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The Role of Macroprudential Policies under Carbon Pricing[*]

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Abstract

This paper analyses the effectiveness of macroprudential policy on macro-financial fluctuations when the government enforces carbon pricing to reduce carbon emissions and achieve the net-zero target. A carbon tax policy alone can reduce carbon emissions by 2030, but at the cost of a deep and prolonged recession, with consequential financial instability due to a higher probability of default on entrepreneurs in the brown sector. This result suggests that carbon pricing should be coupled with complementary policies, such as macroprudential policy. In particular, differentiated LTV ratios and differentiated capital requirements that penalise the brown sector in favour of the green sector tend to decrease the probability of default in the green sector and encourage green lending in supporting the transition to a green economy. However, such policies have little contribution in offsetting the negative impact on the macroeconomy. More stringent levels of prudential regulations are needed to reduce the fall in GDP and consumption. More specifically, the "one-for-one" prudential capital requirements on fossil fuel financing can effectively reduce defaults and move to a greener economy.

Keywords: E-DSGE model; environmental policy; carbon pricing; net-zero; transition risk; macroprudential policy; welfare analysis;
JEL-Codes: E32, E44, E52, G18, G50, G58

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”Time is running out: dramatically reducing emissions is not an option, it is an imperative.” by the WorldBank, May 23, 2022.[1]

1. INTRODUCTION

Over the last several decades, governments have collectively pledged to prevent average global temperatures from increasing by 2^oC above preindustrial levels. Despite intensified diplomacy to reduce greenhouse gas emissions, such as the Kyoto Protocol and the Paris Agreement, the amount of carbon dioxide in the atmosphere keeps rising and some researchers forecast that global temperatures will rise by 2.6^oC by the end of the century, underlining the need for stronger actions.[2] Many experts consider carbon pricing the most cost-effective tool to mitigate emissions and achieve net zero targets.[3] See Stiglitz et al. (2017), Mehling and Tvinnereim (2018) and Tvinnereim and Mehling (2018). Carbon pricing policies, implemented through an emissions trading system (ETS) or carbon tax, are planned to be set very high to provide an effective signal to society to reduce fossil fuel consumption.[4] The Network for Greening the Financial System’s “Net Zero 2050” scenarios (NGFS (2021)) estimate carbon prices will reach between $100 and $200 a ton of CO2 by 2030, rising sharply until 2050. In Singapore, the carbon tax will be raised from the current value of S$25/tCO2e to S$45/tCO2e between 2026 and 2027, with a view of reaching S$50-80/tCO2e by 2030. The government of Singapore aims to provide a strong price signal to businesses and individuals to reduce their carbon footprint in line with national climate goals. Similarly, the Government of Ireland intends to steadily increase the carbon tax rate to reach EUR 100 per tonne of CO2 by 2030 from EUR 26 per tonne set in 2020. Although carbon pricing can be an effective instrument to support decarbonization and promote climate change mitigation, several studies have proved that carbon taxes alone are not sufficient to reach the ambitious net-zero target.[5] Further, the long-term goal of limiting the use of fossil fuels energy, or encouraging a shift towards renewables, comes with short-term costs, that could

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[1] See `https://www.worldbank.org/en/news/feature/2022/05/23/what-you-need-to-know-about-net-zero`

[2] See the report by the Climate Action Tracker (Tracker (2023)). Available online: `https://climateactiontracker.org/global/temperatures` (accessed on 5 December 2023).

[3] Carbon pricing is an instrument that captures the external costs of greenhouse gas (GHG) emissions by passing the cost of emitting on to emitters. There are two main types of carbon pricing: emissions trading systems (ETS) and carbon taxes. An ETS – sometimes referred to as a cap-and-trade system – caps the total level of greenhouse gas emissions and allows those industries with low emissions to sell their extra allowances to larger emitters. A carbon tax puts a direct price on GHG emissions and requires economic actors to pay for every ton of carbon pollution emitted.

[4] For instance, Diluiso et al. (2021) show that a climate policy set 3 years later still has an impact on reducing carbon emissions, but need to be much stronger as agents will have less time to adapt to the new policy framework.

[5] See for instance Rosenbloom et al. (2020), Aldy and Stavins (2012), Ball (2018), and Baranek et al. (2021).

materialize in economic slowdown and financial instability. Indeed, tightening environmental regulations tends to increase prices in carbon-intensive supply chains, and such higher production costs reduce profitability, which lowers investment and equity prices. All those factors could deteriorate firms' ability to service their debts and affect banks' ability to fully recover the corresponding value of a loan. See Huang et al. (2021) and Huang et al. (2022).

Given this background, this paper explicitly considers the potential adverse feedback loops to the wider economy and financial stability when mitigating climate change through environmental policies that force companies to assume the cost of carbon emissions. The objectives of this study can be explained in two folds. Firstly, the paper links climate-related policies to corporate default risk, which leads to higher interest rates, making the green transition harder to achieve. Second, the paper considers the rule of macroprudential policies in accelerating the orderly transition to a greener economy, while avoiding larger shocks or abrupt changes in the financial system stemming from climate-related policy risks. To do so, this paper develops an environmental dynamic stochastic general equilibrium (E-DSGE) model with "brown" (i.e., high-carbon emitting industries) and "green" (i.e., low-carbon emitting industries) production sectors, and two sources of inefficiencies: a pollution externality and financial frictions in a banking sector.[6] The model setup extends the work of Huang et al. (2021) and Huang et al. (2022) by assessing the net-zero pledge of a mixed policy of carbon taxes and macroprudential policies. The model helps answer the following questions: (i) How does carbon pricing affect the macro-economy and the financial system, and through which channels does it propagate? (ii) What kind of climate policies can directly/indirectly support decarbonization and promote climate change mitigation and adaptation? (iii) Climate-related uncertainty and risk can threaten financial institutions; what policies can reinforce funding flows to the green transition without compromising financial stability? Understanding climate-related risk and its propagation offers opportunities to reduce the potential negative impacts throughout the economy and financial system, prompting banks to launch more green credit projects, which promotes the green transformation of the macroeconomy and makes credit resources flow more to low-carbon industries.

Results from the model simulation show that carbon pricing policies curb carbon emissions by reducing production in the brown sector. However, carbon pricing discourages investments in brown assets, which lose value, leading banks to cut loans and increase

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[6] The brown sector refers to the highest greenhouse gas and carbon emitting industries. The green sector refers to firms that are considered more environmentally sustainable because they produce products or services by contributing directly to preserving and enhancing the quality of the environment. For instance, companies that use clean energy such as solar panel installed on the rooftop.

lending rates. This further contributes to the decline in investment and output because of the financial accelerator mechanism. However, because banks still hold brown assets on their balance sheet, the risk of brown-stranded assets reveals a spillover effect on the green sector. Thus, climate-related policies affect financial stability by increasing the default rate in both sectors, compromising a smooth transition to a low-carbon economy. This occurs through two channels: (i) the *banking capital channel* induces banks to supply fewer loans as a result of less bank capital, making it difficult to start new projects; (ii) the *banking funding channel* induces banks to charge higher lending rates in both sectors to reestablish their profitability.

This paper offers two main contributions. *First*, this paper extends the work of Diluiso et al. (2021) and Carattini et al. (2023) by explicitly considering an endogenous default rate in both productive sectors, which allows us to consider the role of banking capital and banking funding channels in supporting financing the green sector. *Second*, this paper extends the mentioned literature by investigating the interacting role of specific green macroprudential policies and carbon pricing in addressing associated systemic risks of climate change.[7] More specifically, this paper considers sectoral leverage ratios and sectoral bank capital requirements. For the leverage ratio, authorities allow a relaxation on the loan-to-value (LTV) ratio to the green sector in trying to boost green and sustainable growth, versus a more tightened LTV to the sectors using fossil fuels energy. Caps on LTV ratios are lender-based measures used to influence the amount of lending to particular targeted companies or sectors that are involved primarily in carbon-intensive activities. A lower LTV ratio implies a larger downpayment to be made in advance. As firms are financially constrained, acquiring a larger amount of cash could be difficult, discouraging borrowing to finance new projects. In the opposite case, a higher LTV ratio encourages borrowing as less cash is required to be paid in advance. Therefore, green differentiated LTV ratios in favour of green lending can support the transition to a low-carbon economy.

Regarding bank capital requirements, 72.4% of 29 central banks use capital requirements as a tool against financial instability according to the Financial Stability Benchmarks 2023.[8] This tool requires maintaining a capital conservation buffer of greater than 2.5 percent above the regulatory minimum capital requirement of 8 percent in order to avoid restrictions on capital distributions and other payments. Such capital buffer was mandated under the Basel III regulatory reforms, following the 2007-2008 financial

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[7] Green macroprudential tools include sectoral prudential instruments that aim to penalize the brown sector and favor the green sector during the lending process. See D'Orazio and Popoyan (2019) for a complete list of instruments.

[8] `https://www.centralbanking.com/benchmarking/financial-stability/7959500/reserve-requirements-and-countercyclical-buffers-are-most-common-macro-pru-tools`

crisis. Since then, and given the large use of this macroprudential instrument, this paper focuses specifically on bank capital requirements, for which two policies are evaluated. One policy requires banks to hold a mandatory 2.5 percent capital conservation buffer on assets related to funds to the fossil fuel sector over and above the minimum capital adequacy ratio (CAR) of 8 percent of "brown" risk-weighted assets, while a very low requirement is required for loans and assets to the green sector. The second policy assesses the implementation of the "one-for-one" prudential capital requirements for financing new fossil fuels. This prudential policy requires that for each euro/dollar that finances new fossil fuel projects, banks and insurers should hold a euro/dollar to guard against future risks.[9] Regarding the use of macroprudential policy in limiting carbon emissions and thus shrinking lending to polluting firms, this paper is very close to D'Orazio and Popoyan (2019), who find that green macroprudential tools can play an important role in supporting the decarbonization of banks' balance sheets and promote green investments. This current paper extends the intuition behind D'Orazio and Popoyan (2019), and analyzes the business cycle properties, as well as the macro-financial linkage, of the implementation of carbon pricing under a mix of macroprudential policies that have the ultimate goal of reducing the transition risk that arises from adjustments towards carbon neutrality.

The results suggest that introducing the "one-for-one" prudential capital requirements help stimulate investment in the green sector and reduce the negative impact on output generated by higher carbon taxes. Furthermore, such a policy limits the default rate in both sectors generated by the higher risk premium that banks tend to charge when internalising the climate-related risk. In contrast, a lower LTV ratio and an increase in CAR (2.5% conservation capital buffer) to the fossil fuel sector have marginal effects in attenuating the macroeconomic and financial instability that occur in the aftermath of carbon pricing shocks (i.e., an increase in the carbon tax rate).[10] This mainly depends on the fact that a larger default rate in the brown sector spillovers to the green sector even in the presence of more favourable lending conditions. Overall, extremely differentiated policies are able to shut down the banking capital and funding channels in the green sector by avoiding the negative impact of cutting loans to the green sector by banks and avoid the increase in lending rates to the green sector. This occurs because banks prefer lending to the green sector instead of financing the brown sector with their own funds. To stimulate green lending, they offer lower interest rates in order to facilitate the green transition.

