaneously when $\phi_{\tau_x}^i \in [0, 0.01]$. In short, regardless of the environmental policy, it is possible for both savers and entrepreneurs to enjoy higher welfare simultaneously.

Consumption preference shock Panel B of Table 5 reports the results when only the consumption preference shock is present. Similar to Panel A and Table 3, nonzero reactions to emission activity improve social welfare. Moreover, the optimal policies feature more active reactions to both inflation and emission activity, as seen from the larger coefficients compared to those in Table 3.

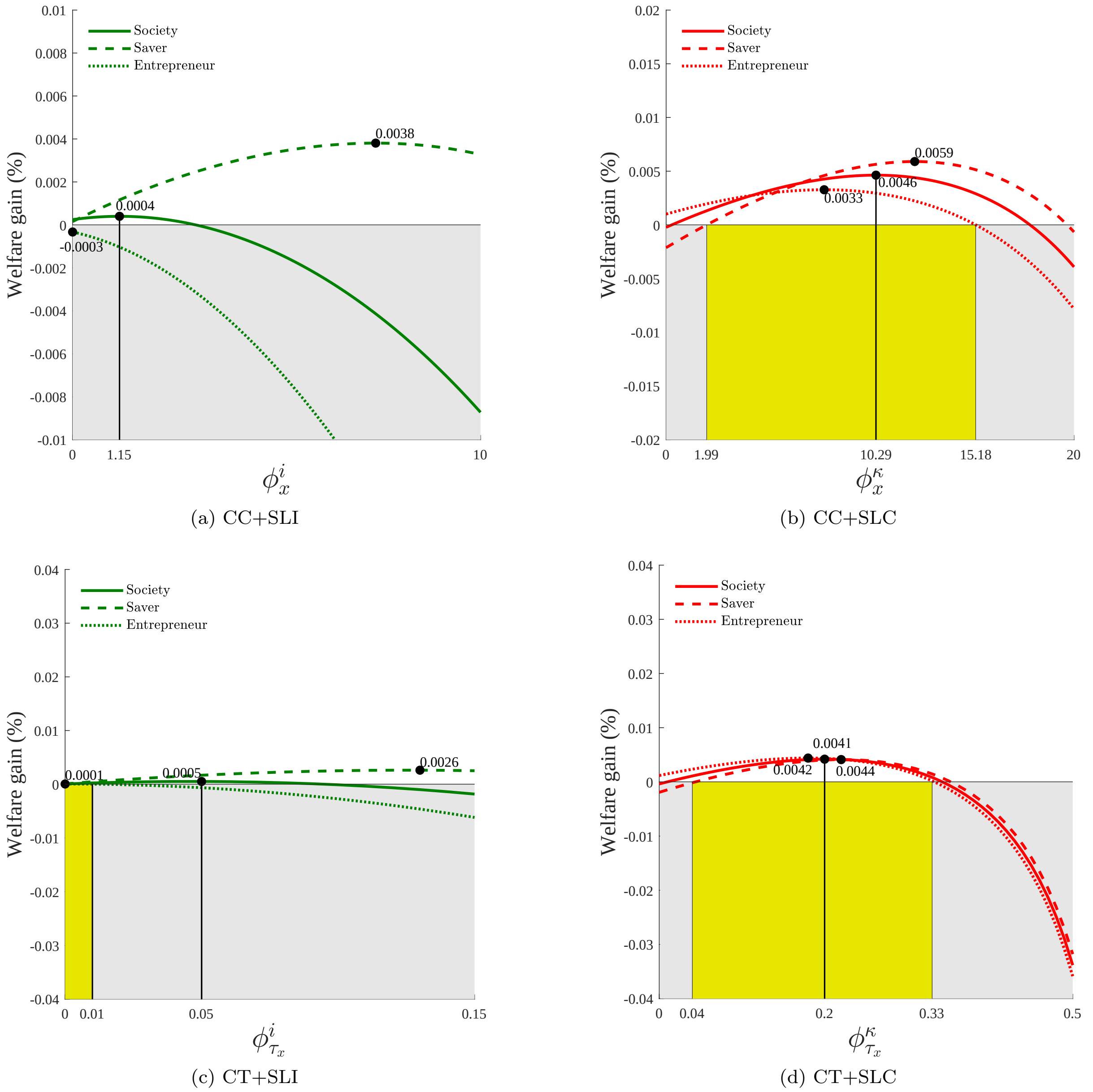

Figure 1: Welfare gain with respect to emission coefficient in SLMP (Productivity shock).

Table 6: Variance decomposition of shocks in CC regime (%).

