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Navigating Climate Policy Shocks: Optimal Monetary Policy Responses*

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Abstract

How should monetary policy respond to climate policy shocks? We develop an Environmental New-Keynesian model with green and fossil energy to assess the macroeconomic impacts of carbon pricing and green subsidy shocks and to identify the optimal monetary policy responses. Our findings indicate that these shocks create a policy trade-off between stabilizing inflation and the output gap. This trade-off is resolved in favor of output-gap stabilization, with optimal monetary policy focusing on dampening real output fluctuations while temporarily looking through inflation movements. Dual mandate Taylor rules yield lower welfare costs than inflation-only targeting rules and align the welfare performances of core and headline inflation targeting regimes.

Keywords: climate policy, E-DSGE models, monetary policy trade-offs, supply shocks.
JEL codes: E31, E52, Q43, Q58.

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1 Introduction

Complying with international climate targets and keeping global warming well below 2°C will require a massive amount of resources to flow to low-carbon sectors in the upcoming years (IPCC, 2022). The transition to a sustainable economy will imply substantial changes both in energy consumption and production, and a significant restructuring of most economies, as relative prices across sectors will adjust. While setting appropriate climate policies to navigate the challenges of the transition will be a primary focus for fiscal authorities, there are aspects that directly speak to the way monetary policy is conducted.

This paper studies the optimal monetary policy response to climate policy shocks (i.e. rises in carbon prices or green subsidies) and employs it as a benchmark to evaluate the welfare costs of various Taylor rules that focus on either headline or core inflation. While climate policies such as carbon pricing and green subsidies are designed to correct an environmental externality and be efficient in this strict sense, their implementation in an environment characterized by nominal rigidities can generate short-run distortions and inefficient interactions that end up being directly relevant for monetary policy. Additionally, while the underlying externality is global, in our setting climate policy is undertaken at the level of the Euro Area, and this implies that climate policy shocks necessarily reflect only a partial and uneven correction of the externality from the perspective of domestic monetary stabilization.

To conduct our analysis, we develop a multi-sector Environmental Dynamic Stochastic General Equilibrium (E-DSGE) model[1] with price and wage rigidities and a distinction between core and headline inflation. The results on optimal monetary policy are derived from the perspective of a social (Ramsey) planner who maximizes under commitment the expected discounted utility of households.

Importantly, the model accounts for imperfect substitutability between fossil and green energy and imperfect complementary between energy and labor, as well as between fossil resources and labor. On the consumer side, we model household consumption as a mix of non-energy and energy goods, which are assumed to be imperfect complements. Accounting for these complementarities has non-trivial implications for the adjustment of the economy to climate policy shocks and for the optimal monetary policy response.

Our key findings are as follows. Firstly, in the presence of imperfect complementarities in production and consumption, the welfare relevant output-gap is large enough

[1]Following the terminology introduced by Khan et al. (2019), this class of models refers to Real Business Cycle (RBC) or New Keynesian (NK) models incorporating environmental characteristics (e.g. emissions, climate damages).

that the optimal monetary policy response to a carbon price (green subsidy) hike, which is inflationary and contractionary (deflationary and expansionary), is to lower (increase) the policy rate. This response aims at dampening real output fluctuations while maintaining long-term price stability. Secondly, dual mandate Taylor rules perform better than those targeting only inflation, and rules that stabilize core inflation result in lower welfare costs compared to those targeting headline inflation. Lastly, the welfare gains of targeting core inflation diminish in the presence of complementarities between energy and other production inputs or consumption goods or when dual mandate Taylor rules are adopted.

Related literature. Our paper primarily contributes to the modeling literature on the macroeconomic effects of climate policies and their implications for monetary policy. This literature is still scant but growing rapidly.[2] One key strand focuses on the business cycle horizon. Annicchiarico and Di Dio (2015) demonstrate that optimal carbon pricing responses to business cycle shocks depend on price rigidities and monetary policy. Expanding on this, Annicchiarico and Di Dio (2017) look at the optimal carbon pricing and monetary policy mix in response to TFP shocks and show that achieving optimal emissions levels requires high carbon prices and low markups. Annicchiarico and Diluiso (2019) expand the analysis of climate-monetary interactions to an open economy, demonstrating that the type of carbon pricing policy adopted by different countries can reverse the direction of international spillovers from monetary policy shocks. Holtemöller and Sardone (2024) adopt a two-sector model to show that, conditionally to the type of environmental policy in place, sector-specific inflation targeting outperform standard Taylor rules by improving welfare without increasing emissions. Finally, Känzig (2023) studies the macroeconomic effects of carbon pricing shocks finding that they are recessionary and inflationary and propagate primarily through energy prices.

To the best of our knowledge, our paper is the first to analyze the optimal monetary policy response to carbon pricing and green subsidy shocks in a multi-sector model with differentiated energy sectors, and to explicitly examine the welfare benefits of targeting core versus headline inflation.[3] In a similar estimated setup, Semik (2025) finds results

[2]For the monetary policy implications of climate change see, among others, Faccia et al. (2021) and Kim et al. (2025) for empirical studies and Cantelmo et al. (2024), Giovanardi and Kaldorf (2025), Annicchiarico and Crofils (2025), and Economides and Xepapadeas (2025) for model-based analysis. These papers show how climate change, along with climate-related weather shocks and natural disasters, can affect price stability and, consequently, the formulation of (optimal) monetary policy.

[3]We focus on temporary and unexpected changes in carbon price that might materialize over the monetary policy horizon (next 3 years) and affect the way monetary policy is conducted. Prominent examples of this type of shocks are the fluctuations of the emission permit price in carbon markets as

in line with our optimal monetary policy analysis.

A second strand of the climate-macro literature examines the inflationary impacts of the green transition. Diluiso et al. (2021) find that an orderly transition has contractionary effects but minimal impact on price stability. Similarly, Olovsson and Vestin (2025) report modest, short-lived inflationary pressures, suggesting monetary policy should focus on core inflation and look through rising energy prices. Coenen et al. (2024) confirm temporary inflationary effects and a lasting GDP decline. Del Negro et al. (2023) show that the inflationary effects depend on sectoral price stickiness and the type of climate policy (taxes or subsidies). They find a sizable but short-lived trade-off between output and inflation, with efforts to limit inflation potentially causing a deep recession, while Airaudo et al. (2023) find that monetary policy can help contain inflationary pressures in the short run, but it has limited ability to offset the real costs of the transition. Ferrari and Pagliari (2023) and Bartocci et al. (2024) find recessionary and disinflationary effects, while Annicchiarico et al. (2024) and Ferrari and Nispi Landi (2025) show that when the rational expectations assumption is relaxed, the transition can be characterized by higher and more persistent inflationary pressures. Sahuc et al. (2024) present a model that includes both global warming dynamics and climate policies, finding that transition policies create long-lasting inflationary pressures. Finally, Nakov and Thomas (2023) adopt a normative approach to examine how optimal monetary policy navigates the trade-off between price stability and climate goals. They conclude that a trade-off arises only in the case of sub-optimal carbon taxes and resolves in favor of price stability. While we do not focus on transition dynamics, our findings align with many of the insights provided by transition studies: climate policies' inflationary impacts seem to be contained and short-lived compared to output effects. Our contribution emphasizes the optimality of dampening output fluctuations in the short-run and restore price stability in the medium term.

Our paper also contributes to the broader literature on optimal monetary policy in the presence of supply and sectoral shocks. Our model consists of perfectly competitive, differentiated energy sectors and a sticky-price intermediate goods sector that uses energy as an input, and allows for imperfect complementarity between energy and other production factors, as well as between energy and other consumption goods. In this respect, our work relates to e.g. La'O and Tahbaz-Salehi (2022) and Rubbo (2023), who emphasize the role of sectoral heterogeneity and input-output linkages for optimal pol-

the EU Emissions Trading System (ETS) reported in Figure A-1. These movements can be attributed both to regulatory events, as in the case of the carbon policy surprises identified by Känzig (2023), and economic conditions along the cycle, like the fluctuations in energy markets characterizing the last part of the sample in Figure A-1.

icy design, as well as to Montoro (2012) and Natal (2012), which highlight how limited substitutability between energy and other goods generates a non-trivial inflation–output trade-off. In contrast to these studies, we explicitly model energy production and we distinguish between fossil and clean sources. By differentiating between core and headline inflation, we also connect to Aoki (2001) and Bodenstein et al. (2008), which study the appropriate inflation target in the presence of sector-specific relative-price shocks. We find that sectoral climate-policy shocks have sizable effects on aggregate demand and widen the welfare-relevant output gap, supporting the case for an optimal monetary policy aimed at stabilizing real activity and, therefore, for a dual-mandate approach concerned with both inflation and real activity.[4] An important implication of our framework is that stabilizing headline inflation is not necessarily inferior to stabilizing core inflation in the presence of imperfect complementarities across inputs and consumption goods.