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[9] This basic risk management principle is already applied to other high-risk exposures, such as risk to cryptocurrencies' exposures.

[10] A carbon pricing shock can also refer to a lower limit or cap on the amount of total direct GHG emissions allowed to be emitted in the form of carbon permits or allowances. However, in this paper, we only consider a carbon tax system.

Related literature. There is a booming literature that studies climate aspects at business cycle frequencies under the lens of DSGE models, building on Angelopoulos et al. (2010)), Fischer and Springborn (2011), Dissou and Karnizova (2016), Heutel (2012), and Annicchiarico and Di Dio (2015), among others. All these pioneering studies have only evaluated the business cycle implications of the fiscal side of environmental policies. However, climate-related financial risk has become an urgent issue that threatens the stability of the financial system. Thus, a recent emerging body of literature has focused on the pivotal role of the banking system in addressing climate change and in driving an orderly transition towards a low-carbon economy. Huang et al. (2021) and Huang et al. (2022) analyze climate-related risks in Chinese areas where stringent environmental policies have been implemented. They highlight the potential adverse feedback loops to the wider economy and financial stability using a DSGE model with the banking sector. Comerford and Spiganti (2023) analyze how a carbon bubble would generate a fire-sale as investors rush in selling assets from polluting industries. With respect to the safeguarding of the financial institution's resilience against the adverse impacts of climate change, Punzi (2019), Annicchiarico and Di Dio (2017), Carattini et al. (2023), Diluiso et al. (2021), Ferrari and Nispi Landi (2023), Giovanardi et al. (2023) and Ferrari and Landi (2024) incorporate financial frictions *à* la Gertler and Karadi (2011) into the E-DSGE framework with the goal of assessing the role of different fiscal, monetary, and macroprudential policies on climate change. According to studies, a consensus emerges that the use of monetary policy and macroprudential policy alone is not effective in fighting against climate change. In particular, while Carattini et al. (2023), Diluiso et al. (2021), and Giovanardi et al. (2023) focus on the role of macroprudential policies, Ferrari and Landi (2024) explore the potential effects of a green quantitative easing policy in the Euro-Area under the hypothesis of imperfect substitutability between green and brown assets. While all these previous studies analysis business cycle fluctuations of environmental policies, as well as the related performance of monetary and macroprudential regulations during the transition to carbon neutrality, this paper focuses on the role of green differentiated macroprudential policies under a scenario in which environmental policies become more stringent. Indeed, many governments consider carbon pricing a central tool to facilitate the transition to net-Zero by 2050.

The paper is organized as follows. Section 2 presents the model, and Section 3 describes the calibration. Sections 4 presents the simulation results of carbon pricing shocks. Section 5 evaluates and discusses the implications of macroprudential policies. Section 6 concludes.

2. MODEL

The model recalls the setup used in Bernanke et al. (1999) and Christiano et al. (2014), augmented by carbon pricing. In particular, the government penalizes brown firms, who produce goods by using fossil fuel, by making their carbon emissions very costly. The model consists in a close economy characterized by households, who consume, work and save, by capital producers, by a banking sector, that collects deposits from households and supply funds to firms, by green and brown goods productive sectors, and by a government who levies carbon pricing.[11]

The goal of this model is to understand the macro-financial implications of a transition to a carbon-free economy. In the event of disorderly green transition, environmental-related risks could spread throughout the financial system, as surge in carbon pricing could trigger corporate default because of financial market losses. While this particularly applies to high-carbon companies whose production depends on the usage of fossil fuel energy, it could also affect less-carbon-intensive companies. Given this background, the model is characterized by an endogenous default that affects the ability of entrepreneurs to service their loans. Further, the model features financial frictions, such as limits on loan to value (LTV) ratios and mandatory regulatory minimum capital requirements on loans, to discourage lending to coal companies, and speed up the transition to net-zero.

2.1. HOUSEHOLDS

The model assumes that households are identical, with a constant population normalized to 1. A representative household maximizes real consumption of goods, C_t, labor supplied to firms, L_t, and nominal savings (deposits) held at the commercial banks, D_t, in order to satisfy the following lifetime expected utility:

$$\max V_0 = E_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{c_t^{1-\sigma_c}}{1-\sigma_c} - \mu_L \frac{L_t^{1+\phi_L}}{1+\phi_L} \right], \tag{1}$$

subject to the following intertemporal budget constraint:

$$C_t + D_t \leq W_t L_t + \frac{R_{t-1}}{\pi_t} D_{t-1} + F_t - T_t. \tag{2}$$

where $\beta \in (0,1)$ is the discount factor, σ_c is the relative risk aversion, μ_L is the labor

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[11] Similar setup can be found in Huang et al. (2021) and Huang et al. (2022).

disutility indicating the preference of leisure relative to consumption, and ϕ_L is the inverse of the Frisch elasticity of work effort. W_t represents the real wage, and R_t is the risk-free gross nominal interest rate received on deposits, and $\pi_t = P_t/P_{t-1}$ is the inflation rate. Households also receive real dividends from firms, F_t, and lump-tax or transfers from the government, T_t.

2.2. FINAL GOODS FIRMS AND PRICE SETTING

The model assumes there is a continuum of monopolistic competitive firms, indexed $i \in [0,1]$, who combine differentiated intermediate goods $Y_t(i)$ into a final consumption good Y_t, according to a constant elasticity of substitution technology:

$$Y_t = \left[\int_0^1 Y_t(i)^{\frac{\xi-1}{\xi}} di\right]^{\frac{\xi}{\xi-1}}, \tag{3}$$

where $\xi > 1$ is the elasticity of the substitution between the different intermediate goods.

The standard profit maximization problem determines the input demand for the intermediate good i as follows:

$$Y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\xi} Y_t, \tag{4}$$

with

$$P_t = \left[\int_0^1 P_t(i)^{1-\xi} di\right]^{\frac{1}{1-\xi}}. \tag{5}$$

where $P_t(i)$ and P_t are the price of intermediate goods and the CES-based final (consumption) price index, respectively.

Price setting

Each period prices of intermediate goods can be adjust with a probability $(1-\theta)$. See Calvo (1983). $P_t^*(i)$ is the price that intermediate producers are able to adjust. Thus, firms maximize the following expected profit:

$$\max E_t \sum_{k=t}^{\infty} (\beta_s \theta)^{k-t} \frac{U_{C_{st+k}}}{U_{C_{st}}} \left\{ (\frac{P_t^*(n)}{P_{t+k}} - \frac{X_t}{X_{t+k}}) Y_{t+k}^*(i) \right\} \tag{6}$$

where $Y_{t+k}^{*}(i) = \left(\frac{P_t^*(i)}{P_{t+k}}\right)^{-\xi} Y_{t+k}$. X_t is the markup of final over intermediate goods and in steady state is equal to $X = \xi/(\xi - 1)$. The Calvo price evolves according to the following:

$$P_t = \left[\theta P_{t-1}^{\xi} + (1-\theta)(P_t^*)^(1-\xi)\right]^{\frac{\xi}{\xi-1}}. \tag{7}$$

Combining these two last equations, and after log-linearizing, an expression for the Phillips curve can be obtained as follows:

$$\pi_t = \beta_s E_t \pi_{t+1} - \Omega \hat{X}_t, \tag{8}$$

with $\Omega = \frac{(1-\theta)(1-\beta)\theta}{\theta}$, being marginal cost of production.

2.3. ENTREPRENEURS AND BORROWING CONSTRAINTS

The intermediate goods market is divided into two sectors: a green sector (g) that produces goods using clean and renewable energy, and a brown sector (ng) that produces goods using fossil fuel energy:[12]

$$Y_t(n) = \sigma_g Y_{e,t}^{g} + \sigma_{ng} Y_{e,t}^{ng} \tag{9}$$

where σ_g and σ_{ng} represents the market share of green and brown firms, respectively.[13] Accordingly, the price level is set such that $P_t(i) = \sigma_g P_{e,t}^{g}(n) + \sigma_{ng} P_{e,t}^{ng}(n)$.

Each sector is populated by many entrepreneurs, indexed by $j \in [0, n^j]$, where n^j indicates the total number of green and brown firms in the economy.[14]

Entrepreneurs in each sector are credit-constrained. In order to finance new projects, entrepreneurs in each group purchase the stock of capital, $k_{e,t}^{j}$ at the real price, q_t^k, which

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[12] Similar to Huang et al. (2021), the model assumes a perfect substitution among intermediate goods, allowing to have the same levels of intermediate goods' prices according to whether they are produced by green or brown intermediate firms. Benkhodja et al. (2023) find that the effectiveness of green policies increases for higher elasticity of substitution between green and brown goods. Chan et al. (2023) assume an equal elasticity of substitution between the green and brown sectors, as well as within each sector for intermediate goods. They make this assumption for the sake of simplicity.

[13] $\sigma_g + \sigma_{ng} = 1$.

[14] Entrepreneurs in each sector produce intermediate goods to sell to final good producers.

can be financed by either entrepreneurs' net worth, $N^j_{e,t+1}$, and bank loans, $b^j_{e,t+1}$:[15]

$$q^k_t k^j_{e,t} = N^j_{e,t+1} + b^j_{e,t+1} \tag{10}$$

Each undertaken project can be risky, as the decision on how much capital and how much credit to request for the project by entrepreneurs occur in advance and prior the realization of the project itself. Thus, entrepreneurs j can become insolvent if the following expression no longer satisfies:

$$\bar{\omega}^j_{t+1} R^j_{K,t+1}(q^k_{t+1} k^j_{e,t+1}) = b^j_{e,t} R^j_{z,t+1} \tag{11}$$

where $\bar{\omega}^j_{t+1}$ indicates a threshold value that differentiate between profitable and non-profitable projects. This threshold variable reflects the quality of capital in each sector, in the form of risk shocks as in Christiano et al. (2014), to capture changes in the value of capital due to investors' perceptions of climate risks from adverse weather events or policy announcements.[16] The random variable $(\omega^j_{t+1})^i$ is an i.i.d. idiosyncratic shock which is log-normally distributed with cumulative distribution $F_{j,t}[(\omega^j_{t+1})^i)]$,[17] affecting the ex post gross return on capital for entrepreneurs j, given by $\omega^j_{t+1} R^j_{K,t+1}$. The ex-post profit for each project is $\Pi(\omega^i_{t+1}) = \omega^j_{t+1} R^{K,j}_t q^k_{t+1} (k^j_{e,t+1})^i - R^j_{z,t+1} b^j_{e,t}$, where $R_{z,t+1}$ the gross contractual state-contingent loan rate paid to the bank by non-defaulting entrepreneurs. Eq. 11 indicates that entrepreneurs are solvent if and only if the ex-post value of the return to capital on new projects (left hand side) is higher than the loan repayment, i.e. loan value plus interests, (right hand side). The idiosyncratic shock $(\omega^j_{t+1})^i$ can alter the realization of Eq. 11. If $(\bar{\omega}^j_{t+1})^i \in \left[\bar{\omega}^j_{t+1}, \infty\right]$, entrepreneurs are solvent and repay the loan to the bank; while for loans with low realizations, $(\bar{\omega}^j_{t+1})^i \in \left[0, \bar{\omega}^j_{t+1}\right]$, entrepreneurs declare bankruptcy and defaulting members loose their capital.