	Shocks	
	Productivity	Consumption preference
y_t	53.46	46.54
c_t	51.66	48.34
π_t	20.05	79.95
b_{et}	82.74	17.26
k_{ct}	84.52	15.48
k_{dt}	45.06	54.94
x_t	84.52	15.48

The directions of welfare changes resemble those seen in Table 3. The maximum welfare for the society does not imply simultaneous improvements for both savers and entrepreneurs. Under the regimes with the SLI, entrepreneurs gain while savers lose, whereas the regimes with the SLC show the opposite. The SLI regimes deliver higher welfare for the society, compared to the SLC regimes.

In contrast to the results for the productivity shock, we find that under the consumption preference shock, Pareto improvements are only possible with the SLI. The plots are shown in Fig. 2. From Fig. 2a and Fig. 2c, to achieve Pareto improvements, the reactions of the interest rate to emission activity have to be smaller than the optimal coefficients shown in Panel B of Table 5. For the SLC regimes, the entrepreneurs always suffer from welfare losses.

The above analysis shows that the welfare effects reported in Table 3 are more consistent with those under a consumption preference shock. To gain a better understanding of the relative importance of the productivity shock and the consumption preference shock, we conduct a variance decomposition. The results are reported in Table 6, which demonstrates that the consumption preference shock accounts for almost 80% of variations in inflation, and about half of the variations in total output, consumption, and dirty capital inputs. The consumption preference shock therefore turns out to be a more important one in our model, due to its importance in driving the inflation dynamics.

5 Equilibrium dynamics

In this section, we analyze the dynamic properties of our model following either a supply or demand shock for mixes of environmental and monetary policies. Specifically, Fig. 3 and Fig. 4 show the impulse response functions of key macroeconomics variables following a 1% productivity shock, 1% consumption preference shock and a 25-basis-point shock expansionary monetary shock, when the central bank adopts the SLI while the environmental agency implements either constant carbon tax or cap-and-trade policy. Fig. 5 and Fig. 6 display the counterparts of the previous figures when the central bank adopts the SLC.