Finally, we contribute to a recent strand of the literature showing that, in the presence of inefficient policy distortions, optimal monetary policy may deliberately tolerate higher inflation and sustain output. Bianchi and Coulibaly (2025), Monacelli (2025), and Werning et al. (2025) show that, in response to tariff shocks, the optimal monetary policy entails a temporary increase in inflation and an expansion of output above its natural level. Consistent with these findings, we show that climate-policy shocks can generate a similar policy trade-off: since such shocks affect both marginal costs and aggregate demand, strict inflation stabilization is generally suboptimal.

The paper proceeds as follows. Section 2 describes the model, Section 3 outlines the calibration strategy, Sections 4, 5, and 6 present the results, Section 7 concludes.

2 The model

We build a New Keynesian model featuring price and wage rigidities and different sectors producing non-energy goods, green energy, and fossil energy. We assume that the good-producing sector is subject to price rigidities while the two energy sectors work under flexible prices. This captures the fact that in markets where the goods are differentiated, prices adjust slowly, while prices of energy usually exhibit high variability and are adjusted frequently. In addition to including energy as a production input demanded by firms in the good-producing sector, we also consider the energy share consumed by households. This allows to capture an important component of the aggregate demand for energy and a relevant transmission channel of climate policy.

[4] On the demand implications of sectoral supply shocks, see Guerrieri et al. (2022).

2.1 Households

We assume a continuum of monopolistically competitive households indexed by $h \in [0,1]$. Each household supplies a differentiated labor service $N_t(h)$ and posts the nominal wage $W_t(h)$ at which it is willing to work. A representative labor aggregator N combines households' labor services and supplies them to firms:

$$N_t = \left(\int_0^1 N_t(h)^{\frac{\sigma_W - 1}{\sigma_W}} \right)^{\frac{\sigma_W}{\sigma_W - 1}}, \tag{1}$$

where $\sigma_W > 0$ is the elasticity of substitution between labor services. The aggregator's demand for labor is equal to the sum of firms' labor demands in the three sectors $\{Y, F, G\}$: $N = N_Y + N_F + N_G$. The aggregator minimizes its production costs taking each household's wage rate as given, and then sells labor to the three production sectors at the unit cost W:

$$W_t = \left(\int_0^1 W_t(h)^{1-\sigma_W} \right)^{\frac{1}{1-\sigma_W}}. \tag{2}$$

Given the wages which are effective at any point in time for the different types of labor services, cost minimization yields a corresponding demand schedule for the labor service of household h:

$$N_t(h) = \left(\frac{W_t(h)}{W_t} \right)^{-\sigma_W} N_t. \tag{3}$$

From the three equations above we have that: $\int_0^1 W_t(h) N_t(h) = W_t N_t$. We assume that each period only a fraction $1 - \theta_W$ of households, drawn randomly from the population, re-optimizes its posted nominal wage. Under the assumption of full consumption risk sharing across households, all households resetting their wage in any given period will choose the same optimal wage W_t^*. The optimal wage setting problem is presented in Appendix B.

Households maximize utility out of consumption C_t and hours worked:

$$U_0 = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{1}{1-\zeta} C_t^{1-\zeta} - \chi \frac{N_t(h)^{1+\varphi}}{1+\varphi} \right), \tag{4}$$

and are subject to the following budget constraint:

$$P_{C,t} C_t + B_t = W_t(h) N_t(h) + D_t + R_{t-1} B_{t-1} + P_{C,t} T_t, \tag{5}$$

where $P_{C,t}$ is the consumption price index, B_t is a one period risk-free public bond, R_t is the risk-free interest rate, D_t are dividends from the ownership of firms, and T_t

are lump-sum transfers, including proceeding from fossil resources.[5] The households' consumption basket is defined as a CES aggregator of energy consumption $C_{E,t}$ and non-energy consumption ("core consumption") $C_{Y,t}$[6]:

$$C_t = \left[\varpi_{CE}^{1/\sigma_C} C_{E,t}^{(\sigma_C-1)/\sigma_C} + (1-\varpi_{CE})^{1/\sigma_C} C_{Y,t}^{(\sigma_C-1)/\sigma_C}\right]^{\sigma_C/(\sigma_C-1)}, \tag{6}$$

where $\sigma_C < 0$ is the elasticity of substitution between core and energy consumption. The energy consumption bundle is in turn a combination of fossil energy consumption $C_{EF,t}$ and green energy consumption $C_{EG,t}$:

$$C_{E,t} = \left[\varpi_{CF}^{1/\sigma_E} C_{EF,t}^{(\sigma_E-1)/\sigma_E} + (1-\varpi_{CF})^{1/\sigma_E} C_{EG,t}^{(\sigma_E-1)/\sigma_E}\right]^{\sigma_E/(\sigma_E-1)}, \tag{7}$$

where $\sigma_E > 0$ is the elasticity of substitution between different energy types. The first order conditions of the utility maximization problem and the demand schedules for $C_{Y,t}$, $C_{E,t}$, $C_{EF,t}$, and $C_{EG,t}$ derived from the intratemporal cost minimization problem are reported in Appendix C.

2.2 Firms

2.2.1 Final good sector

We assume that firms producing final goods are symmetric and act under perfect competition. In each period the representative firm producing the final good Y_t combines a bundle of differentiated intermediate goods $Y_{j,t}$ indexed by $j \in [0,1]$ according to the following technology: $Y_t = \left(\int_0^1 (Y_{j,t})^{(\sigma-1)/\sigma} dj\right)^{\sigma/(\sigma-1)}$, where σ is the elasticity of substitution among different varieties. The demand schedule for variety j is equal to $Y_{j,t} = (P_{CY,j,t}/P_{CY,t})^{-\sigma} Y_t$, where $P_{CY,j,t}$ is the price of good j and $P_{CY,t}$ is the price of the final good. Perfect competition and free entry drive the final good-producing firms' profits to zero. From the zero-profit condition we obtain $P_{CY,t} = \left(\int_0^1 P_{CY,j,t}{}^{(1-\sigma)} dj\right)^{1/(1-\sigma)}$.

2.2.2 Intermediate good sector

Firms in the intermediate sector are monopolistically competitive. Output $Y_{j,t}$ is produced with a CES technology that combines value added $VA_{Y,j,t}$ and a bundle of inter-

[5] In the notation we have dropped the index h for consumption and bonds, since we have complete markets for consumption, which implies it is identical across households in every period.

[6] At the aggregate level the consumption basket can be regarded as produced by perfectly competitive consumption distributors whose production function mirrors the preferences of households over consumption of energy and non-energy goods.

mediate energy inputs $M_{E,j,t}$:

$$Y_{j,t} = \left[\varpi_Y^{1/\varepsilon_Y} \left(VA_{Y,j,t}\right)^{(\varepsilon_Y-1)/\varepsilon_Y} + (1-\varpi_Y)^{1/\varepsilon_Y} \left(M_{E,j,t}\right)^{(\varepsilon_Y-1)/\varepsilon_Y}\right]^{\varepsilon_Y/(\varepsilon_Y-1)}, \tag{8}$$

where $\varepsilon_Y < 0$. Value added is defined as:

$$VA_{Y,j,t} = A_{Y,t} N_{Y,j,t}, \tag{9}$$

where $A_{Y,t}$ is total factor productivity and $N_{Y,j,t}$ is labor used by sector Y.
As for consumption, we assume that the intermediate energy composite used by firms is a CES aggregate of green and fossil energy inputs:

$$M_{E,t} = \left[\varpi_{MG}^{1/\varepsilon_E} M_{EG,t}^{(\varepsilon_E-1)/\varepsilon_E} + (1-\varpi_{MG})^{1/\varepsilon_E} M_{EF,t}^{(\varepsilon_E-1)/\varepsilon_E}\right]^{\varepsilon_E/(\varepsilon_E-1)}, \tag{10}$$

where $\varepsilon_E > 0$. Finally, following Calvo (1983), we assume that prices of differentiated goods are sticky and are changed at exogenous random intervals. A fraction $1-\theta_Y \in (0,1)$ of firms can change their prices at each period t, while the others must continue charging their old prices. The typical firm able to re-optimize in period t will choose the optimal price, P_t^*, to maximize the current market value of the expected profits generated while that price will stay put. Firms in this sector choose labor, intermediate energy inputs and prices as to maximize profits. The optimal price setting problem is described in Appendix B while the optimal demand for labor and energy, as well as the optimal energy mix chosen by firms are reported in Appendix C.