Eq. 11 is the key equation in determining the endogenous default. Indeed, fluctuations in asset prices, capital stock, credit flow, expected return on project and lending rates will change the threshold value $\bar{\omega}^j_{t+1}$. For instance, if the ex-post value of the project (left hand side) is lower relative to the amount of credit requested, entrepreneurs will default.[18]

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[15] Entrepreneurs assign equal resources to each member i to purchase capital $(k^j_{e,t})^i$, where $\int_i (k^j_{e,t})^i di = k^j_{e,t}$.

[16] See also Huang et al. (2021), Huang et al. (2022) and **?**.

[17] We allow for idiosyncratic risk, such that $E_t[(\omega^j_{t+1})^i] = 1$. This implies that $\log[(\omega^j_t)^i] \sim N(-\frac{\sigma_{\omega^2_{j,t}}}{2}, \sigma_{\omega^2_{j,t}})$, where $\sigma_{\omega_{j,t}}$ is a time-varying standard deviation for each type of entrepreneurs, which follows an AR(1) process.

[18] See Fig. 3 in Huang et al. (2021).

Entrepreneurs Maximization Problem.

Entrepreneurs in each sector maximize the following utility function, subject to the budget constraint and the bank participation constraint:

$$\max E_0 \sum_{t=0}^{\infty} (\beta^e)^t \left[ln(C^j_{e,t}) \right] \tag{12}$$

subject to:

$$\begin{aligned} C^j_{e,t} + P^X_t X_t + q^j_t k^j_{e,t} + w^j_t L^j_t + R^{j,K}_t q^j_t k^j_{e,t} + [1 - F_t(\bar{\omega}^j_t)] R^j_{z,t} B^j_{e,t-1} \\ = Y^j_{e,t} + B^j_{e,t} + q_t(1-\delta_k) k^j_{e,t-1} [1 - G_t(\bar{\omega}^j_t)], \end{aligned} \tag{13}$$

with

$$Y^j_{e,t} = \frac{A_t}{(\Upsilon_{t+1})} (k^j_{e,t-1})^{\alpha} (L^j_t)^{1-\alpha-\gamma_j} X^{\gamma_j}_t, \tag{14}$$

and

$$B^j_{e,t} \leq m^j_{e,t} \; E_t \frac{(q^{j,k}_{t+1} \pi_{t+1} (1-\delta_k) k^j_{e,t})}{R^L_t}, \tag{15}$$

where β^e is the entrepreneurs discount factor, $(1-\delta_k)$ is the depreciation rate of capital stock. A_t is the TFP shock and Υ_t the temperature. As in Papoutsi et al. (2021), TFP declines with temperature Υ_t, which increases with emissions, EM_t.[19] Temperature is defined as follows: $\Upsilon_{t+1} = \Upsilon_t + \phi_{\Upsilon} EM_t$, with ϕ_{Υ} is the degree by which temperature increases for a any unit of emission.[20]

The budget constraint in Eq. 13 indicates that entrepreneurs use revenues from selling intermediate goods, $Y^j_{e,t}$, to finance the entrepreneur's consumption, $C^j_{e,t}$, to pay wages to workers, $w^j_t L^j_t$, to pay for the rental of capital, $R^{j,K}_t q^j_t k^j_{e,t}$, to invest in new capital $q^j_t I^j_{e,t} = q^j_t (k^j_{e,t} - (1-\delta_k) k^j_{e,t-1})$, and to acquire energy, X_t, as an input factor for the production process. Eq. 15 indicates that in each period, entrepreneurs borrow the quantity $B^j_{e,t}$ from commercial banks to finance the acquisition of new capital for new projects, $q^j_t I^j_{e,t} = q^j_t (k^j_{e,t} - (1-\delta_k) k^j_{e,t-1})$. Each project financed is subject

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[19] Donadelli et al. (2017) use a VAR model to prove that temperature shocks reduce productivity growth.

[20] van der Ploeg and Rezai (2021) study the impact of global warming by developing a general equilibrium model in which temperature is a linear function of cumulative emissions, and thus the proportion of output lost due to global warming is also a linear function of temperature.

to individual contract where the financial institution charges an interest rate equal to $R^j_{z,t}$.[21] If the entrepreneur is solvent, next period repay the amount $R^j_{z,t}B^j_{e,t-1}$, while if the entrepreneurs defaults, then the bank will receive a lower amount equal to $[1 - F_t(\bar{\omega}^j_t)]R^j_{z,t}B^j_{e,t-1}$, where $F_t(\bar{\omega}^j_t)$ represents the default rate. Under the defaulting assumption, banks seize part of the capital, and the entrepreneurs is left with $[1 - G_t(\bar{\omega}^j_t)]q_t(1 - \delta_k)k^j_{e,t-1}$, where $G_t(\bar{\omega}^j_t)$ represents the share of capital seized by the bank. Entrepreneurs can use the capital they own as a collateral to pledge more credit from the banking sector. Eq. 15 indicates that entrepreneurs can borrow a fraction of the value of their capital, with $m^j_{e,t} = \left[\Gamma_{t+1}(\bar{\omega}_{bj,t+1}) - \mu_{ej}G_{t+1}(\bar{\omega}_{bj,t+1})\right]$, being the loan-to-value ratio, which is endogenously determined, and μ_j is the fraction of the capital value that banks pay to monitor and seize the collateral in case of default.

The variables $X = \{REN, E\}$ define the difference between green and brown sectors, where REN indicates clean and renewable energy, while E is dirty and polluting energy. P^X_t is the corresponding energy price.

Green Sector

Entrepreneurs' budget constraint in the green sector is given by the following:

$$\begin{gathered} Y^g_{e,t} + B^g_{e,t} + q_t(1 - \delta_k)k^g_{e,t-1}[1 - G_t(\bar{\omega}^g_t)] = \\ C^g_{e,t} + w^j_t L^g_t + R^{g,K}_t k^g_{e,t} + q^j_t K^g_{e,t} + [1 - F_t(\bar{\omega}^g_t)]R^g_{z,t}B^g_{e,t-1} + P^{Ren}_t REN_t, \end{gathered} \tag{16}$$

with

$$Y^g_{e,t} = \frac{A_t}{(\Upsilon_{t+1})}(k^g_{e,t-1})^{\alpha}(L^g_t)^{1-\alpha-\gamma_g} REN_t^{\gamma_g}, \tag{17}$$

REN_t is the consumption of clean and renewable energy that entrepreneurs buy at the price P^{Ren}_t.[22]

Brown Sector

Entrepreneurs' budget constraint in the brown sector is given by the following:

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[21] Loan rate $R^j_{z,t+1}$ is determined at time t, after the realization of the shocks.

[22] The model assumes that the price of clean/renewable energy is equal to 1 ($P^{Ren}_t = 1$).

$$
\begin{gathered}
Y^{ng}_{e,t} + B^{ng}_{e,t} + q_t(1-\delta_k)k^{ngr}_{e,t-1}[1 - G_t(\bar{\omega}^{ng}_t)] = \\
C^{ng}_{e,t} + w^j_t L^{ng}_t + R^{ng,K}_t k^{ng}_{e,t} + q^j_t K^{ng}_{e,t} + [1 - F_t(\bar{\omega}^{ng}_t)]R^{ng}_{z,t} B^{ng}_{e,t-1} + P^e_t E_t + (1-\theta^P)P^{em}_t EM_t,
\end{gathered} \tag{18}
$$

with

$$
Y^{ng}_{e,t} = \frac{A_t}{(\Upsilon_{t+1})}(k^{ng}_{e,t-1})^{\alpha}(L^{ng}_t)^{1-\alpha-\gamma_{ng}} E_t^{\gamma_{ng}}, \tag{19}
$$

E_t is the consumption of fossil fuel energy that entrepreneurs buy at the price P^e_t. The production process in the brown sector generates CO_2 emissions as a byproduct. Total emission, EM_t are equal to:

$$
EM_t = (1-\xi_t)\phi^{energy}_t E_t, \tag{20}
$$

with ϕ^{energy}_t being a comprehensive carbon emissions coefficient calculated according to the corresponding ratio in the total energy use, and ξ_t is the ratio of renewable energy to the total energy consumption during period t. See Zhao et al. (2020) and Yang et al. (2021). The government imposes environmental regulations with the aim of cutting carbon emissions through carbon tax or carbon trading scheme (CTS). The most common carbon trading scheme adopted so far from many governments is the cap-and-trade mechanism which sets a cap on the total amount of carbon emissions. The total amount of emissions is allocated to the CTS participants by adopting a combination of free distribution and auction for permit allocation. Thus, entrepreneurs in the brown sector pay the permit auction price, P^{em}_t, for a given amount of pollution allowed, $(1-\theta^P)EM_t$, where θ represents the ratio of free carbon permits.[23] The model assumes that the carbon permit price follows an exogenous shock. Alternatively, the government can impose carbon taxes on each level of emissions produced, then $(1-\theta^P)P^{em}_t EM_t$ in Eq. 18 becomes τEM_t, with τ being the carbon tax rate.[24]

Both P^e_t and P^{em}_t follow an autoregressive process AR(1) as below:

$$
P^e_t = \rho_{pe} P^e_{t-1} + \epsilon_{pe,t}
$$

---

[23] For instance, Aatola et al. (2013) assumes that the price of the European Union (EU) emission allowance is related to the structural energy consumption. For details about CTS in China, see Song et al. (2018).

[24] Both carbon pricing methods generate similar qualitative results, and they can use in this model interchangeably.

and

$$P^{em}_t = \rho_{em} P^{em}_{t-1} + \epsilon_{em,t}$$

with $\epsilon_{pe,t}$ and $\epsilon_{em,t}$ being an i.i.d. shocks.

2.4. BANKING SECTOR

The model assumes that there is a banking sector which receives at time t deposits from domestic households, D_t, and finance loans to entrepreneurs in the green and brown sector. The banker maximizes her preferences defined as:

$$\max E_0 \sum_{t=0}^{\infty} \beta_b^t \ln(C_{b,t}), \tag{21}$$

subject to the flow of funds

$$C_{b,t} + \frac{R_{t-1}}{\pi_t} D_{t-1} + B_t + G_t(\bar{\omega}^j_t) q_t (1-\delta_k) k^j_{e,t-1} + \Theta(x_t) = D_t + [1 - F_t(\bar{\omega}^j_t)] \frac{R^L_t}{\pi_t} B_{t-1} \tag{22}$$

and

$$D_t \leq (1-\kappa) B_t, \tag{23}$$

where $C_{b,t}$ denotes the banker's consumption (dividends) and β_b is its discount factor; $B_t{=}(\sigma_g B^g_{e,t} + \sigma_{ng} B^{ng}_{e,t})$ represents one-period bank loans extended to green and brown firms in period t. Eq. 23 describes the capital adequacy ratio (CAR), under which the amount of deposits that bankers can take cannot exceed a fraction $(1-\kappa)$ of bankers' assets net off the expected loan losses.[25] See Kollmann et al. (2011), Kollmann (2013) and Liu and Molise (2019). As in Punzi and Rabitsch (2018), the bank can hold less capital than the required or desired level, but deviating from this requirement implies a cost, Θ_t, which is a function of bank's excess capital, $\Theta_t = \Theta(x_t)$.[26]

The flow of fund described in Eq. 22 reports the expenditure side of the banker which includes current consumption, the interest payment on deposits to households, $\frac{R_{t-1}}{\pi_t} D_{t-1}$,

---

[25] The higher discount factor for bankers relative to entrepreneurs guarantees that the capital adequacy constraint is always binding in the neighbourhood of steady state.