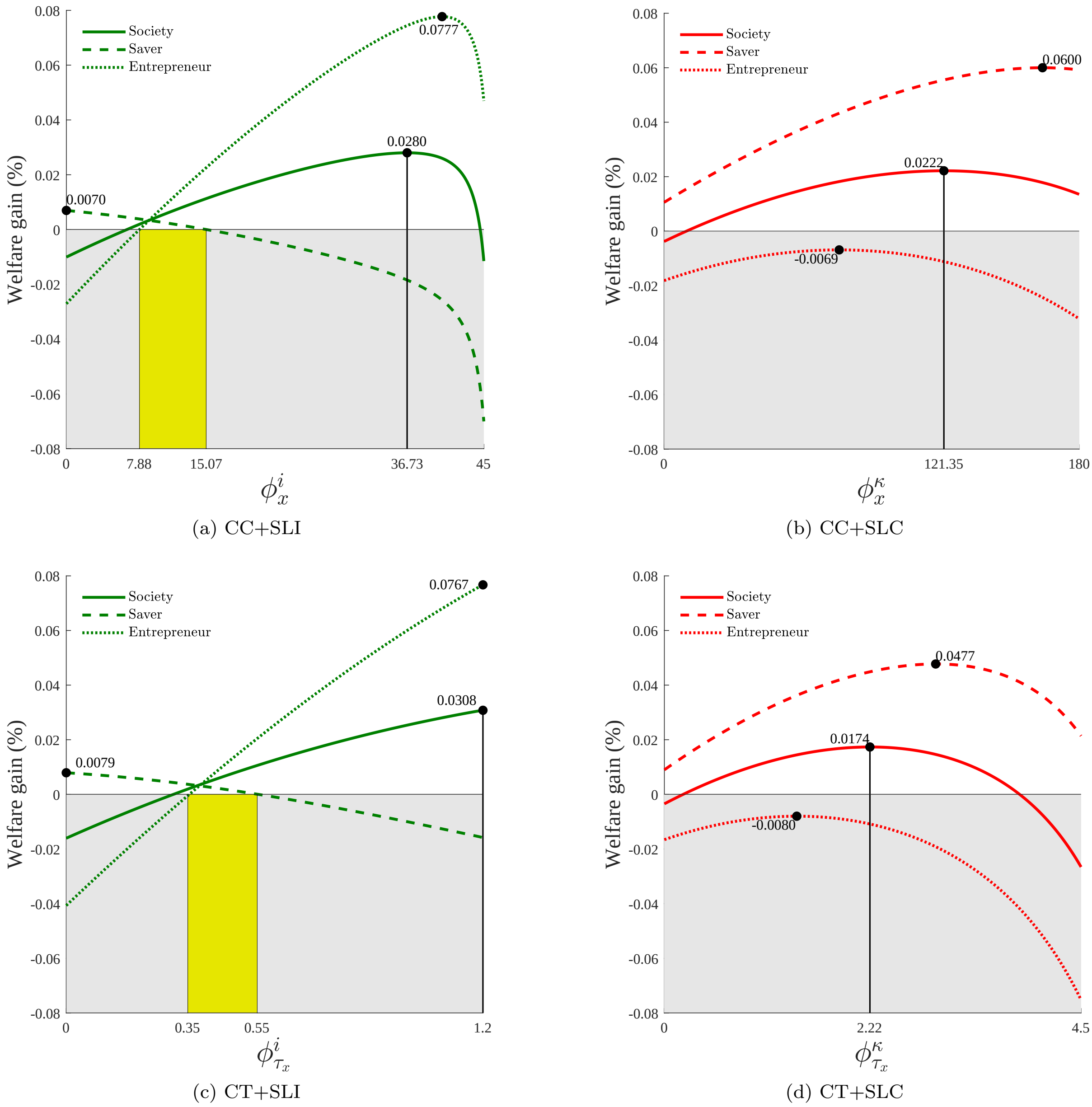

Figure 2: Welfare gain with respect to emission coefficient in SLMP (Consumption preference shock).

Sustainability-linked interest rate Fig. 3 compares CC with CT when the central bank adopts the SLI. A positive productivity shock leads to an economic boom. Upon impact, firms' output increases, which puts a downward pressure on the inflation. The central bank reduces the nominal interest rate to anchor inflation expectations. At the same time, higher productivity results in higher dividends that increase savers' income. This income effect reduces savers' labor supply, but raises savers' consumption and savings. The latter increases the supply of loans to entrepreneurs. A lower interest rate and a higher supply of loans relax the budget constraint for entrepreneurs, encouraging consumption and investment for both dirty and clean capital. A larger supply of capital thus reduces the rental costs for dirty and clean capital.

There are several differences between CC and CT as shown in Fig. 3. For CC, taxes on carbon emissions are constant, therefore there is no incentive for firms to exert extra abatement efforts. With the cap-and-trade (CT) policy, emission taxes increase, imposing stronger incentive for firms to increase abatement efforts. This greater abatement efforts incur higher marginal cost of production for using dirty capital, which reduces its demand. This partially offsets the positive impact of higher productivity. Therefore, the equilibrium dirty capital investment is lower with CT than with CC.

The responses of the economy to a consumption preference shock are substantially different from a productivity shock. As shown in Fig. 4, a positive consumption preference shock induces higher consumption for both savers and entrepreneurs, which comes at the expenses of lower savings for savers and lower investment for entrepreneurs, because the marginal utility of consumption becomes higher. The lower investment leads to a lower capital supply over time, which results in higher capital prices. In addition, the higher consumption demand has an expansionary impact on output, leading to an increase in labor. Furthermore, the demand shock imposes an upward pressure on inflation, causing the central bank to raise the nominal interest rate. Lastly, the higher real interest rates in addition to the crowding out of investment by the rise in consumption causes a drop in loan demand.

It is interesting to note, in spite of higher output, the positive preference shock leads to lower investment of dirty capital and thus lower carbon emissions if the environmental agency implements the constant carbon tax policy. This is in contrast to the case of positive productivity shocks shown in Fig. 3, where carbon emissions increase with output. Therefore, depending on the nature of shocks that hit an economy, the relationship between output and carbon emission activities is ambiguous even for the same mix of environmental and monetary policies.

Sustainability-linked constraint Fig. 5 displays the impulse responses of several macroeconomic variables following a positive productivity shock when the central bank adopts the SLC. The patterns of evolution for most of the variables are similar to those observed in Fig. 3. The increase in productivity