2.2.3 Energy sectors

The energy market is perfectly competitive and composed by firms producing green energy and firms producing energy based on fossil fuel sources.
Green energy is produced according to:

$$E_{G,t} = A_{G,t} N_{G,t}, \tag{11}$$

where N_G represents the labor demand by the green energy sector and $A_{G,t}$ is the sector-specific productivity.
Fossil energy, instead, is produced according to:

$$E_{F,t} = \left[\varpi_O^{1/\varepsilon_F} \left(VA_{F,t}\right)^{(\varepsilon_F-1)/\varepsilon_F} + (1-\varpi_O)^{1/\varepsilon_F} O_t^{(\varepsilon_F-1)/\varepsilon_F}\right]^{\varepsilon_F/(\varepsilon_F-1)}, \tag{12}$$

where $\varepsilon_F < 0$ is the elasticity of substitution between fossil resources and labor inputs, O_t represents fossil resources, and $VA_{F,t}$ is defined as $VA_{F,t} = A_{F,t}N_{F,t}$.
The price of fossil resources P_O is determined exogenously on international markets and is taken as given by firms. Production in the fossil energy sector entails emissions X_t as a byproduct. In particular, we assume that $X_t = \xi O_t$, where ξ is a scale parameter. We assume the stock of cumulative emissions, Z_t, in the atmosphere evolves as:

$$Z_t - \overline{Z} = (1 - \delta_Z)\left(Z_{t-1} - \overline{Z}\right) + X_t + X_t^{RoW}, \tag{13}$$

where X_t is the country's emissions flow, $\overline{Z}$ is the pre-industrial concentration of pollutant, $\delta_Z \in (0, 1)$ measures the natural rate at which the atmosphere recovers and X_t^{RoW} are emissions from the rest of the world, that we keep constant for convenience.[7]

The first order conditions from the cost minimization problems of energy firms can be found in Appendix C.

2.3 Aggregate output, monetary policy, and climate policy

To obtain a measure of aggregate output, we consider production in the public, intermediate and energy sectors, net of the expenses for intermediate inputs. GDP in the model can be defined as:

$$GDP_t = P_{CY,t}C_{Y,t} + P_{CE,t}C_{E,t}. \tag{14}$$

Monetary policy is conducted according to the following Taylor rule:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\iota_R}\left[\left(\frac{\Pi_{C,t}}{\Pi_C}\right)^{\iota_\pi}\left(\frac{GDP_t}{GDP_t^*}\right)^{\iota_y}\right]^{1-\iota_R}, \tag{15}$$

where GDP_t^* is output under flexible prices and wages, R is the steady state value of the interest rate and Π_C is the steady state value of headline inflation, defined as:

$$\Pi_{C,t} = \left[\varpi_{CE}\left(\Pi_{CE,t}\frac{P_{CE,t-1}}{P_{C,t-1}}\right)^{1-\sigma_C} + (1-\varpi_{CE})\left(\Pi_{CY,t}\frac{P_{CY,t-1}}{P_{C,t-1}}\right)^{1-\sigma_C}\right]^{\frac{1}{1-\sigma_C}}, \tag{16}$$

where $\Pi_{CE,t} = \frac{P_{CE,t}}{P_{C,t}}\frac{P_{C,t-1}}{P_{CE,t-1}}\Pi_{C,t}$ is the energy inflation rate and $\Pi_{CY,t} = \frac{P_{CY,t}}{P_{C,t}}\frac{P_{C,t-1}}{P_{CY,t-1}}\Pi_{C,t}$

[7]We do not model the effects of the pollution stock on the economy since on the horizon we consider climate damages hardly materialize and therefore do not analyze optimal climate policies or transition dynamics. Including feedback effects from pollution does not alter the results of our analysis (results are available upon request).

is our measure of core inflation.

On the fiscal side, we abstract from the existence of public debt and assume that the fiscal authority runs a balanced budget at all times. We assume that fossil resources are extracted with no cost by the government, which sells them to fossil energy producers and distributes the proceeds as lump-sum transfers to households together with the revenues from climate policy. We explore two types of climate policies: a carbon pricing $\tau_{o,t}$ on the use of fossil fuels, whose proceedings are redistributed lump-sum to households,[8] and a subsidy $\tau_{g,t}$ on the price of green energy, financed via lump-sum taxes. The government budget reads as:

$$T_t = \tau_{o,t} P_O O_t - \tau_{g,t} P_{G,t} E_{G,t}, \tag{17}$$

where $P_{G,t}$ is the price of green energy and the fiscal instruments are modeled as AR(1) processes: $\log \tau_{o,t} = \rho_o \log \tau_{o,t-1} + \eta_{o,t}$ $\eta_{o,t} \sim N(0, \sigma_o)$ and $\log \tau_{g,t} = \rho_g \log \tau_{g,t-1} + \eta_{g,t}$ $\eta_{g,t} \sim N(0, \sigma_g)$.

3 Calibration

The model is calibrated at a quarterly frequency using Euro Area data. Table 1 presents the steady-state targets and parameter values. We start by normalizing prices and core consumption C_Y to 1 and then match a set of expenditure shares, production shares, and environmental targets. Our calibration strategy is the following.

The subjective discount factor β is set to 0.99, consistent with a real annual interest rate of 4%. The risk aversion parameter ζ, and the inverse of Frisch elasticity φ are set to 1.5 and 0.7, respectively, based on estimates by Diluiso et al. (2021).

Price and wage contracts are assumed to have a duration of four quarters, leading to $\theta_Y = 0.75$ and $\theta_W = 0.75$. Empirical estimates for the markups in the major EU economies range from 1.1 to 1.5 (see e.g. Deutsche Bundesbank, 2017), therefore, we assume an elasticity of substitution between good varieties and between labor services equal to 6, implying a markup of 1.2.

The elasticity of substitution between energy and labor inputs, ε_Y, and between core consumption and energy consumption, σ_C, is set to 0.4 implying imperfect complementary.[9] The quasi-share of energy in the consumption basket, ϖ_{CE}, and the quasi-share

[8] Note that since we assume that emissions are proportional to O_t, the implementation of this upstream carbon price is equivalent to a downstream price on emissions. Note also that unlike an oil price shock, which would imply a transfer of resources abroad given that the euro area is largely an oil-importing region, carbon pricing generates fiscal revenues that remain domestic and are redistributed to households in our framework. This distinction is relevant for the macroeconomic transmission of the two shocks.

[9] This is consistent with the literature on Integrated Assessment Models (see e.g. Aboumahboub

of value added in the production function of the intermediate sector, ϖ_Y, are calibrated as to obtain energy expenditure shares of 6% in consumption and 7% in production, in line with the OECD TiVA database (see Coenen et al., 2024).

Evidence on the elasticity of substitution between fossil and renewable energy is limited, but long-run estimates range from 1.8 and 3 (Papageorgiou et al., 2017). Considering the short-run nature of our model we opt for a value in the lower end of the range and set σ_E and ε_E to 2. We set the share of renewable energy in the consumption (7) and production energy bundles (10), as to have an overall energy mix in the economy of 20% renewable and 80% fossil, in line with the current Euro Area energy mix. We set the weight of labor in the fossil energy sector, ϖ_O, to match the 70% share of fossil resources used in production, as reported by Coenen et al. (2024) based on the OECD TiVA database. The elasticity of substitution between labor and fossil resources, ε_F, is set to 0.3 following Diluiso et al. (2021).

To calibrate the environmental part of the model we anchor the stock of atmospheric carbon concentration to 891 gigatons of carbon (GtC), the approximated value observed in the no-policy scenario in the DICE model in 2020 (see e.g. Nordhaus, 2018). We know that the pre-industrial atmospheric concentration of carbon, $\overline{Z}$, is approximately 581 GtC (Golosov et al., 2014) and we set the quarterly decay rate of greenhouse gases δ_Z to 0.0021 to reflect a half-life of carbon in the atmosphere of almost 83 years (Reilly and Richards, 1993). From (13) we obtain the worldwide emissions flow. Based on emission data provided by Crippa et al. (2021) we set the share of Euro Area emissions on worldwide carbon dioxide emissions, X, to 7.3%. X^{RoW} and the scale parameter ξ are implied.

Finally, in the baseline calibration, the policy parameters of the Taylor rule are set to $\iota_\pi = 1.5$, $\iota_y = 0$ and $\iota_R = 0$.

4 Optimal monetary response to climate policy shocks

This section illustrates how carbon pricing and green subsidy shocks transmit into the economy and the associated optimal monetary policy response. The results are derived by solving the problem of a social (Ramsey) planner who maximizes the expected discounted utility of households (4) given the constraints of the decentralized economy reported in Appendix C.[10] In particular, we assume that the planner represents a mon-

et al., 2020) and with DSGE models with clean and fossil energy (see e.g. Annicchiarico et al., 2017 and Varga et al., 2022).