[26] Θ_t is is a convex function with first derivative is $\Theta^{'} < 0$, which implies that a higher excess capital reduces the cost of deviating from the required capital ratio, and the second derivative $\Theta^{''} > 0$, which implies that a higher excess capital reduces the cost but at a decreasing rate.

new credit loans to the green B_e^g and brown sector B_e^{ng}, as well as the cost of deviating from the required capital ratio $\Theta(x_t)$. The flow of income includes the household deposits and the repayment of loans by green and non-green entrepreneurs net of the defaulting share, $[1-F_t(\bar{\omega}_t^j)]\frac{R_t^L}{\pi_t}B_{t-1}$. Then, in case of default, the bank seizes part of the capital, which then will become part of the banks' balance sheet, $G_t(\bar{\omega}_t^j)q_t(1-\delta_k)k_{e,t-1}^j$.[27]

The *optimal contract* is defined as a one-period loan contract which guarantees a risk neutral banks to obtain a predetermined rate of return on their total loans to entrepreneurs. At time t, the expected return from granted loans should guarantee the bank at least the gross rate of return, R_t^L times the total loans $B_{e,t+1}^j$ to entrepreneurs. This leads to the following participation constraint:

$$\begin{aligned}\overbrace{R_t^L B_{e,t}^j}^{\text{Expected Return from Lending}} &= + \underbrace{\left\{ \int_{\bar{\omega}_{j,t+1}}^{\infty} R_{Z,t+1}^j B_{e,t}^j f_{t+1}(\omega_j^i) d\omega_j^i \right\}}_{\text{Repayment in case of no default}} \\ &+ \underbrace{\left\{ (1-\mu^j) \int_0^{\bar{\omega}_{j,t+1}} \omega_{j,t+1}^i (1-\delta_h) q_{t+1}^{j,k} \pi_{t+1} k_{e,t+1}^j f_{t+1}(\omega_j^i) d\omega_j^i \right\}}_{\text{Seized capital value in case of default}} \end{aligned} \tag{24}$$

where $f(\omega_j^i)$ is the probability density function of ω_j^i, and μ^j is the monitoring cost that goes to lenders in case of default. More specifically, banks pay an auditing cost, μ^j, to verify the state of the project in order to potentially assess default, and eventually seize a fraction of the capital used as collateral to pledge loans equal to $\mu^j \bar{\omega}_{t+1}^j R_{K,t+1}^j (q_{t+1}^k k_{e,t+1}^j)$.[28]

The first term on the right hand side in Equation 24 measures the revenues that banks receive in case of no default, from the fraction of entrepreneurs with successful projects, for which $\omega_{j,t+1} \in (\bar{\omega}_{j,t+1}, \infty)$. The second term on the right hand side in Equation 24 indicates the revenues banks obtain in case of default, which are equal to the undepreciated expected value of the capital stock, net of monitoring costs. Therefore, in the bank's balance sheet is left a fraction $(1-\mu^j)$ of the seized capital if no repayment occur. Once the idiosyncratic and environmental policy shocks hit the economy, the threshold values $\bar{\omega}_{t+1}^j$ and the state-contingent mortgage rate $R_{Z,t+1}^j$ are determined, to fulfill the above participation constraint. As the banks can recover only a fraction of capital in case if default, this implies that banks will charge higher lending rate to satisfy the participation constraint. Equation 24 is defined as in Bernanke et al. (1999) and Christiano et al.

---

[27] $G_{t+1}(\bar{\omega}_{bj,t+1}) \equiv \int_0^{\bar{\omega}_{t+1}^j} \omega_{bj,t+1}^i f_{t+1}(\omega_{bj}^i) d\omega_{bj}^i$ is the expected value of the idiosyncratic shock for the case $(\omega_{t+1}^j)^i \in \left[0, \bar{\omega}_{t+1}^j\right]$ multiplied by the probability of default.

[28] See Rabitsch and Punzi (2017) for similar setup.

(2014). However, while they only focus only changes in $\omega_{j,t+1}$ as an exogenous process, this paper assumes that environmental policies can affect if by affecting its components, $\omega_{j,t+1} = \frac{R_t^L B_{e,t}^j}{R_{K,t+1}^j (q_{t+1}^k k_{e,t+1}^j)}$, and thus affecting the expected return from lending.

2.5. Capital Producers

The capital production market is perfectly competitive. Capital producers use existing capital and investment goods, I_t^j, to produce new capital. Existing capital is subject to an adjustment cost specified as $\frac{\psi_k}{2}\left(\frac{i_{k,t}}{k_{t-1}} - \delta_k\right)^2 k_{t-1}$, where ψ_k governs the slope of the capital producers adjustment cost function. Capital producers choose the level of $I_{k,t}$ that maximizes their profits

$$\max_{I_{k,t}} q_t^k i_{k,t} - \left(I_{k,t} + \frac{\psi_k}{2}\left(\frac{I_{k,t}}{k_{t-1}} - \delta_k\right)^2 k_{t-1}\right). \tag{25}$$

From profit maximization, it is possible to derive the supply of capital

$$q_t^k = \left[1 + \psi_k\left(\frac{I_{k,t}}{k_{t-1}} - \delta_k\right)\right], \tag{26}$$

where q_t^k is the relative price of capital. In the absence of investment adjustment costs, q_t^k, is constant and equal to one. The usual capital accumulation equation defines aggregate capital investment:

$$I_{k,t} = k_t - (1 - \delta_k)\, k_{t-1}. \tag{27}$$

2.6. Authorities

The Central Bank follows a standard Taylor-type rule that adjusts the nominal interest rate in response to deviations in both inflation and output from their steady-state values:

$$\frac{R_t}{\bar{R}} = \left(\frac{R_{t-1}}{\bar{R}}\right)^{\phi_R} \left(\frac{\pi_t}{\bar{\pi}}\right)^{\phi_\pi(1-\phi_R)} \left(\frac{Y_t}{\bar{Y}}\right)^{\phi_Y(1-\phi_R)} \tag{28}$$

where ϕ_π is the coefficient on inflation in the feedback rule, ϕ_Y is the coefficient on output, and ϕ_R determines the degree of interest rate smoothing.

For the public sector, the model assumes that the government meets the balance of payments, and the government budget constraint can be expressed as:

$$G_t = (1-\theta^P)P_t^{em}EM_t \tag{29}$$

2.7. MARKET CLEARING

$$Y_t = C_t + i_{k,t} + E_t + M_t + \Sigma_j \mu^j G_{t+1}(\bar{\omega}_{j,t+1})q_{t+1}^{j,k}(1-\delta_k)k_{e,t}^j) \tag{30}$$

$$C_t = C_t + \sigma_g C_{e,t}^g + \sigma_{ng} C_{e,t}^{ng} + C_{b,t} \tag{31}$$

$$k_t = \sum_j \sigma_j k_{e,t}^j \tag{32}$$

$$L_t = \sum_j \sigma_j L_t^j \tag{33}$$

$$C_t = \sum_j \sigma_j C_{e,t}^j \tag{34}$$

$$q_t^k = \sum_j \sigma_j q_t^{j,k} \tag{35}$$

3. PARAMETERIZATION

Table 3 reports parameters that help to match quarterly standard values of a real business cycle model. The discount factor β is set to 0.98 to meet the average annualized real short-term interest rate of 4%. Similar to Campbell and Hercowitz (2009), Krusell and Smith (1998) and Iacoviello (2015), entrepreneurs are assumed to be more impatient and willing to borrow because they are financially constrained, therefore their discount factor is lower relative to savers, and equal to $\beta^e = 0.94$. The lower discount factor implies a steady-state lending rate of 5%.The discount factor for bankers is assumed to be the same as households. The depreciation rate of physical capital δ_k is set equal to 0.025, while the adjustment cost parameter on investments is equal to 5, as is generally used in the literature. The capital share of Cobb-Douglas productivity function is set to 0.35, a value broadly used in the DSGE literature.

The share of clean and renewable energy in the production function of the green sector is set to 0.0248, which together with a 30% of firms size in the green sector, matches the share of the US renewable energy relative to the total U.S. primary energy consumption of 13% recorded in 2021. In contrast, The elasticity of output with respect to fossil fuel energy is set to 0.15 to match the fossil fuel share in worldwide electricity production of around 62% in 2021.[29] The coefficient of temperature relative to emissions, ϕ_{Υ}, is set equal to 0.01.

As in Gali (1999), the inverse elasticity of labor supply, η, is set equal to 2 and the coefficient of relative risk aversion, σ_c, is set to 1.01. We follow estimates by Leduc and Natal (2018) in setting the price elasticity ξ equal to 6 and the Calvo probability to adjust prices, θ, equal to 0.67. Both values allow to match the markup of price over marginal costs of 1.1. For the monetary policy parameters of the Taylor rule, we follow Justiniano et al. (2015) and the coefficient for the interest rate inertia, ρ_R, equal to 008, the reaction to the output gap, $\rho_Y = 0.125$, and the reaction to inflation of $\rho_\pi = 1.5$.

As in Liu and Molise (2019), the banking regulator imposes a required bank capital ratio, κ, equal to 0.08. The bank cost parameter for deviating from capital requirements is set equal to 0.25.[30]

The steady-state value of the loan-to-value ratio for the green and brown sector is set to 63% and 75%, respectively. In order to obtain those values, the monitor cost and the standard deviation of the idiosyncratic capital risk shock for the green and brown sector are set equal to 0.125 and 0.201 for the green sector, and to 0.25 and 0.108 for the brown sector.[31] There is no information about the loan-to-value ratio for the green and brown sector. Therefore, for the brown sector, the ratio is set equal to 75% reflecting the average ratio for the U.S. corporate sector. Regarding the green sector, we assume that banks can offer a lower loan-to-value ratio as firms are in general new and the banks don't know too much about them, relative to the brown sector in which entrepreneurs are probably old customers, such as the oil and gas sector. Therefore, we simply set a lower loan-to-value ratio in the green sector relative to the brown sector.

To replicate an emission cut of around 30% when the government uses carbon pricing as environmental tool, the persistence of the environmental policy shock is set equal to 0.97 and the standard deviation is set to 0.01.