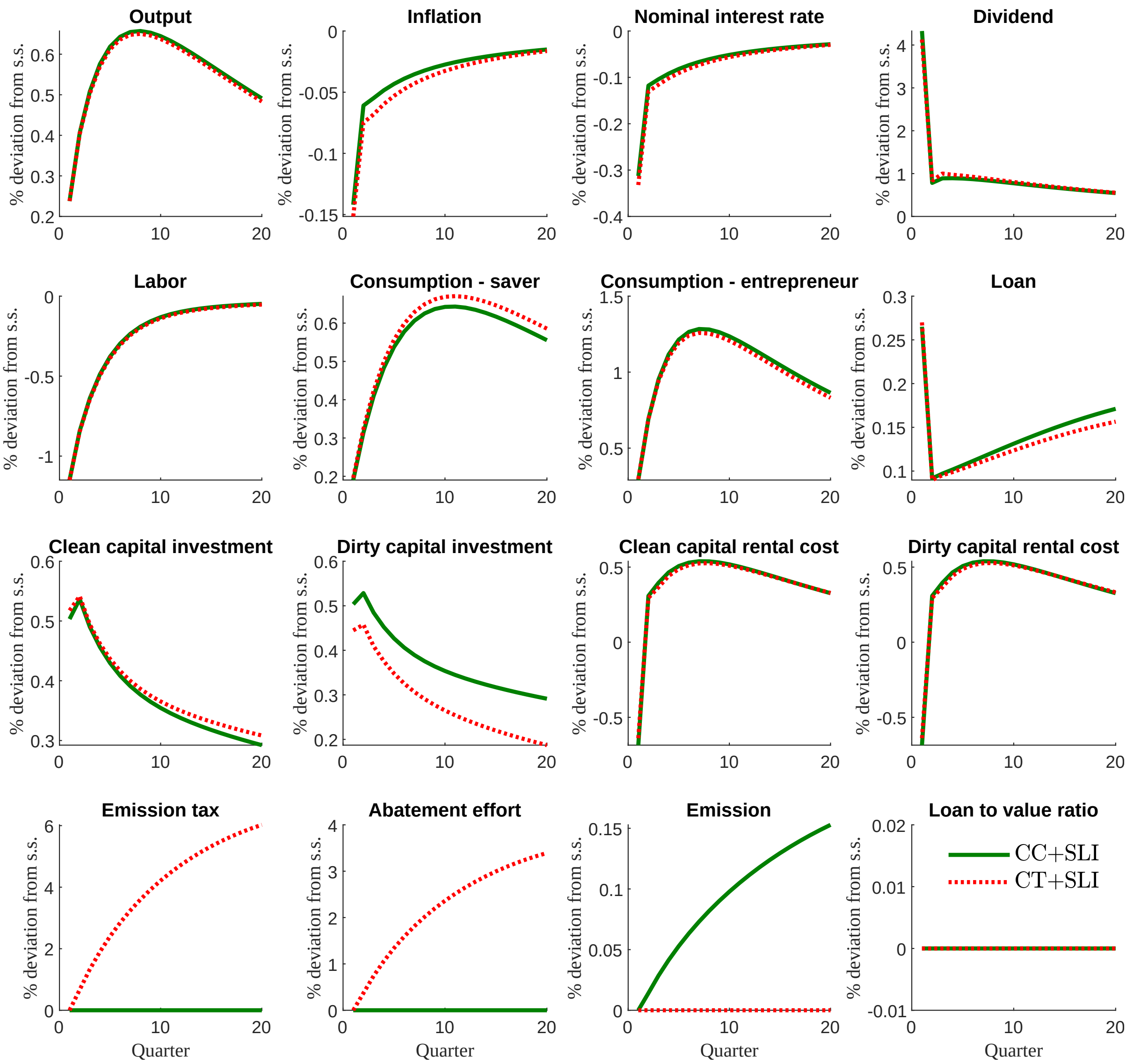

Figure 3: Environment policy scenarios with SLI: 1% technology shock

induces higher consumption, investment and output, but a lower inflation. A key difference between SLC and SLI is that the central bank uses the loan to value ratio as an instrument to target emission activities in the former while using the nominal interest as an instrument in the latter. This difference is clearly reflected by a comparison between Fig. 3 and Fig. 5, where the loan to value ratio remains constant in the former but declines in the latter. Given that the adjustment of nominal interest rate does not target emissions under the SLC, the change of nominal interest rate only depends on the change of inflation rate regardless of the environmental policies implemented.

Fig. 6 is the counterpart of Fig. 4. Savers and entrepreneurs substitute their consumption for investment in response to the positive consumption preference shock. Overtime, a decline in investment for dirty capital depresses emissions, which induces the central bank to increase the loan to value ratio. Con-