[10]The problem is solved numerically via Dynare 5.5 (Adjemian et al., 2024).

Table 1: Calibrated Parameters and Steady-State Ratios

	Description	Value
Steady state ratios		
$P_{CE}C_E/P_C C$	Share of energy in consumption	0.06
$P_{ME}M_E/P_{CY}Y$	Share of energy in production	0.07
$E_F/(M_E+C_E)$	Share of fossil energy in total energy	0.80
$P_O O/P_F E_F$	Share of fossil fuels in fossil energy production	0.70
$X/(X+X^{row})$	Share of Euro Area emissions	0.073
Z	Stock of carbon (GtC)	891
Preferences Parameters		
β	Discount factor	0.99
ζ	Risk aversion coefficient	1.5
φ	Inverse of Frisch elasticity	0.7
Price and Wage Setting		
θ_Y	Calvo's price parameter	0.75
θ_W	Calvo's wage parameter	0.75
σ	Elasticity of substitution between good varieties	6
σ_W	Elasticity of substitution between labor services	6
Consumption		
σ_C	Elasticity between C and C_E	0.4
σ_E	Elasticity between C_{EG} and C_{EF}	2
ϖ_{CE}	Weight of energy in consumption	0.06
ϖ_{CF}	Weight of fossil energy in consumption	0.80
Production		
ε_Y	Elasticity between N_Y and M_E	0.4
ε_E	Elasticity between M_{EG} and M_{EF}	2
ϖ_Y	Weight of labor in core production	0.92
ϖ_{MG}	Weight of clean energy in production	0.20
ε_F	Elasticity between N_F and O	0.3
ϖ_O	Weight of labor in fossil energy production	0.3
Environmental Parameters		
$\bar{Z}$	Pre-industrial concentration of carbon	581
δ_z	Decay rate of greenhouse gases	0.0021
ξ	Emissions scale parameter	0.6166
Monetary Policy		
ι_R	Smoothing parameter of the Taylor rule	0
ι_y	Output gap coefficient of the Taylor rule	0
ι_π	Inflation coefficient of the Taylor rule	1.5

etary authority that chooses the policy rate $\{R_t\}_{t=0}^{\infty}$ given exogenous processes $\{\tau_{k,t}\}_{t=0}^{\infty}$ with $k \in \{o, g\}$ and is able to commit to the contingent policy rule announced at time 0.

We calibrate the carbon pricing shock to induce a 5% reduction in emissions within the first year in a flexible economy (i.e., an economy without price and wage rigidities). This reduction aligns with the average annual cuts in emissions required from 2024 to 2030 to keep a trajectory consistent with limiting global warming to below 2°C (United Nations Environment Programme, 2023). We set the standard deviation of the green subsidy shock to be the same as the carbon pricing case. The persistence of the shocks is set to 0.9.

4.1 Carbon pricing shock

Figure 1 and 2 illustrate the reaction of the economy to a carbon pricing shock in our baseline economy under optimal monetary policy (solid line) and in the economy characterized by flexible prices and flexible wages (dashed line).

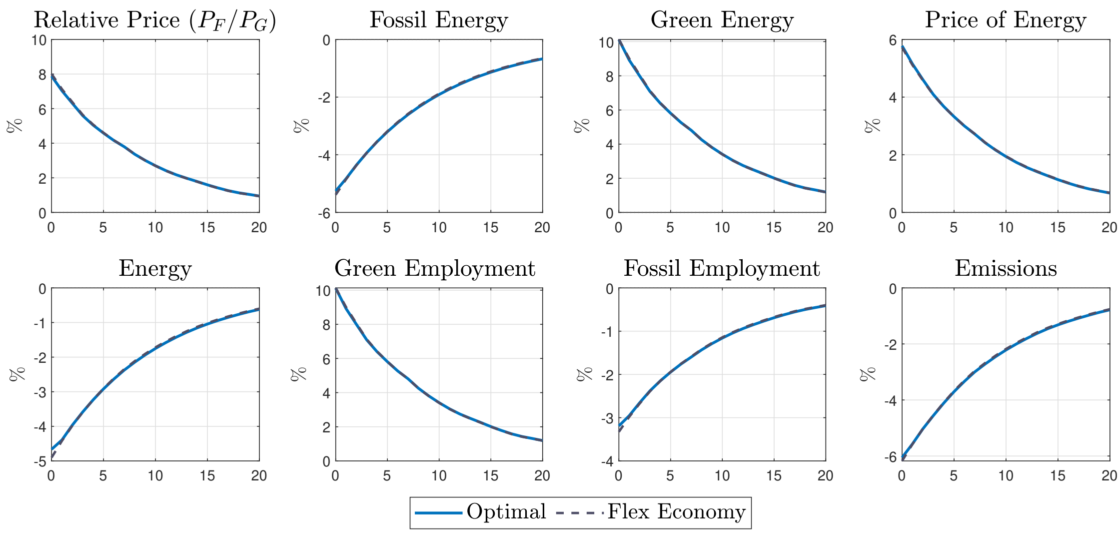

Figure 1: Dynamic response to a carbon pricing shock - Energy variables and emissions

Note: Results are reported as percentage deviations (%) and percentage point deviations (p.p.) from the steady state. Prices are expressed in real terms with respect to P_C. Time on the horizontal axis is in quarters.

Let us start by analyzing the dynamics under the flexible economy. Following the increase in the price of fossil fuels, directly subject to the carbon pricing scheme, the price of fossil energy rises, bringing with it a decline in the demand for fossil energy and an increase in the demand of green energy, which becomes relatively cheaper (substitution effect). Nevertheless, the overall price of energy increases and we observe a decline in energy demand (expenditure effect). The latter effect prevails due to the imperfect substitutability between the two types of energy and the larger share of fossil energy in the energy mix. The change in the relative price between energy sources lead to reallocation effects in the labor market: employment rises in the green sector and declines in the fossil sector.

Turning to Figure 2 we can see that core consumption decreases together with energy consumption with contractionary effects on output. Firms in the good-producing sector face higher energy prices and they also decrease their labor demand.[11] The employment in the core sector goes down and we observe a decline in the real wage. Overall this shock leads to a decrease in production and affects households negatively through two main channels: a decrease in their real wage and an increase in the price they pay for energy.

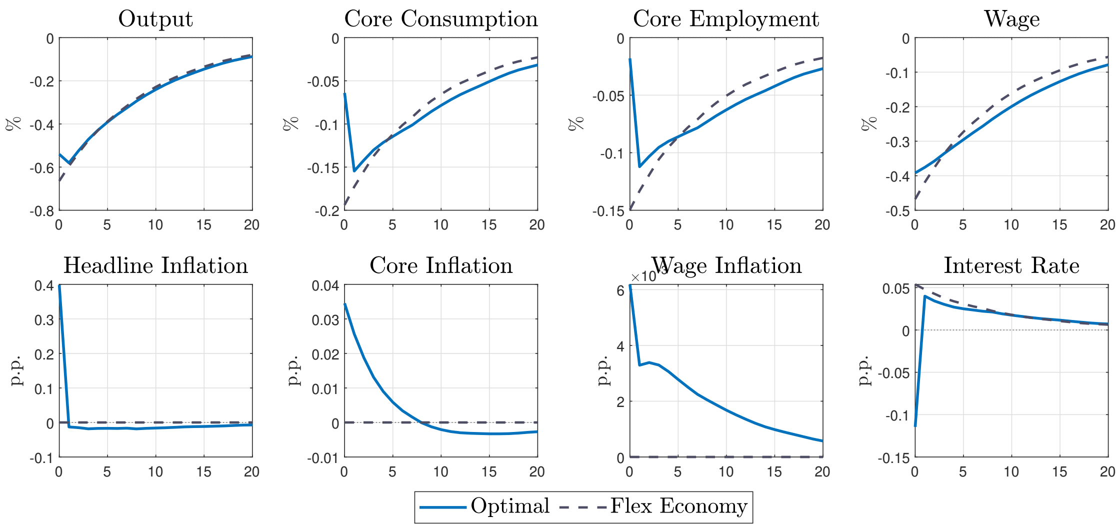

Figure 2: Dynamic response to a carbon pricing shock - Macroeconomic variables

Note: Results are reported as percentage deviations (%) and percentage point deviations (p.p.) from the steady state. Wage is expressed in real terms with respect to P_C. Time on the horizontal axis is in quarters.