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[29] Source: `https://www.statista.com/statistics/1303803/global-fossil-fuel-share-in-power-generation/`

[30] Similar values were used in Kollmann et al. (2011), Punzi and Rabitsch (2018).

[31] Similar values are used in Punzi and Rabitsch (2018) to match a loan-to-value of 67% and 73% for different types of households.

Table 1: The calibrated and estimated parameter values used for numerical analysis.

Calibrated Parameters	Value	Description
β	0.98	Discount factor of households
β^e	0.94	Discount factor of entrepreneurs
β^b	0.98	Discount factor of bankers
δ_k	0.025	Capital depreciation parameter
ψ_k	5	Adj cost of capital
α	0.35	Share of capital in production
γ_g	0.0248	Share of renewable energy in green production
γ_{ng}	0.15	Share of fossil fuel energy in brown production
η	2	Inverse elasticity of labor supply
σ_C	1.01	Risk aversion parameter
ξ	6	Price elasticity
ν	0.67	Parameter of Calvo pricing adjustment
ρ_π	1.5	Taylor-rule parameter, inflation
ρ_R	0.8	Taylor-rule parameter, int. rate smoothing
8 ρ_Y	0.125	Taylor-rule parameter, output
κ	0.08	Capital adequacy ratio
Θ	0.25	Parameter for deviating from capital requirements
μ^g	0.125	Monitor cost for the green sector
σ^g	0.201	Standard deviation of the idiosyncratic risk in the green sector
μ^g	0.25	Monitor cost for the brown sector
σ^g	0.108	Standard deviation of the idiosyncratic risk in the brown sector
p^E	1	Steady-state of energy price
p^E	1	Steady-state of polluting permits
A	1	Steady-state of technology level
ϕ_Υ	0.01	Coefficient of temperature level
n_g	0.30	Market size of green sector
ρ_{pe}	0.90	Persistence of energy price shock
ρ_{em}	0.90	Persistence of emission permit shock
$\sigma_{\epsilon_{pe,t}}$	0.01	Standard deviation of energy price shock
$\sigma_{\epsilon_{em,t}}$	0.01	Standard deviation of emission permit shock

4. IMPULSE RESPONSES

The following Section reports the impulse response functions of macroeconomic, financial and environmental variables under two types of carbon price shocks: (i) shock to the price of fossil fuel energy; (ii) tax on carbon emissions. All variables are expressed in terms of percentage deviations from the steady-state.

Figure 1 reports recent IMF predictions showing that global greenhouse gas emissions must be cut 25 to 50 percent below 2019 levels by 2030.[32] In contrast, based on current pledges made by countries who commit to reach net-zero carbon emissions by 2040, global emission would be cut only by 11 percent if no further incentives will be implemented to push firms and households to prioritize clean goods and technologies.[33]. Given this background, the model *first* simulates a mitigation scenario in which government gradually increases carbon taxes in order to cut carbon emission by around 50% by the end of 2030, which translates into a lower temperature of about 8%. The purpose of this initial exercise is to emphasize the macro-financial consequences of a gradual and abrupt increase in carbon prices if no further policies are implemented. This simulation highlights the negative impact on the banking system, thus motivating the need for additional policies to ensure financial stability when climate policies are in place. Similar to Diluiso et al. (2021) and Ferrari and Nispi Landi (2023), the model assumes that there will be no change in technology. Further, the simulation is based on a positive analysis, in which the gradual increase in carbon taxation is set in such a way that 2030 carbon emission are reduced by 50%.[34] Figure 2 shows that in order to achieve the designed carbon emission target, government would need to gradually increase carbon taxes up to 20% by 2030. In absence of other climate-related or macroeconomic policy, output and consumption will gradually decline by around 0.35% and 0.30%, respectively. In line with this result, Kalman et al. (2023) use two scenarios developed by the Network for Greening the Financial System (NGFS) – Net Zero 2050 and Divergent Net Zero – to show that GDP in Slovakia would decrease by less than 1% few years after a shock to emission prices, when considering MESSAGE and REMIND models.[35]

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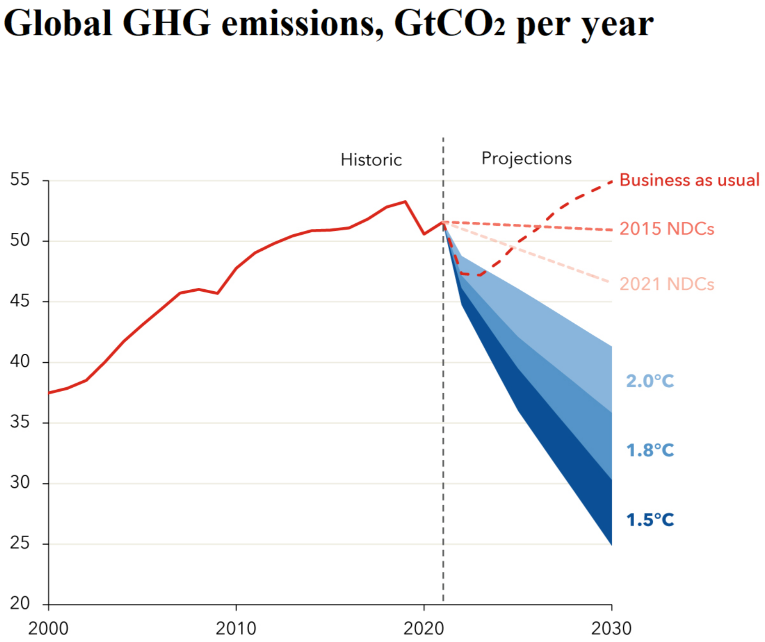
[32] See `https://www.imf.org/en/Blogs/Articles/2022/11/04/getting-back-on-track-to-net-zero-three-critical-priorities-for-cop27`

[33] Black et al. (2022) discuss possible options to accelerate the global green transition by cutting emissions in high-income countries. They also point out that the goal of $1.5^O C$ would be put beyond reach under further delays in climate actions.

[34] In contrast, a normative analysis would take into account any optimizing behavior from the public sector.

[35] MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) framework is an open-source energy systems optimization modelling environment including macroeconomic feedback using a stylized computable general equilibrium model. The Integrated Assessment Model REMIND (Regional Model of Investments and Development) is a global energy-economy-climate

Figure 1: Pledging Net-Zero.



Note: Source: `https://www.imf.org/en/Blogs/Articles/2022/11/04/getting-back-on-track-to-net-zero-three-critical-priorities-for-cop27`

This results is very similar to Diluiso et al. (2021) who report emission cuts by around 50% in 2030, and a decline in output and consumption by around 0.8% and 1.2%, respectively.[36] As in Diluiso et al. (2021) and Ferrari and Nispi Landi (2023), the transition to net-zero decreases inflation, despite the steady output fall due to higher costs associated to the carbon taxes. This is due to a contraction in demand.[37] However, inflation gradually returns to its initial steady-state level, and even becomes positive after 2028. Figure 2 also reports a quick deterioration of assets in fossil fuels, reflecting the risk of becoming stranded through the carbon regulation. Consequently, banks cut loans to the brown sector in view of the assets devaluation, and production in the polluting sector falls as well. This situation creates incentives for the green sector, which is able to afford more lending thanks to higher LTV ratio. However, even if the economy move to a more greener economy, the carbon taxation scheme would generate a prolonged recession, if other interactive policies are not taken into consideration.

Figure 3 and 4 (black solid line) report impulse responses for a baseline model to a 1% increase in the price of fossil fuel energy and in the taxes on carbon emissions, respec-

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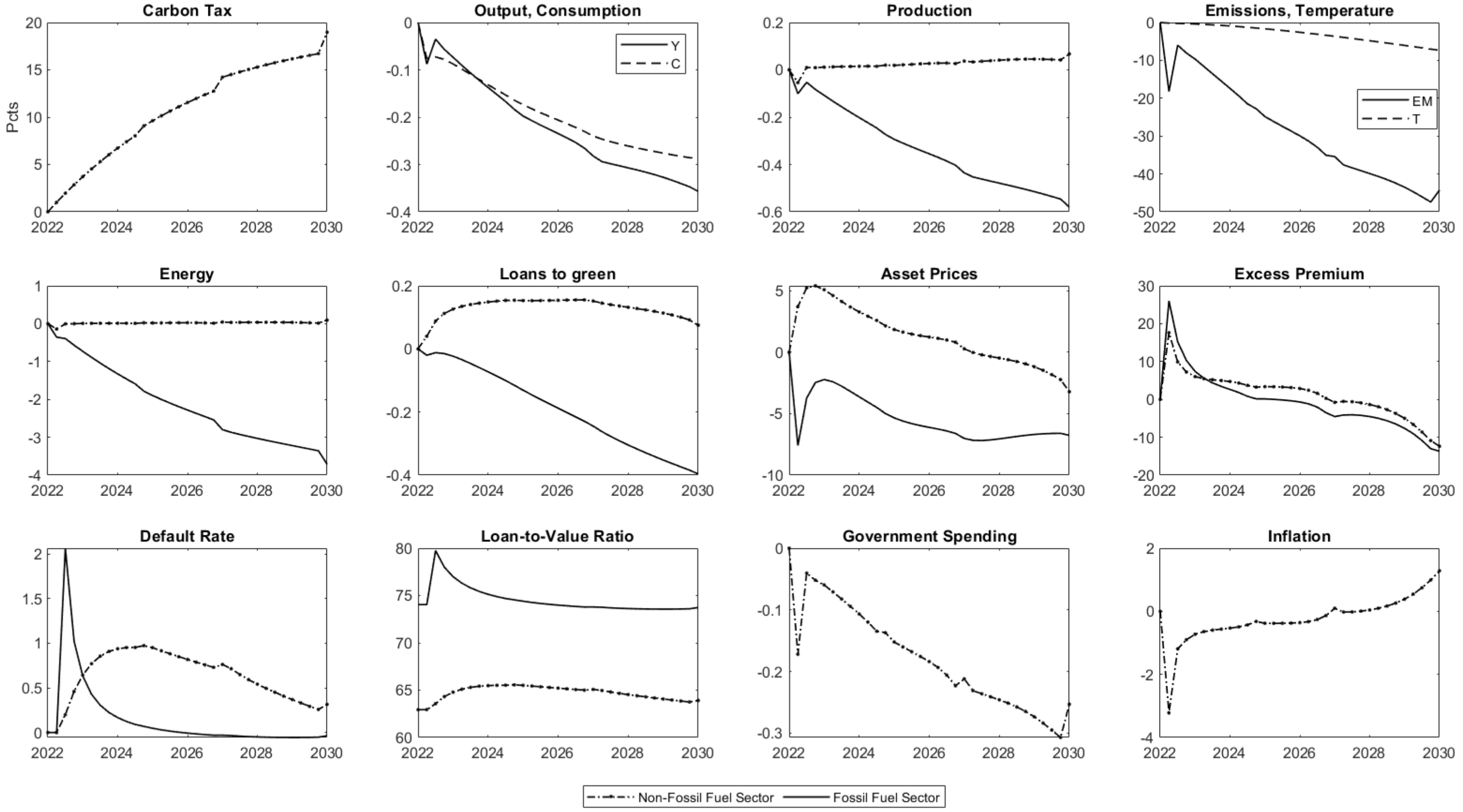
Ramsey-type optimal growth model in which inter-temporal welfare is maximized.