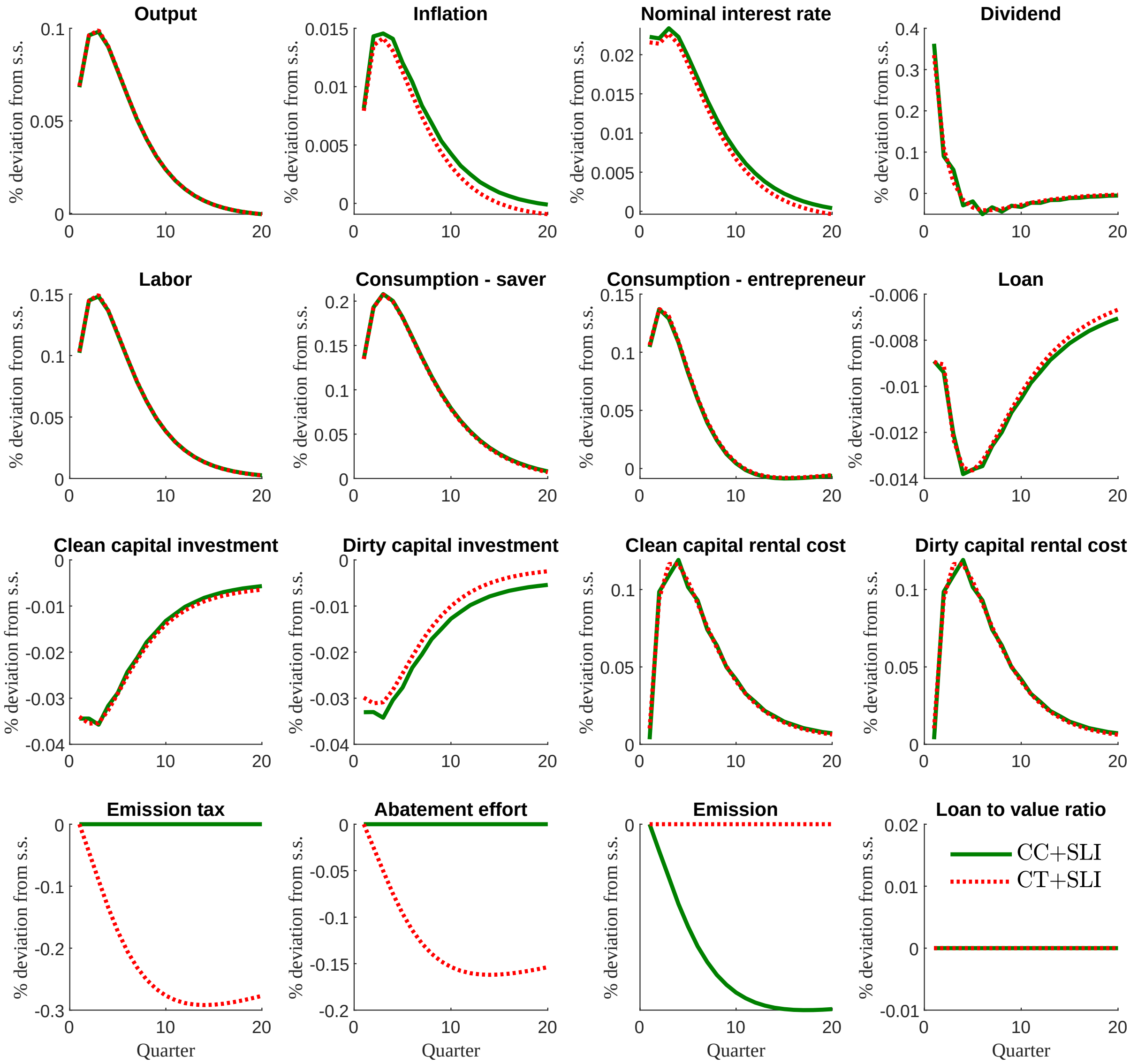

Figure 4: Environment policy scenarios with SLI: 1% consumption preference shock

sequently, entrepreneurs increase their borrowing. This is in contrast with Fig. 4, where entrepreneurs' loans decline with the dirty capital stock, as the loan to value ratio stays constant.

6 Conclusion

In this paper, we assess the dual mandate of central bank's sustainability-linked monetary policy (SLMP). We propose a framework in which the central bank can influence firm's emission either through the interest rate or the provision of loans. Our simulations show that the SLMP enhances social welfare while promoting environmental sustainability. Re-distributions of welfare are to be expected. We also find that under the SLMP, a cap-and-trade measure is bettern in promoting the adoption of clean capital.