Under optimal monetary policy, although not clearly visible due to the scale of the plots in Figure 1, the relative price between fossil and green energy increases slightly less than in the flex case leading to a milder decline in overall energy demand, fossil energy demand, and employment in the fossil sector. The (small) wedge between the

[11]The effects on overall employment in the economy are slightly positive and driven by the increase in labor demand in the green energy sector. We have also run a counterfactual simulation in which green labor supply is kept fixed, effectively preventing any reallocation of labor towards the green sector. Quantitatively, the results are very similar to those in the baseline model, largely reflecting the relatively small size of the green sector. This indicates that labor reallocation across energy sectors is not a key driver of our results.

two scenarios can be explained by the presence of wage rigidities in the baseline model, which prevent wages (and consequently energy prices) to fully adjust in response to the shock. The differences between scenarios can be better appreciated in Figure 2.

From the bottom left panel we can see that higher energy costs translate into higher headline inflation. They also raise marginal costs in the intermediate-good sector leading to an increase in core inflation that reacts less than headline but stays above target for longer. The increase in core inflation is, however, moderate and counteracted by the contraction in aggregate demand. It is interesting to notice that GDP is higher than in the flex case, as a result of the monetary policy conduct. The optimal monetary policy response to a rise in the carbon price is to lower the policy rate, and consequently the real interest rate upon impact (bottom right panel), to dampen output fluctuations. By reducing the interest rate, the planner is able to sustain consumption, reduce the fall in core employment and real wage and cushion some negative income effects of the shock. The policy trade-off is resolved in favor of output stabilization. This result is mainly driven by the variable cost shares in production and consumption, resulting from the presence of the CES aggregators in eq. 7 and 10. Variable cost shares refer to the proportion of total variable costs attributed to each input and depend on both relative input prices and the elasticity of substitution between inputs. Unlike the Cobb-Douglas production function, where input cost shares are constant and directly reflect the exponents in the production function (i.e., they are fixed regardless of changes in relative prices), the CES formulation allows for these shares to vary as input prices change. This variation arises because the elasticity of substitution in the CES case is not restricted to one (as in Cobb-Douglas), allowing firms to adjust input use more flexibly in response to price changes. Variable cost shares matter in the context of optimal monetary policy because they influence how marginal costs respond to shocks, which in turn affects inflation dynamics and the transmission of policy. In a CES framework, when the share of an input increases due to a price shock, firms substitute away from that input depending on the elasticity of substitution. This endogenous adjustment changes the marginal cost of production dynamically, making inflation more sensitive to input price fluctuations. As a result, stabilizing inflation may require larger movements in output compared to a setting with fixed cost shares, such as in a Cobb-Douglas framework. (see Appendix D.1). As demonstrated by Natal (2012) for oil price shocks, varying cost shares play a key role in shaping the monetary policy trade-off and perfect price stabilization in this setting would result in inefficient output fluctuations: the *divine coincidence* breaks down.

A rise in the carbon price leads to an increase in both the fossil energy cost shares and overall energy cost shares, with implications on production and consumption. Appendix D.1 sheds light on the role played by complementarities. On the one hand, complementarities in production amplify the distortion from monopolistic competition. When cost shares vary, stabilizing marginal costs (and thus inflation) requires a larger reduction in real wages and employment than in an economy with constant cost shares (e.g., a Cobb-Douglas economy). On the other hand, as energy directly enters the consumption basket, changes in energy cost shares induced by the carbon pricing shock act as a distortionary tax on labor income. This effect becomes more pronounced as the complementarity between energy and other goods increases. This channel seems to be the main driver for the decrease in the policy rate, since the welfare-maximizing policy seeks to cushions the economy against the real effects of a carbon pricing shock by lowering the policy rate and sustaining aggregate demand immediately after the shock. Monetary policy guarantees a milder decline of output and mitigates the direct impact of the shock on households' consumption and employment. However, medium-term price stability is ensured through a credible commitment to stabilize inflation and inflation expectations, which explains the undershooting of both headline and core inflation shown in Figure 2.

Figure D-1 shows how in a "Cobb-Douglas" economy in which the elasticity between labor and energy in the intermediate sector, the one between energy consumption and core consumption, and the one between labor and fossil fuels are all equal to 1, the optimal reaction to a positive carbon pricing shock is to raise the policy rate. We can see that, in the presence of constant cost shares, monetary policy can fully stabilize the output gap. The figure shows that the main factor driving the output gap in the baseline economy is the varying cost share in consumption, which generates negative income effects, thereby amplifying the negative demand impact of carbon pricing shocks.

Finally, the transmission of optimal monetary policy is partially influenced by wage rigidities. Figure D-2 and D-3 illustrate the behavior of optimal policy in the absence of wage rigidities. As shown by Erceg et al. (2000), while wage stickiness helps limit the immediate rise in core inflation, it confronts the monetary policymaker with an additional distortion. In this setting, optimal monetary policy primarily focuses on stabilizing wage inflation, in line with the goal of sustaining employment and output, but this comes at the cost of a slower adjustment in core inflation. Without wage rigidities, the action of the planner is not targeted to the labor market as wage is flexible and reacts more to changes in the real interest rate. The real wage closely follows the marginal rate of substitution and declines less than in an economy with rigid wages, exerting greater pressure on marginal costs. This translates in a sharper increase, on impact, in core inflation. However the decrease in output and consumption is milder and more gradual and monetary policy is able to tame core inflation more rapidly as the real wage keeps declining in the first quarters after the shocks and price markup are more strongly reduced. Notably, also in this case, we observe a decrease in the interest rate, despite the inflationary nature of the shock. This finding highlights the importance of the output-inflation trade-off, shaped not by wage stickiness but rather by the underlying structure of the economy.

4.2 Green subsidy shock

We now turn to the transmission of the green subsidy shock (Figures 3 and 4).

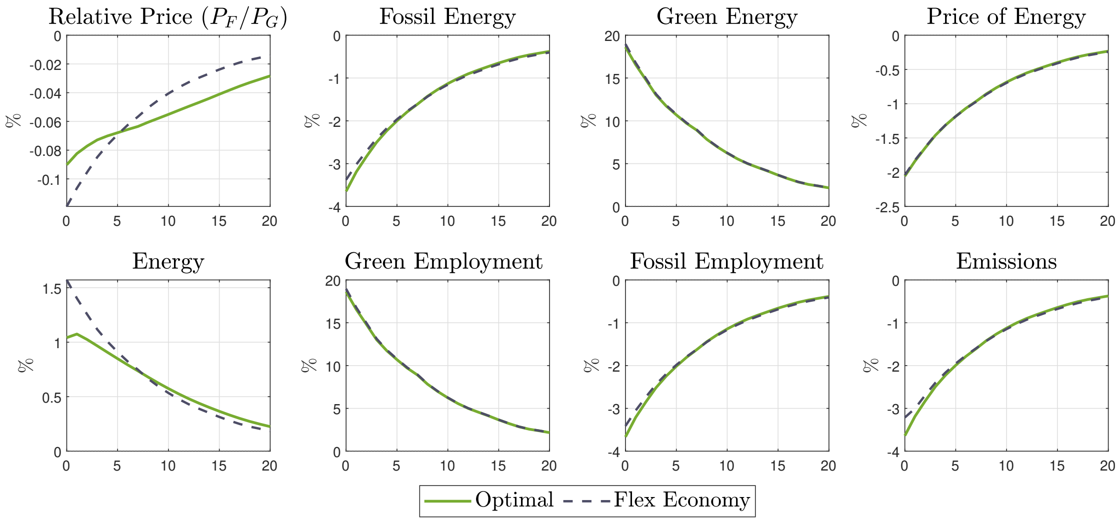

Figure 3: Dynamic response to a green subsidy shock: Energy variables and emissions

Note: Results are reported as percentage deviations (%) and percentage point deviations (p.p.) from the steady state. Prices are expressed in real terms with respect to P_C. Time on the horizontal axis is in quarters.

Unlike a carbon price increase, which directly discourages fossil energy use, a green subsidy operates through an incentive mechanism that promotes clean energy adoption. The subsidy directly lowers the price paid by households and firms for green energy, inducing a sharp increase in demand for this input. The resulting surge in demand, and in the employment required in the green sector, raises the real price of green energy and leads to an increase in the relative price between fossil and green energy. At the same time, the consumption of fossil energy, which is not subsidized, declines. Overall, energy becomes cheaper and energy demand increases. This, together with the fact that green energy accounts only for 20% of the energy mix, explains why, despite the same size of the shock, emissions decreases by less than in the carbon pricing case. Qualitatively, the reaction of energy variables and emissions is similar under optimal monetary policy and mainly characterized by a milder increase in energy demand.