[36] The more severe impact on output and consumption found in Diluiso et al. (2021) depends on the absence of temperature, which in our model is an inverse function of emissions.

[37] Ferrari and Nispi Landi (2023) explain that the expected further increase in carbon taxes reduces expected income, thus lowering aggregate demand via the Euler equation. This generates a downward pressure on prices.

Figure 2: Transition to Net-Zero driven by emissions of carbon taxes.



Note: Results are reported as percentage deviations from the initial steady state.

tively. Both figures display a similar transmission mechanism of carbon pricing increase. Production in the brown sector falls, which allows emissions to decline. The climate-related policy discourages investments in brown assets, which loose values, leading banks to cut loans and increase lending rate. This would further contribute to the decline in investment and output because of the financial accelerator mechanism.

However, because banks still hold brown assets in their balance sheet, then the risk of some brown assets to become stranded, due to a lost value in face of changes in environmental regulations and policies, generates a negative spillover effect to the green sector.[38] Indeed, banks tend to supply less loans to the green sector, or charge higher lending rate, to restore their balance sheet. This results in an increasing default rate in both sectors, thus affecting financial stability. This occurs through two channels: (i) the banking funding channel induces banks to charge higher lending rates in both sectors in order to satisfy the participation constraint in Eq. (24), which makes difficult for firms to repay back existence loans; (ii) the banking capital channel induces banks to supply less loans as a result of less bank capital, which affects the threshold value defined in Eq. (11), and thus the likelihood of default. Therefore, even if the carbon pricing mechanism targets only brown firms, through the banking sector, which will see a lower values of the assets in its portfolio, less funding will be channeled to the green sector, making more difficult the green transition.

The main difference between energy price and carbon tax shocks is that under carbon taxes the endogenous response of the LTV ratio is larger, giving opportunities for more lending to the green sector. This is due to the fact that a carbon tax policy induces banks to switch lending in favour of the green sector, contributing to more lending favourable conditions. As a result, a booming green sector would contain the debt repayment and banks would charge lower interest rates for green loans. Furthermore, the monetary policy would respond differently, as under energy prices shocks the central banks react to the deflation impact by cutting policy rates, while carbon tax is inflationary because of its pass-through to consumer price, and the central bank increases policy rate to contrast the higher inflation. The impact on inflation affirms that the energy price shock acts as a negative demand shock, while the carbon tax shock acts as a negative supply shock. Indeed, higher energy prices reduce the use of energy in the production of brown goods, which affects the marginal productivity of all other input factors, as well as the level of other inputs. Therefore, labor income decreases and negatively affects the total demand through the Euler equation. In contrast, carbon tax represents an extra operating cost for polluting firms, who can decide if keep producing the same output by paying carbon

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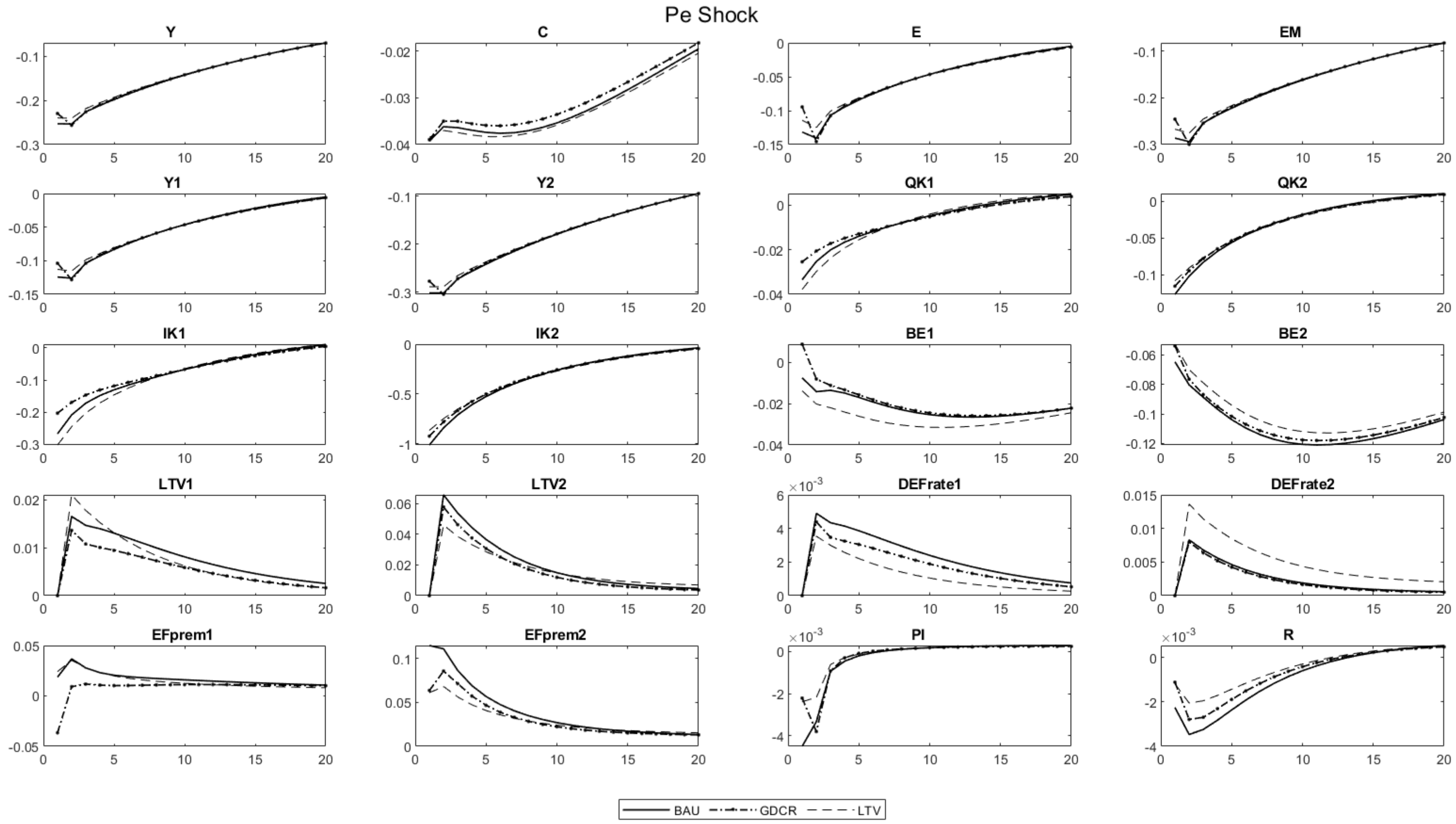
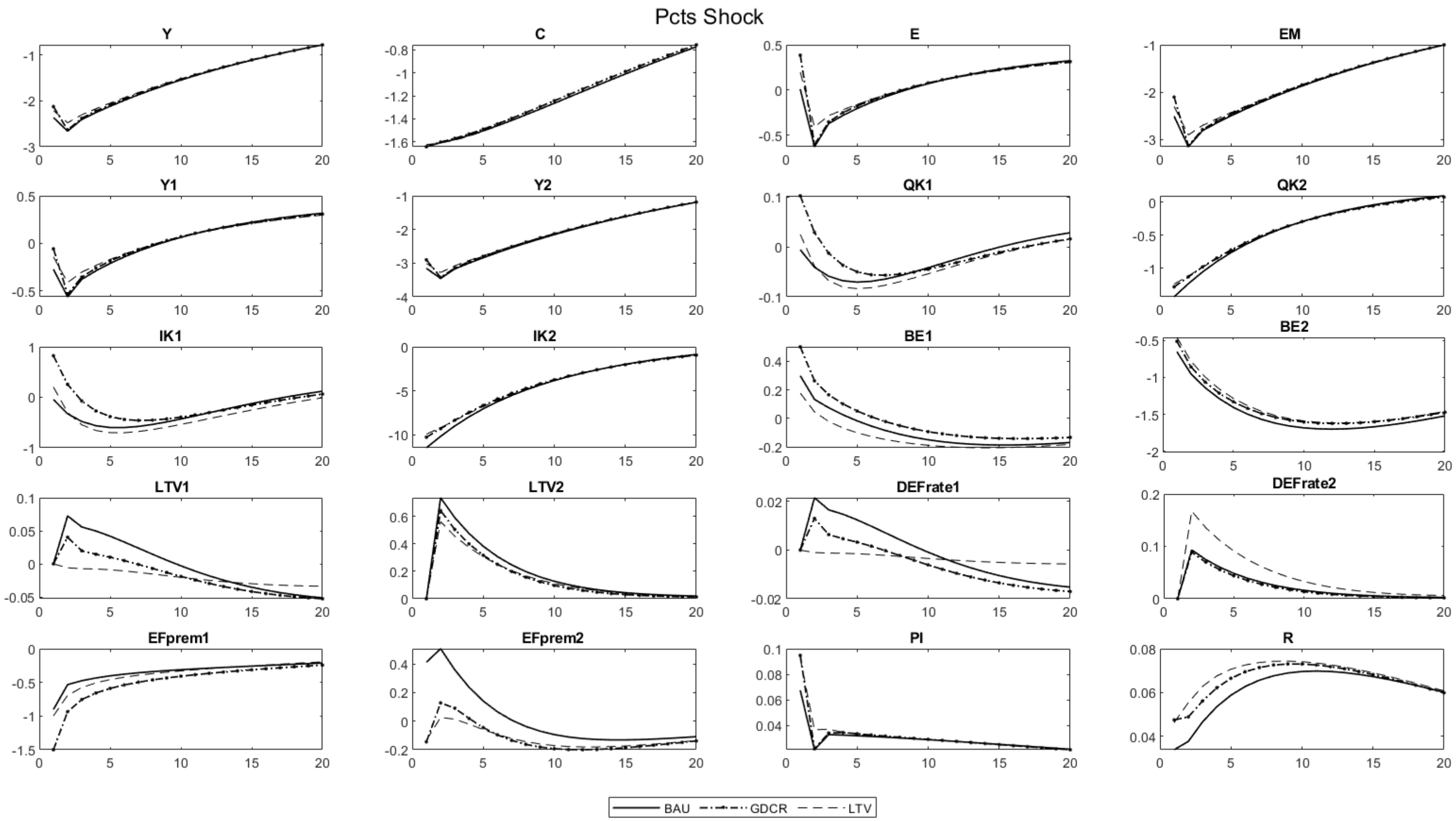
[38] Stranded assets arise due to unexpected negative changes in the assets earning power, caused primarily by external factors.

Figure 3: Shock to Fossil Fuel Energy Price.



Note: Results are reported as percentage deviations from the initial steady state.

Figure 4: Shock to Carbon Tax.