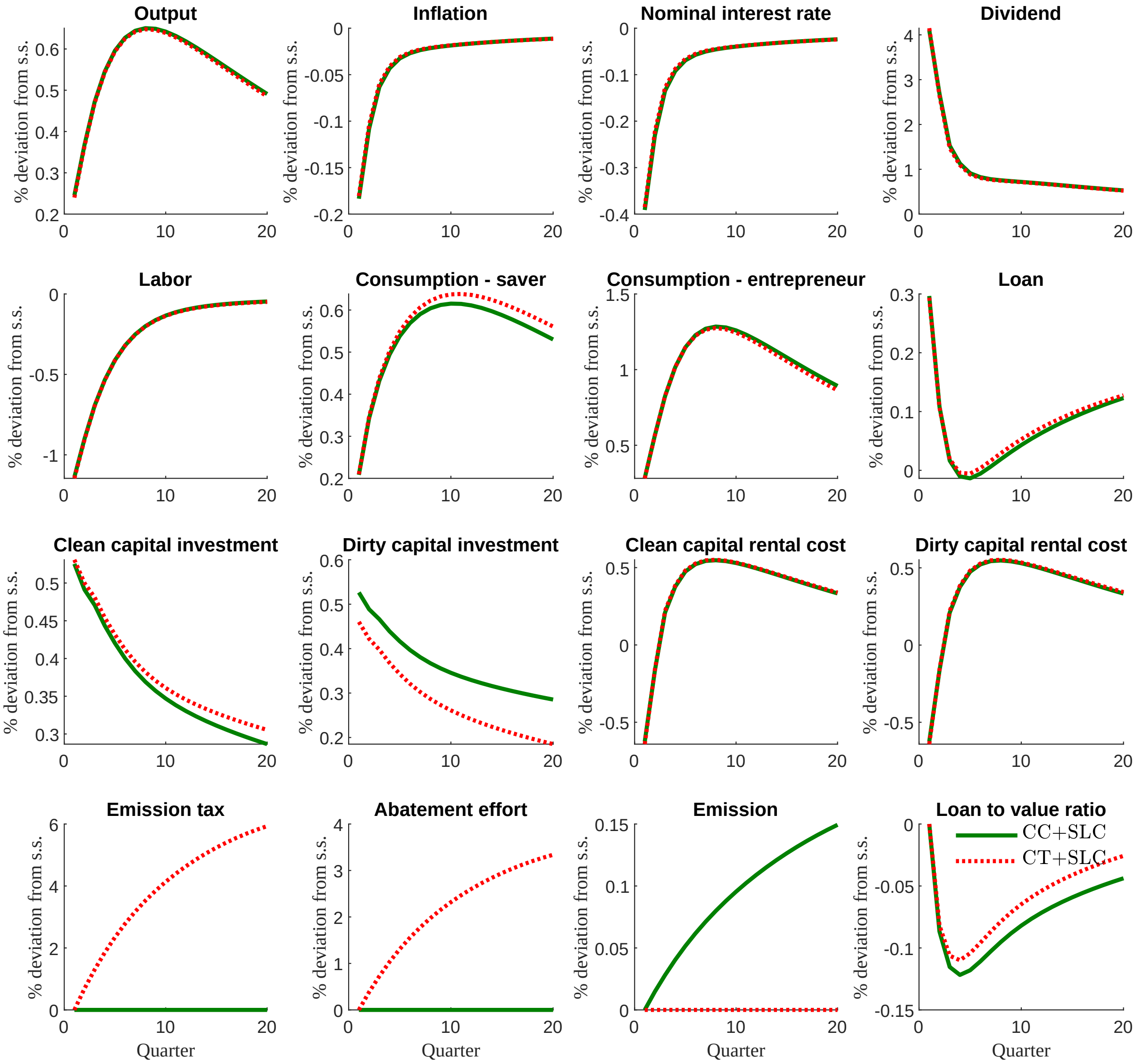

Figure 5: Environment policy scenarios with SLC: 1% technology shock

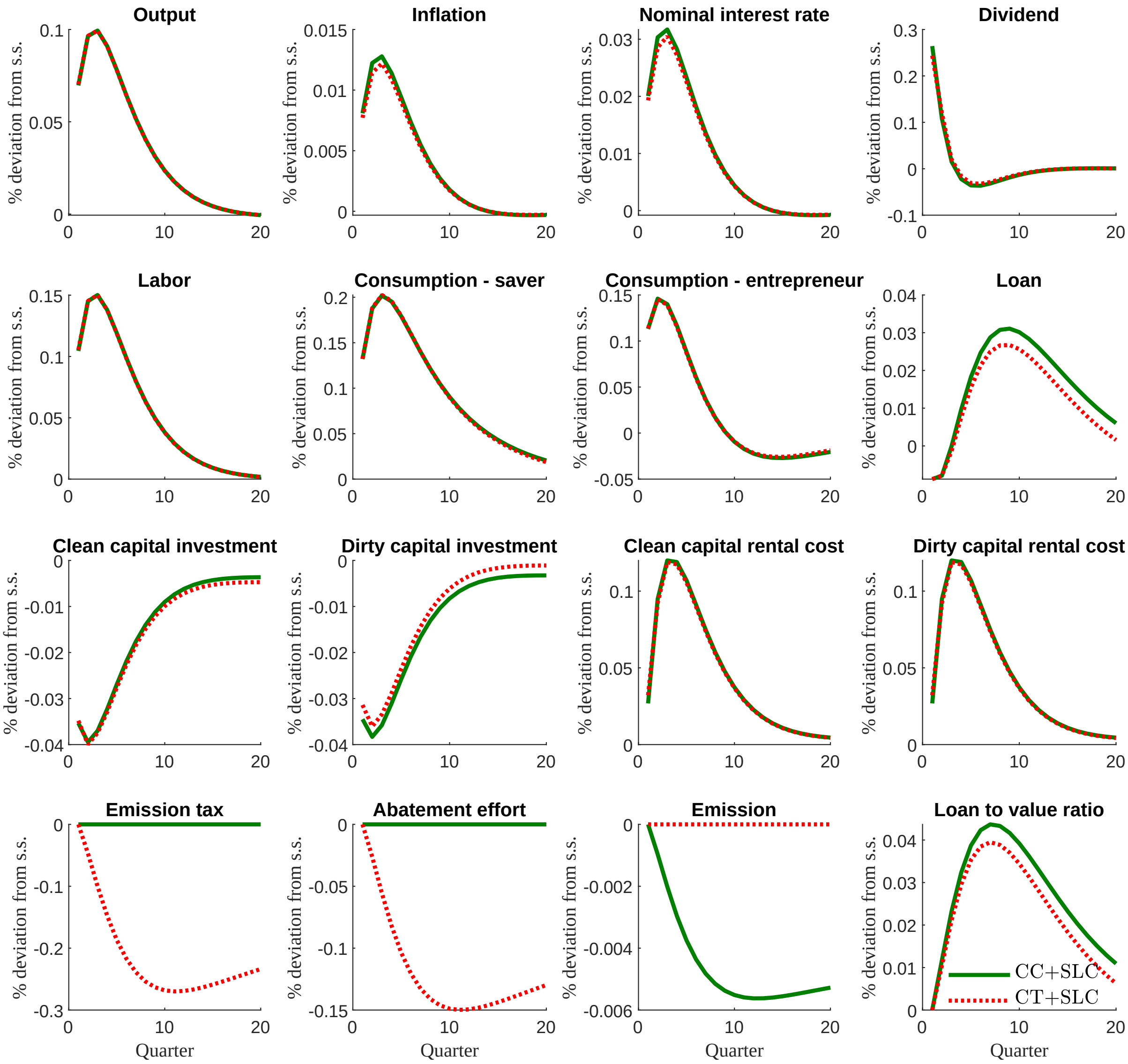

Figure 6: Environment policy scenarios with SLC: 1% consumption preference shock

This research joins the strand of literature on the role of the central bank in promoting sustainability. There is room to expand, including having a full-fledged banking sector or a more detailed production network. We leave these important aspects for future research.

References

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous (2012, February). The Environment and Directed Technical Change. *American Economic Review 102*(1), 131–166.

Annicchiarico, B., S. Carattini, C. Fischer, and G. Heutel (2021, July). Business Cycles and Environmental Policy: Literature Review and Policy Implications. Working Paper 29032, National Bureau of Economic Research. Series: Working Paper Series.

Annicchiarico, B., S. Carattini, C. Fischer, and G. Heutel (2022). Business cycles and environmental policy: A primer. *Environmental and Energy Policy and the Economy 3*(1), 221–253.

Annicchiarico, B. and F. Di Dio (2015, January). Environmental policy and macroeconomic dynamics in a new Keynesian model. *Journal of Environmental Economics and Management 69*, 1–21.

Annicchiarico, B. and F. Di Dio (2017, August). GHG Emissions Control and Monetary Policy. *Environmental and Resource Economics 67*(4), 823–851.

BOJ (2021). Establishment of "principal terms and conditions of the funds supplying operations to support financing for climate change responses". Bank of Japan.

Boldrin, M., L. J. Christiano, and J. D. Fisher (2001). Habit persistence, asset returns, and the business cycle. *American Economic Review 91*(1), 149–166.

Campiglio, E. (2016, January). Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy. *Ecological Economics 121*, 220–230.

Chan, Y. T. (2020, June). Are macroeconomic policies better in curbing air pollution than environmental policies? A DSGE approach with carbon-dependent fiscal and monetary policies. *Energy Policy 141*, 111454.

Chen, C., D. Pan, Z. Huang, and R. Bleischwitz (2021, August). Engaging central banks in climate change? The mix of monetary and climate policy. *Energy Economics*, 105531.

Christiano, L., M. Eichenbaum, and C. Evans (2005). Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy. *Journal of Political Economy 113*(1), 1–45.

DBS (2021). Sustainability-linked Transactions. DBS Bank.

Dikau, S. and U. Volz (2021, June). Central bank mandates, sustainability objectives and the promotion of green finance. *Ecological Economics 184*, 107022.

Economides, G. and A. Xepapadeas (2018, April). Monetary Policy under Climate Change. Technical Report 7021.