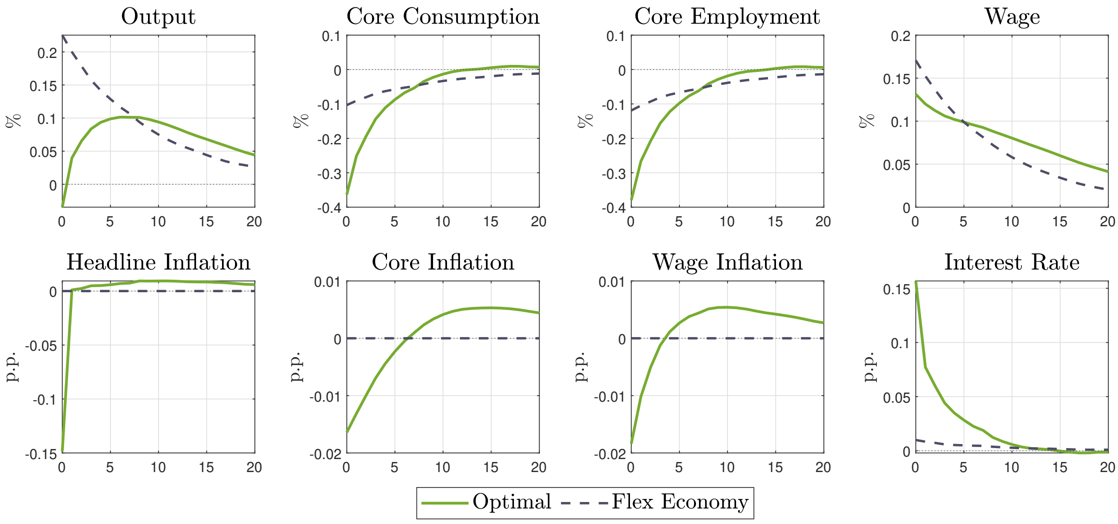

Figure 4: Dynamic response to a green subsidy shock - Macroeconomic variables

Note: Results are reported as percentage deviations (%) and percentage point deviations (p.p.) from the steady state. Wage is expressed in real terms with respect to P_C. Time on the horizontal axis is in quarters.

From Figure 4 we can see that this shock is expansionary. However, the increase in GDP is completely driven by the increase in energy consumption. Due to the increase in real wage and the reallocation of labor toward the green sector, firms in the intermediate sector reduce labor input and production. Core consumption declines as a consequence. Notwithstanding the deflationary nature of the shock, the optimal monetary response in this case prescribes an increase in the nominal interest rate to limit the expansion and volatility in economic activity induced by the subsidy. Optimal monetary policy again appears to act first on the labor market distortion, containing wage inflation and trying to avoid the excessive increase in overall employment, driven by increasing labor demand in the green energy sector.

5 Taylor rules

In this section we compare the dynamic reaction of the economy under different Taylor rules and evaluate their welfare performance compared to the optimal policy.

5.1 Dynamic analysis

Figure 5 and Figure 6 show the IRFs to carbon pricing and green subsidy shocks under optimal monetary policy (solid line), core inflation targeting (dotted line), and headline inflation targeting (dashed-dotted line). To simplify the comparison, we assume the Taylor rules react only to movements in inflation, but do not react to movements in the output gap. The reaction coefficients ι_π is set to 1.5.

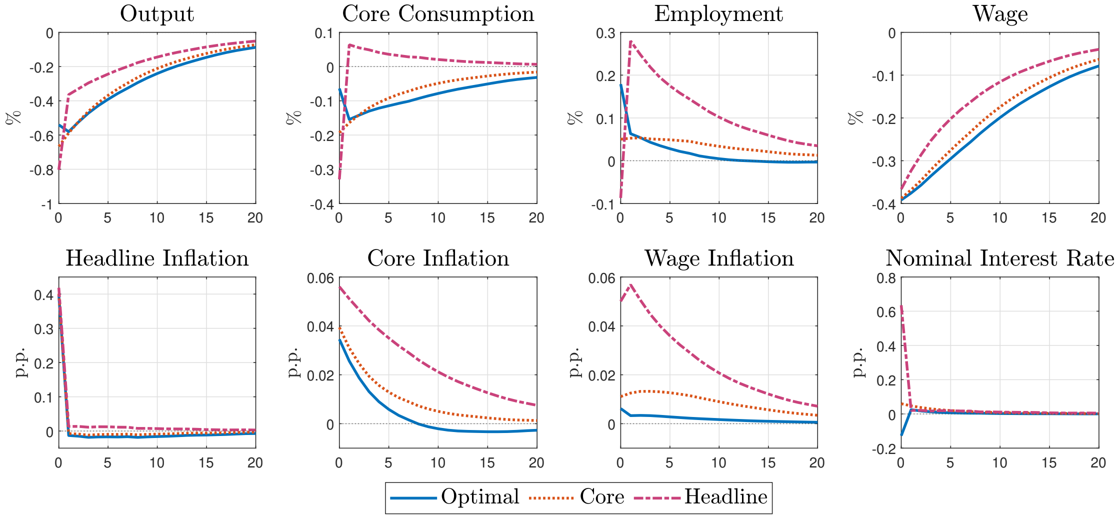

Figure 5: Dynamic response to a carbon pricing shock: optimal monetary policy vs headline inflation targeting vs core inflation targeting

Note: Results are reported as percentage deviations (%) and percentage point deviations (p.p.) from the steady state. Wage is expressed in real terms with respect to P_C. Time on the horizontal axis is in quarters.

Starting with Figure 5 we can see that, dynamically speaking, the choice of the inflation measure is non-neutral. Contrary to optimal policy, under both targeting regimes, the central bank increases the policy rate in response to the shock. However, the magnitude and persistence of the response vary significantly. A headline inflation targeting leads to a sharper but shorter-lived increase in the policy rate, causing a steeper initial decline in output and consumption, followed by a quicker recovery at the cost of more persistent core and wage inflation.

The less accentuated rise of the policy rate under core inflation comes along with an initial smaller drop in output and consumption, compared to headline inflation. At the same time, since the policy stays in a restrictive territory for longer, the central bank stabilizes both core and wage inflation more rapidly but prolongs the negative effects on aggregate demand. Overall, core inflation targeting brings the economy closer to the path achieved under optimal monetary policy.

Turning to the green subsidy case (Figure 6), we observe that, unlike under optimal policy, both headline and core inflation targeting regimes prescribe a reduction in the policy rate. The two targeting strategies appear to be more closely aligned than in the case of a carbon pricing shock. The direct impact on energy prices and headline inflation is less pronounced than under the carbon pricing scheme, reducing the gap between the two inflation measures. Notably, the Taylor rules amplify the expansionary effects of the shock, reversing the sign of core consumption, now boosted by a stronger increase in the real wage. Overall, both rules increase economic volatility and deviate from the optimal policy. In this scenario, identifying a targeting strategy that clearly outperforms the other in aligning with optimal policy is not straightforward based on the IRF analysis.

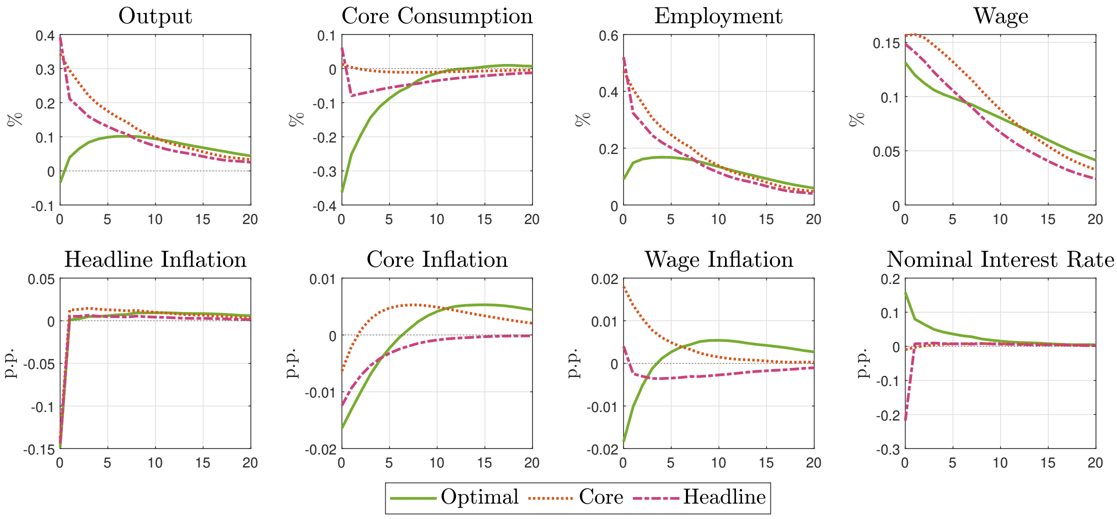

Figure 6: Dynamic response to a green subsidy shock: optimal monetary policy vs headline inflation targeting vs core inflation targeting

Note: Results are reported as percentage deviations (%) and percentage point deviations (p.p.) from the steady state. Wage is expressed in real terms with respect to P_C. Time on the horizontal axis is in quarters.