Note: Results are reported as percentage deviations from the initial steady state.

levies, or to cut production to avoid paying carbon taxes. 4 indicates that polluting firms decrease production by 3% in order to decrease emissions, and thus avoiding to pay a levy on carbon emissions.[39]

5. MACROPRUDENTIAL POLICY

Previous Section has proved that carbon pricing creates financial incentives for brown companies to lower their emissions. Carbon pricing leads to significant costs for firms in the transition to a low-carbon economy, triggering corporate default due to low profitability of firms. The spillover effect from the brown to the green sector induced by banks discourages the shift to more efficient processes or cleaner fuels that policy-makers were hoping to achieve.

Indeed, banks continue to provide financial funds to the fossil fuel industry. Since the Paris Agreement in 2015, the world's 60 largest banks has issued around USD $4.6 trillion of credit to the fossil fuel sector, with $742 billion in fossil fuel financing in 2021 alone. [40] In opposite, green financing surges less than US$2.6 trillion at top banks.

So far bank regulators have been more inclined to take steps aimed at encouraging green lending rather than penalizing dirty lending, but this strategy is not enough to align with the target of limiting climate change to well below 2^oC. Therefore, this Section assesses the effectiveness of macroprudential policies as a tool to decarbonise the financial system and reduce the buildup of environmental-related risks.

In particular, this Section considers the role of two macroprudential policies in line with some standard instruments implemented in the aftermath of the global financial crisis: (i) different LTV ratios between green and brown sector; and (ii) green differentiated capital requirements (GDCRs);

The first policy intends to offer an higher LTV ratio to the green sector when entrepreneurs apply for a credit line to finance new projects, while reducing the LTV ratio on loans to the brown sector in order to limit or avoid exposure to climate-related risk. If entrepreneurs in the brown sector have to pay a larger downpayment in advance, then they will probably borrow less for new loans, or must use their internal resources for financing new projects. However, as entrepreneurs are typically financial constraints, then a higher downpayment will limit their ability to invest, resulting in lower credit demand. In order to address this policy, the model implements a different calibration by

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[39] See Ciccarelli and Marotta (2024) for a discussion of the macroeconomic effects of climate-related issues over the business cycle, who find that physical risks act as negative demand shocks while transition risks act as downward supply movements.

[40] `https://www.ran.org/wp-content/uploads/2022/03/BOCC_2022_vSPREAD-1.pdf`

assuming that in steady-state the LTV ratios for the green and brown sectors are equal to 75% and the 63%, respectively. Using the steady-state value of default rate of 1.5% as in Diluiso et al. (2021), we can derive the LTV ratio for the brown sector equal to 75%. We just assume that the green sector faces a LTV ratio lower than 15% as firms in the green sector are sometimes new or less known, so banks offer a lower LTV to prevent future default.[41]

The second policy introduces different capital requirements by increasing the capital adequacy ratio (CAR) on brown assets holds on the banks' balance sheet over the Basel II and III regulatory requirements. In accordance with the Basel II and III capital regulation, commercial banks face a permanent increase in the capital adequacy ratio only for brown assets from 8% to 10.5%, in line with the capital conservation buffer. In order to stimulate green financing, a lower capital adequacy ratio is offered to the green sector, thus the model assumes a permanent decrease to 4.5%, just to cover the common equity T1 required under basel III.[42] This policy should encourage banks to cut their funding to the brown sector and should reduce systemic risk by stabilizing fluctuations in credit and to the extent possible excess volatility in stranded asset and output. This implies that the capital requirement in Eq. 23 becomes:

$$D_t \leq (1-\kappa_g)B_t^g + (1-\kappa_{ng})B_t^{ng}, \tag{36}$$

with $\kappa_g = 4.5\%$ and $\kappa_{ng} = 10.5\%$. Eq. 36 implies that, in accordance to the green prudential regulation, the banks' net worth, NW must be:

$$\frac{NW_t}{B_t} \geq \kappa_g \varrho^g + \kappa_{ng} \varrho^{ng}, \tag{37}$$

with $\varrho^g = \frac{B_t^g}{B_t}$ and $\varrho^{ng} = \frac{B_t^{ng}}{B_t}$ being the portfolio share of green and brown assets held by the bank, respectively.

Figure 3 and 4 report impulse responses to a 1% increase in the price of fossil fuel energy and in the taxes on carbon emissions, respectively, under various macroprudential policy frameworks: the differentiated LTV ratios (dashed line) and the green differentiated capital requirements (GDCRs) (dotted-dashed line). Under both shocks, all proposed macroprudential policies contribute to reduce the negative spillover effect on the green

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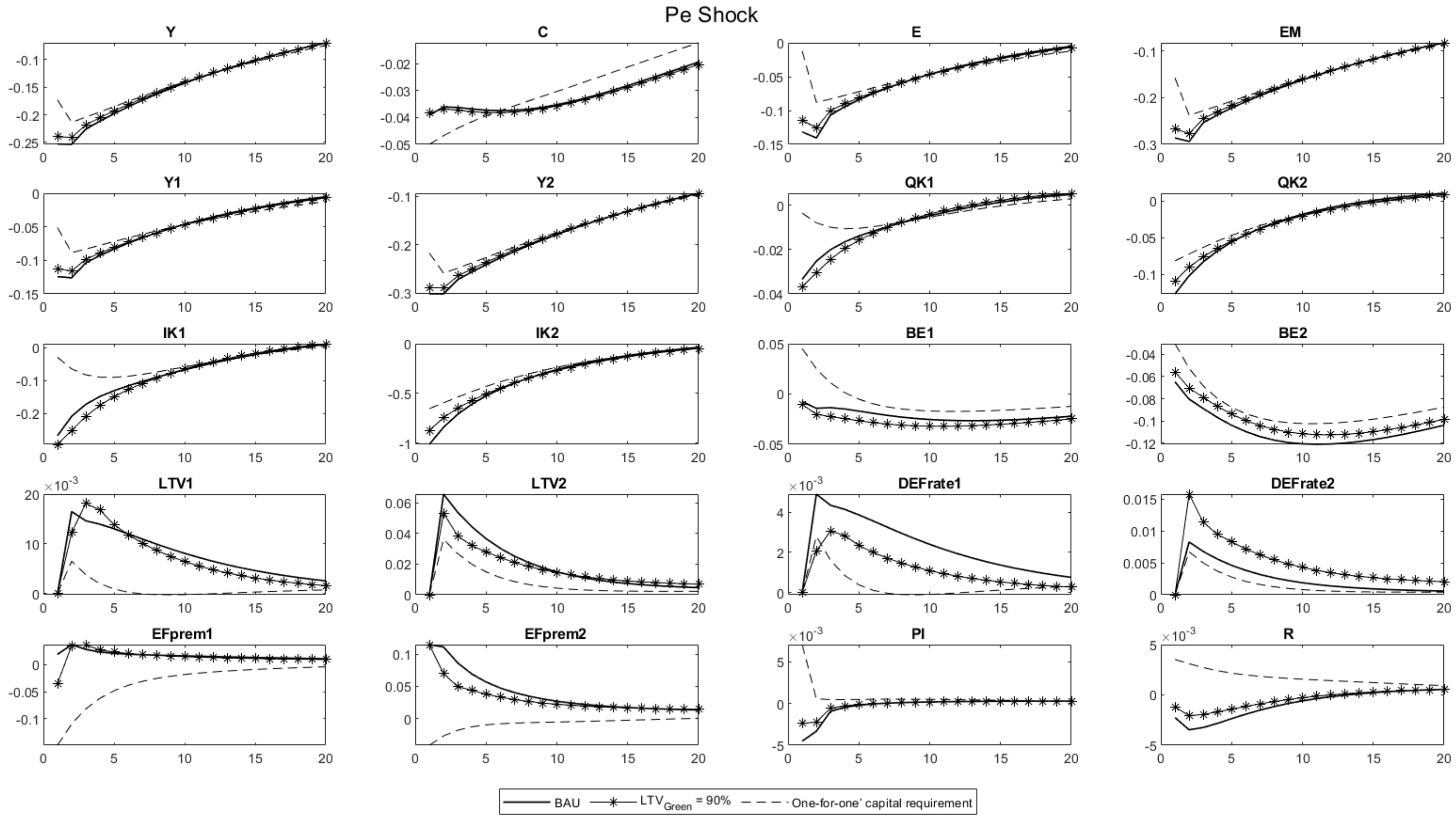
[41] The LTV ratio is endogenously determined, only the initial steady-state values are different across sectors. Thus, the transmission mechanism of the shocks is the same if we assume different values of the LTV ratios, such as 90% and 70% as an example.

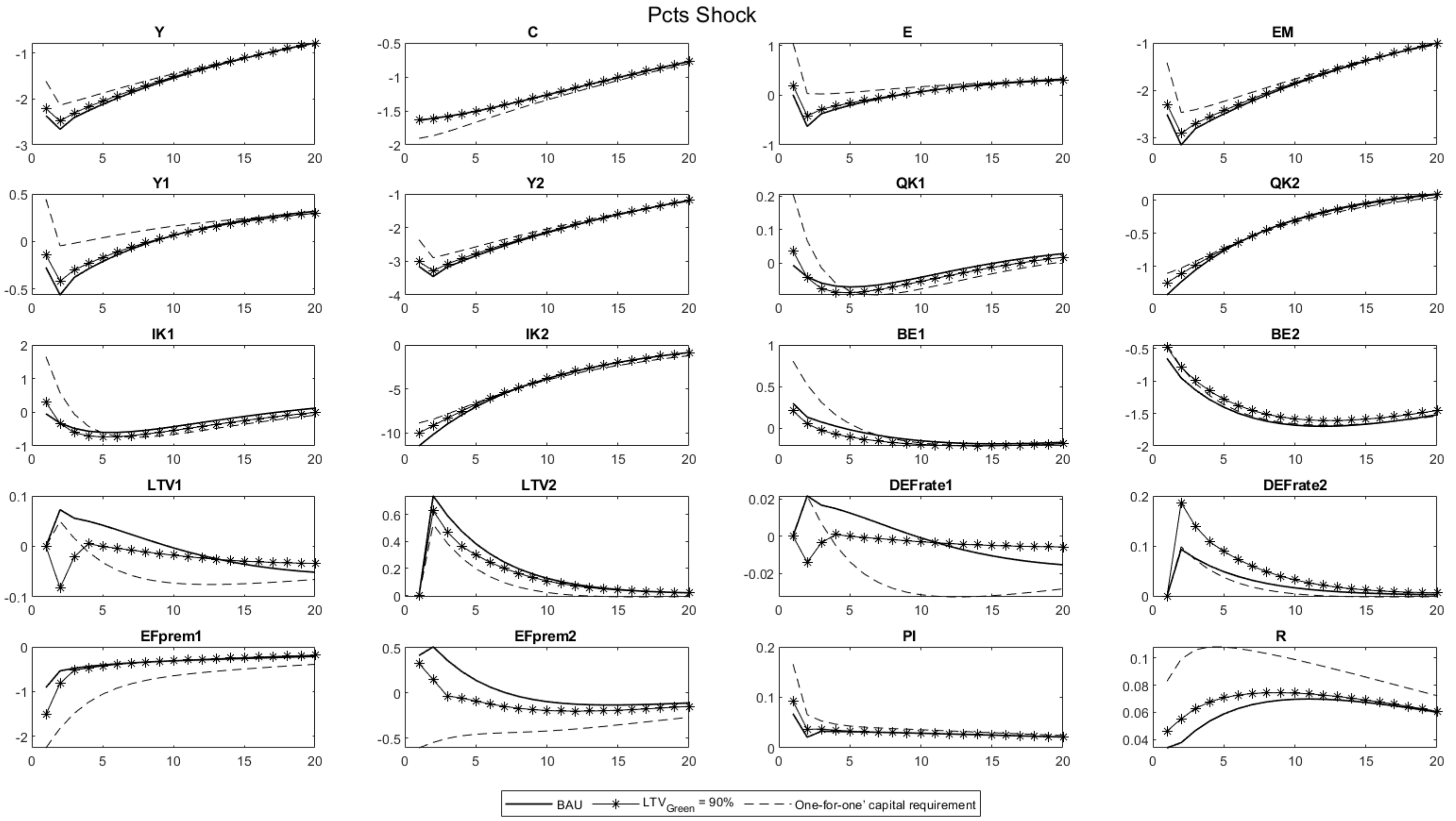
[42] Basel III imposes a common equity T1 of 4.5%, an additional Tier 1 of 1.5%, a Tier 2 of 2% and since 2019 a capital conservation buffer CET1 of 2.5%. All sum up to a 10.5% capital adequacy ratio on assets.