Ferrari, A. and V. Nispi Landi (2020). Whatever it Takes to Save the Planet? Central Banks and Unconventional Green Policy. Technical Report 20202500, European Central Bank.

Fuhrer, J. C. (2000). Habit formation in consumption and its implications for monetary-policy models. *American economic review 90*(3), 367–390.

Herbst, E. P. and F. Schorfheide (2015, December). *Bayesian Estimation of DSGE Models* (1 ed.). The Econometric and Tinbergen Institutes Lectures. Princeton University Press.

Heutel, G. (2012, April). How should environmental policy respond to business cycles? Optimal policy under persistent productivity shocks. *Review of Economic Dynamics 15*(2), 244–264.

Hommes, C. H., K. Mavromatis, T. Ozden, and M. Zhu (2019). Behavioral learning equilibria in the new keynesian model.

Iacoviello, M. and S. Neri (2010, April). Housing Market Spillovers: Evidence from an Estimated DSGE Model. *American Economic Journal: Macroeconomics 2*(2), 125–164.

Jermann, U. J. (1998). Asset pricing in production economies. *Journal of monetary Economics 41*(2), 257–275.

LMA (2019, March). Sustainability Linked Loan Principles. Technical report. Loan Market Association.

MAS (2021, January). MAS Launches World's First Grant Scheme to Support Green and Sustainability-Linked Loans. Monetary Authority of Singapore.

Mizuho (2021). Mizuho utilizing the bank of japan's climate response financing operations. Mizuho Group.

Muller, N. Z. (2021, June). On the Green Interest Rate. Technical Report w28891, National Bureau of Economic Research.

Nordhaus, W. D. (1993). Optimal greenhouse-gas reductions and tax policy in the" dice" model. *The American Economic Review 83*(2), 313–317.

Papageorgiou, C., M. Saam, and P. Schulte (2017). Substitution between clean and dirty energy inputs: A macroeconomic perspective. *Review of Economics and Statistics 99*(2), 281–290.

Papoutsi, M., M. Piazzesi, and M. Schneider (2021, May). How unconventional is green monetary policy? Technical report. Working paper.

Pfeifer, J. (2021). A guide to specifying observation equations for the estimation of dsge models.

Quint, M. D. and M. P. Rabanal (2013). *Monetary and macroprudential policy in an estimated DSGE model of the euro area*. International Monetary Fund.

Ravn, M. O., S. Schmitt-Grohė, L. Uuskula, et al. (2010). Deep habits and the dynamic effects of monetary policy shocks. *Journal of the Japanese and International Economies 24*(2), 236–258.

Smets, F. and R. Wouters (2007). Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach. *American Economic Review 97*(3), 586 – 606.

Wang, R., J. Hou, and Z. Jiang (2021, February). Environmental policies with financing constraints in China. *Energy Economics 94*, 105089.

Woodford, M. (2003). *Interest and Prices: Foundations of a Theory of Monetary Policy*. Princton: Princton University Press.

A Appendix

This section describes the data utilized in the Bayesian estimation of coefficients given in Table 2. We use Pfeifer (2021) for the construction of observable variables in the estimation process. Hence, we have

$$y_t^{obs} = 100log((GDP_t/GDPDEF_t)/CLF160V_t) \tag{A.0.37}$$

$$c_t^{obs} = 100log((PCEC_t/GDPDEF_t)/CLF160V_t) \tag{A.0.38}$$

$$i_t^{obs} = log(1 + FEDFUNDS_t/400) \tag{A.0.39}$$

where,

- **GDP:** Gross Domestic Product, Billions of Dollars, Quarterly, Seasonally Adjusted Annual Rate. Source: Federal Reserve Bank of St. Louis.
- **GDPDEF:** Gross Domestic Product: Implicit Price Deflator, Index 2012=100, Quarterly, Seasonally Adjusted. Source: Federal Reserve Bank of St. Louis.
- **CLF160V:** Civilian Labor Force Level, Thousands of Persons, Monthly, Seasonally Adjusted Source: Federal Reserve Bank of St. Louis[2].
- **PCEC:** Personal Consumption Expenditures, Billions of Dollars, Quarterly, Seasonally Adjusted Annual Rate. Source: Federal Reserve Bank of St. Louis.
- **FEDFUNDS:** Federal Funds Effective Rate, Percent, Monthly, Not Seasonally Adjusted. Source: Federal Reserve Bank of St. Louis[3].

We use the HP filtered series of y_t^{obs}, con_t^{obs}. On the other hand, the deviation of i_t^{obs} from sample mean is used in the estimation procedure.

[2] We used the mean of monthly data to obtain the quarterly figures (billions).
[3] We used the mean of the monthly data to obtain quarterly figures.