5.2 Welfare analysis

In this section, we assess the welfare costs associated with different Taylor rules compared to optimal monetary policy. We consider both inflation-targeting rules and dual mandate Taylor rules. Given the importance of the economic structure for optimal policy and welfare (see Section 4), we compare the results obtained in our baseline economy with those from a "Cobb-Douglas" economy and their counterparts without energy consumption.[12] The findings are summarized in Table 2.

Table 2: Welfare costs of different Taylor rules

	Carbon Pricing		Green Subsidy	
	Headline	Core	Headline	Core
Cobb-Douglas $\iota_\pi = 1.5, \iota_y = 0$	.0905	.0783	.0712	.0709
Cobb-Douglas - No C_E $\iota_\pi = 1.5, \iota_y = 0$	-	.0702	-	.0652
Baseline $\iota_\pi = 1.5, \iota_y = 0$	.0472	.0425	.0425	.0429
Baseline - No C_E $\iota_\pi = 1.5, \iota_y = 0$	-	.0319	-	.0383
Cobb-Douglas - Dual mandate $\iota_\pi = 1.5, \iota_y = 0.5$	.0740	.0720	.0707	.0705
Baseline - Dual mandate $\iota_\pi = 1.5, \iota_y = 0.5$	.0423	.0413	.0422	.0421

Note: Numbers are computed as percentage deviations of unconditional mean welfare under the two rules from unconditional mean welfare under optimal policy.

First, the results show that in the Cobb-Douglas economy a simple Taylor approach leads to higher costs than in the Baseline economy. This is due to the fact that the planner is faced with lower trade-offs and can induce a higher level of welfare than what simple inflation targeting can achieve. On the one hand, a Cobb–Douglas production structure implies constant cost shares and thus reduces the size of the policy-trade off. On the other hand, the absence of complementarity in production and consumption reduces the direct distortionary effects of the carbon price hike that come through households' labor and consumption. Both these channels contribute to attenuate the size of the trade-off faced by the policymaker. The distance between Taylor rules and optimal policy is lower in the Baseline case, where the planner is confronted with a larger trade-off and cannot fully stabilize the economy. Similarly, abstracting from consumption of energy eliminates the distortion coming from households' direct response to shocks and aligns the response of inflation and output gap (see Figure D-1). As overall volatility is

[12]The reasoning behind this choice is detailed in Appendix D.2, where an approximation to the welfare of households is derived analytically.

also reduced, the welfare costs decrease in both economy configurations.

Second, our findings align with previous literature (e.g., Aoki, 2001) suggesting that targeting core inflation would be better from a welfare perspective than targeting headline. Since the price markup influences the intratemporal allocation of energy between households and firms, monetary policy should stabilize the sticky component of the price index, which has the greatest impact on welfare. Interestingly, the welfare gap between core and headline inflation targeting narrows under a more realistic economic structure (Baseline). In this setting, targeting core inflation is less effective in closing the output gap compared to a Cobb-Douglas economy, and it incurs the cost of lower consumption and output levels, as illustrated in Figure 5. In the green subsidy scenario, the welfare outcomes are similar for both targeting strategies. This is due to the relatively mild decline and low volatility in energy prices, resulting in only a minor difference between core and headline inflation. Consequently, the choice between the two targeting strategies has no significant impact on welfare.

Third, dual mandate Taylor rules, which also stabilize the output gap, mitigate both the welfare costs relative to optimal policy and the welfare gap between the two inflation measures. These rules are more effective in addressing the trade-off-inducing nature of climate policy shocks, as they target output gap stabilization in addition to inflation.[13]

6 The role of fiscal policy

So far, we have focused on the response of the monetary authority to policy shocks abstracting from any discussion on the fiscal side.

Recent literature shows that policy interventions in specific sectors can create fiscal externalities that monetary policy might want to offset. Bianchi and Coulibaly (2025) make this point for tariffs, arguing that they create a fiscal externality by inefficiently reducing private incentives to import foreign goods, and that the optimal response of monetary policy is to stimulate aggregate income in order to counteract this distortion. When a tariff is introduced, individuals and firms see imported goods as more expensive than they truly are for society as a whole. This happens because they do not take into account that higher imports generate tariff revenue for the government, which increases overall income in the economy. Because of this, people reduce their imports by more than is socially optimal. In other words, imports fall too much, reason why monetary

[13]Including some degree of interest rate smoothing further aligns the welfare outcomes of the two inflation measures. All results are robust to a different specification of the welfare costs, as shown in Appendix D.4.

policy becomes expansionary.

A similar logic is partially at work also in the current framework: whenever resources are transferred back to households, agents fail to internalize that in equilibrium higher demand of fossil energy raises carbon pricing revenues and aggregate income. Thus, the optimal policy is expansionary, with the aim of sustaining employment and aggregate income to limit the contraction in the demand. On the other hand, when a subsidy is financed lump-sum from households, the monetary authority is pushed to cool down the economy to counteract agents not internalizing that lower demand of green energy reduces subsidy costs.

Given these premises, in this section we explore qualitatively the implications of relaxing the assumption that carbon pricing revenues are redistributed lump-sum and green subsidies are financed lump-sum. Together with the two baseline scenarios, namely an increase in carbon pricing with revenues redistributed lump-sum (solid line) and an increase in the green subsidy financed lump-sum (dashed-dotted line), we consider an alternative fiscal policy design, or policy mix, where both measures are combined and the green subsidy is financed through carbon pricing revenues (dotted line).

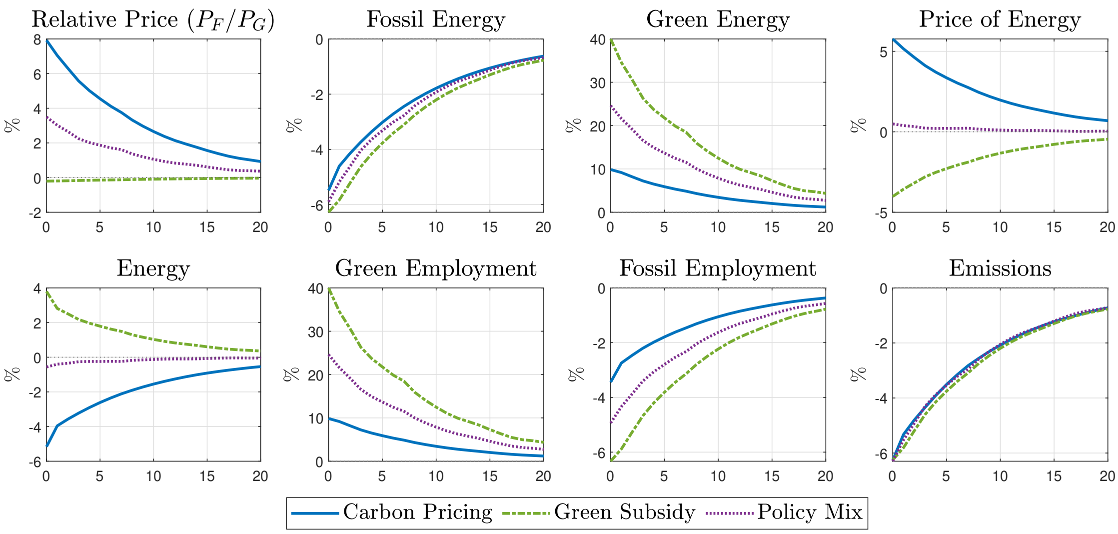

Figure 7: Dynamic response to climate policy shocks - Energy variables and emissions

Note: Results are reported as percentage deviations (%) from the steady state. All prices are expressed in real terms with respect to P_C. The shocks represent increases in carbon pricing and green subsidies, with their magnitudes adjusted to achieve the same emissions reduction within the first year. Time on the horizontal axis is in quarters.

To conduct the experiment shown in Figure 7, we equalize the shocks based on emission reduction rather than standard deviation, as in the main analysis. Achieving a 5% annual

reduction in emissions requires a green subsidy shock that is nearly twice as large as the one used in the main analysis. We maintain a shock persistence of 0.9 across all scenarios and assume a pure headline inflation targeting regime.
The carbon pricing shock raises consumer and producer energy prices by about 6% and increases fossil resource prices by 11%, while the green subsidy reduces energy prices by approximately 4%, with only a marginal 0.4% increase in the price of green energy. The policy mix significantly reduces economic volatility, limiting the increase in energy prices to only 0.5%. The policy mix behaves as an intermediate scenario that achieves the mitigation target while minimizing volatility in the energy aggregates. By offsetting fossil fuel taxation with a subsidy for green energy, fluctuations in relative energy prices are sterilized and expenditure effects are dampened. As a result, aggregate energy prices remain relatively stable.