Figure 5: Shock to Fossil Fuel Energy Price.



Note: Results are reported as percentage deviations from the initial steady state.

Figure 6: Shock to Carbon Tax.



Note: Results are reported as percentage deviations from the initial steady state.

sector. In particular, banks charge lower interest rate to the green sector, which tends to default less relative to the case in which macroprudential policies are absent. This situation encourages lending to the green sector and limit credit to the brown sector. The differentiated loan-to-value ratio appears to be the most inefficient policy as it accelerates the probability of default in the brown sector, which quickly spread from the brown sector to the green sector forcing banks to reduce the supply of credit also to the green sector. Indeed, under a differentiated LTV policy, green borrowing decreases under a fossil fuel energy shock, or increases by less when a carbon tax shock hits the economy.

5.1. MACROPRUDENTIAL POLICY: ROBUSTNESS

Previous Section has proved that macroprudential policies can help reducing the probability of default in the green sector when carbon pricing tools are enforced. Further, macroprudential policies in the form of differentiated LTV ratios and green differentiated capital requirements support lending to the green sector, something important in order to encourage the transition to a green economy. However, the impact on the real economy remains limited, with a very marginal improvement on the negative impact on GDP and consumption. Therefore, this paper asks if more stringent macroprudential policies that penalize more intensively the brown sector for producing pollution and GHG emissions, while supporting the green sector, can eventually be more effective in maintaining macroeconomic stability, without compromise financial stability. In particular, two more stringent macroprudential policies are evaluated: (i) an higher LTV ratio to the green sector of 90%, and (ii) a “one-for-one” prudential capital requirement on fossil fuel financing.[43]

Figure 5 and 6 report impulse responses to a 1% increase in the price of fossil fuel energy and in the taxes on carbon emissions, respectively, under the two more stringent levels of macroprudential regulation. When the green sector is allowed to borrow funds at a LTV ratio of 90% (starred line), default rate in this sector is much contained when carbon pricing policies are implemented. Both policies show that under both shocks, default in the green sector can be contained, although results report a larger default in the brown sector. In terms of macroeconomic variables, and in particular when a carbon tax is enforced, a larger LTV ratio to the green sector generate a drop in consumption of around 1.5%, in spite of a 2% decline that would occur in absence of such higher LTV ratio.

The last policy, “one-for-one” (dashed line), represents an extension of the previous one

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[43] D’Orazio and Popoyan (2019) suggest to use higher capital requirement for banks with brown assets.

by allowing banks to finance fossil fuel projects with only their net-worth, and not by using deposits from households. This policy aims to discourage financing of fossil fuel extraction and to ensure economic and environmental stability letting banks to take the risk on their own if continuing funding fossil fuel projects. To include this policy into the model, κ_{ng} is set to 0.999.

The “one-for-one” macroprudential policy appears to be the most efficient policy. Relative to the other two policies, the one-for-one enforcement is able to reduce the negative impact on output generated by higher carbon pricing, and it is able to encourage higher lending to the green sector. Thanks to the extra funds, the green sector experiences larger new investment to boost production, even if the government increases carbon taxes. However, for a given increase in the price of fossil fuel energy, the “one-for-one” framework is not able to prevent the fall in investment in the green sector, thus the production remains negative, but lower relative to the impact generated from the other two macroprudential policies. This occurs because the endogenous LTV ratio in the green sector does not increase that much, meaning the entrepreneurs needs to pay higher downpayment for financing new projects, thus investment decision are postponed to the future. Therefore, this extremely differentiated policies is able to shut down the banking capital and funding channels in the green sector by avoiding the negative impact of cutting loans to the green sector by banks and avoid the increase in lending rates to the green sector. This occurs because banks prefer lending to the green sector instead of financing the brown sector with their own funds. To stimulate green lending, they offer lower interest rates in order to facilitate the green transition. Overall, the “one-for-one” policy can smooths the spillover effect by softening the banking capital channel and a banking funding channel, and by reducing the high future financial stability risks when brown assets become stranded.

6. CONCLUSIONS

This paper analyses the effectiveness of macroprudential policy on macro-financial fluctuations when the government enforces carbon prices to reduce carbon emissions and achieve the net-zero target. Carbon price policies can be implemented by raising the price of fossil fuel energy or by imposing taxes on each unit of carbon emitted during production. First, the paper simulates the economic and financial implications of a continuous increase in carbon taxes, as many governments are committing to reduce carbon emissions to zero by 2050 by using this environmental policy. A simulation shows that governments can cut carbon emissions by 50% for a steady increase in carbon taxes of around 20% by 2030. However, this policy implies a decrease after eight years of about 0.35% and 0.30% in output and consumption, respectively. Further, the probability of default on debt servicing would increase putting at risk the financial stability. Thus, carbon pricing left alone, can reduce carbon emissions at the cost of a deep recession and higher systemic risk in the banking sector. This result suggests that carbon pricing should be coupled with complementary policies, such as macroprudential policy. In particular, differentiated LTV ratios and differentiated capital requirements that penalise the brown sector in favour of the green sector tend to decrease the probability of default in the green sector and encourage green lending in supporting the transition to a green economy. However, such policies have little contribution in offsetting the negative impact on the macroeconomy. To reduce the fall in GDP and consumption, more stringent levels of macroprudential regulations are needed. More specifically, the "one-for-one" prudential capital requirements on fossil fuel financing can effectively reduce default and move to a greener economy.

This paper offers various policy implications. The absence of strong regulations amplifies the climate-finance doom loop, in which fossil fuel finance enables climate change, and climate change threatens financial stability in unpredictable ways. This paper shows how banking prudential regulation can tackle the link between climate change and financial instability. Indeed, banks have an important role in supporting governments in mitigating climate-related risks. When banks make loans, they must keep a certain amount of funds on their balance sheet to cover any potential losses, through the principle of capital requirements. A policy introducing higher risk weights on any assets linked with new fossil fuel production, in line with a "one-for-one", can break the finance-climate doom loop. However, many regulators seem to be against this radical policy. For instance, members of the European Parliament's Economic Affairs Committee have recently opted not to adopt higher-level capital requirements for lending towards fossil fuel projects. Therefore, adjusting risk weights on existing fossil fuel assets over a gradual phase-in period to appropriately reflect the higher risk of losing value could be an alternative policy if governments keep pushing back the one-for-one rule. Central banks that already consider climate-related risks should now lead by adjusting their capital framework accordingly and use their voice around international standard-setting bodies, such as the Basel Committee, to push for an international set of rules that address climate-related financial stability risks at a global level. However, it is important to keep in mind that although the results of this paper are universally applicable to all countries and regions, the effectiveness of carbon pricing and macroprudential policies can vary significantly based on the economic structure, energy dependence, and policy context of different countries.

To conclude, our paper presents various limitations, and considerable research remains to be done when assessing the risk of financial instability related to climate policies. For example, the model used in this paper abstracts from the inclusion of consumer preferences for green goods. A demand for green goods could help in shifting more loans in favour of the green sector, against the brown sector, and most likely making green differentiated macroprudential policy more effective. The model also abstracts some important features to mitigate climate change, such as carbon abatement technologies and technological changes. Further, allowing carbon and green rational bubbles to emerge would offer a deeper evaluation of macroprudential policies. The inclusion of these model features is left for future research.

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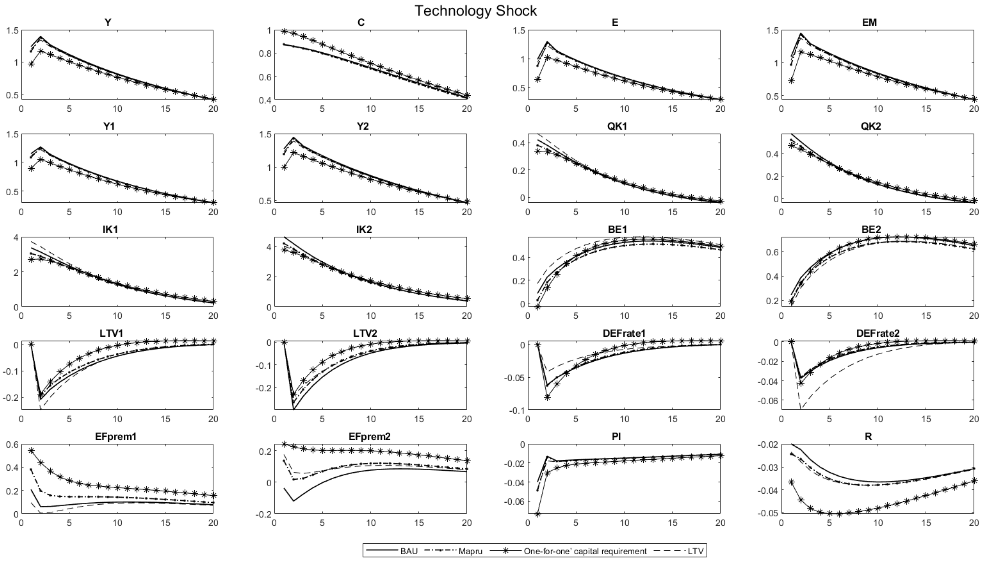
A. APPENDIX: TECHNOLOGY SHOCK

Figure 7 reports the impulse response functions of macroeconomic, financial and environmental variables to a contemporaneous positive technology shock in both green and brown sectors. All variables are expressed in terms of percentage deviations from the steady-state.

Figure 7: Technology Shock.



Note: Results are reported as percentage deviations from the initial steady state.