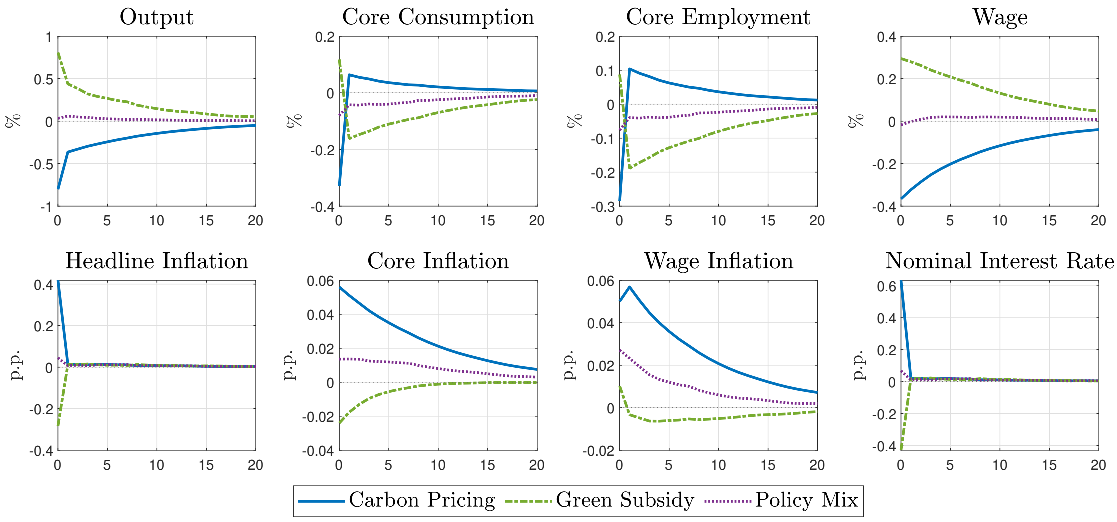

Figure 8: Dynamic response to climate policy shocks - Macroeconomic variables

Note: Results are reported as percentage deviations (%) and percentage point deviations (p.p.) from the steady state. Wage is expressed in real terms with respect to P_C. Time on the horizontal axis is in quarters.

In Figure 8, we can see that the dynamics of the policy mix largely mirror those observed under a pure carbon pricing policy, except for output, which is slightly positive. From a monetary policy perspective it is interesting to notice that this policy achieves the same emissions reduction while exerting less inflationary pressure and allowing for a small increase in GDP. The policy mix aligns the behavior of output and inflation, eliminating the trade-off faced by monetary policy under the other two scenarios. As the policy mix resembles a positive demand shock, monetary policy reacts accordingly by increasing the policy rate. Additionally, as the policy mix significantly reduces economic volatility, monetary policy is less in need of stabilizing the economy and this is reflected in a milder response of the policy rate. Eventually, assuming an alternative way of employing resources in the budget constraint by making better use of the available climate instruments seems to go in the direction of reducing room for monetary policy intervention.[14] Overall, the policy mix approach achieves a more balanced macroeconomic outcome, making it a compelling policy option.

7 Conclusions

This paper investigates the macroeconomic impact of climate policy shocks and how monetary policy can best respond to them in an economy characterized by price and wage rigidities and imperfect complementarities in production and consumption between energy and other production inputs and consumption goods.

We find that climate policy shocks are trade-off inducing for monetary policy. Rises in carbon prices lead to an increase in inflation and a fall in output, while green subsidies decrease inflation and increase output. Complementarities in production and consumption makes the trade-off between output and inflation stabilization larger via distortionary effects on labor and consumption.

In this context, we show that the optimal monetary policy response to an increase in the carbon price implies a decrease in the policy rate after the shock to help dampen real output fluctuation. The opposite is true in response to a green subsidy shock. While long-term price stability is maintained through a credible commitment to keeping inflation and inflation expectations anchored, in the short run the trade-off is resolved in favor of output stabilization.

We also show that dual-mandate Taylor rules that place substantial weight on output gap stabilization perform particularly well. Such rules reduce both the welfare loss relative to optimal policy and the welfare differences associated with targeting headline versus core inflation. Although targeting core inflation can lower welfare losses, especially following a carbon pricing shock, the choice of inflation measure to target becomes less relevant when monetary policy actively stabilizes the output gap.

More broadly, our results highlight that the optimal monetary policy response to climate policy shocks reflects a general principle: when shocks introduce inefficient dis-

[14] This does not exclude a role for optimal policy, although weakened. The different structure of climate policy reduces the fiscal externality, but the monetary authority can still find optimal to sustain aggregate income as higher demand now finances more subsidies. Given the scope of the discussion, we refrain from exploring other alternatives to employ carbon pricing revenues.

tortions that simultaneously affect marginal costs and aggregate demand, strict inflation stabilization is no longer optimal, and monetary policy should instead accommodate short-run inflation in order to limit welfare-reducing output fluctuations.

References

Aboumahboub, T., Auer, C., Bauer, N., Baumstark, L., Bertram, C., et al. (2020). REMIND - REgional Model of INvestments and Development - Version 2.1.0.

Adjemian, S., Juillard, M., Karamé, F., Mutschler, W., Pfeifer, J., Ratto, M., Rion, N., and Villemot, S. (2024). Dynare: Reference Manual Version 6. Dynare Working Papers 72, CEPREMAP.

Airaudo, F. S., Pappa, E., and Seoane, H. D. (2023). The green metamorphosis of a small open economy. CEPR Discussion Paper No. 17863.

Annicchiarico, B., Battles, S., Di Dio, F., Molina, P., and Zoppoli, P. (2017). GHG mitigation schemes and energy policies: A model-based assessment for the Italian economy. *Economic Modelling*, 61:495–509.

Annicchiarico, B. and Crofils, C. (2025). Weather shocks and the optimal policy mix in a climate-vulnerable economy. Mimeo.

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

Annicchiarico, B. and Di Dio, F. (2017). GHG emissions control and monetary policy. *Environmental and Resource Economics*, 67:823–851.

Annicchiarico, B., Di Dio, F., and Diluiso, F. (2024). Climate actions, market beliefs, and monetary policy. *Journal of Economic Behavior & Organization*, 218:176–208.

Annicchiarico, B. and Diluiso, F. (2019). International transmission of the business cycle and environmental policy. *Resource and Energy Economics*, 58:101112.

Aoki, K. (2001). Optimal monetary policy responses to relative-price changes. *Journal of Monetary Economics*, 48(1):55–80.

Bartocci, A., Notarpietro, A., and Pisani, M. (2024). "Green" fiscal policy measures and nonstandard monetary policy in the euro area. *Economic Modelling*, 136:106743.

Bianchi, J. and Coulibaly, L. (2025). The optimal monetary policy response to tariffs. NBER Working Paper 33560.

Bodenstein, M., Erceg, C. J., and Guerrieri, L. (2008). Optimal monetary policy with distinct core and headline inflation rates. *Journal of Monetary Economics*, 55:S18–S33.

Calvo, G. A. (1983). Staggered prices in a utility-maximizing framework. *Journal of Monetary Economics*, 12(3):383–398.

Cantelmo, A., Fatouros, N., Melina, G., and Papageorgiou, C. (2024). Monetary policy under natural disaster shocks. *International Economic Review*, 65(3):1441–1497.

Coenen, G., Lozej, M., and Priftis, R. (2024). Macroeconomic effects of carbon transition policies: an assessment based on the ECB's New Area-Wide Model with a disaggregated energy sector. *European Economic Review*, 104798.

Crippa, M., Guizzardi, D., Solazzo, E., Muntean, M., Schaaf, E., et al. (2021). GHG emissions of all world countries. Publications Office of the European Union.

Del Negro, M., di Giovanni, J., and Dogra, K. (2023). Is the green transition inflationary? FRB of New York Staff Report, 1053.

Deutsche Bundesbank (2017). Mark-ups of firms in selected European countries. *Monthly Report*, 53.

Diluiso, F., Annicchiarico, B., Kalkuhl, M., and Minx, J. C. (2021). Climate actions and macro-financial stability: The role of central banks. *Journal of Environmental Economics and Management*, 110:102548.

Economides, G. and Xepapadeas, A. (2025). Monetary policy stabilization in a new keynesian model under climate change. *Review of Economic Dynamics*, 56:101260.

Erceg, C. J., Henderson, D. W., and Levin, A. T. (2000). Optimal monetary policy with staggered wage and price contracts. *Journal of Monetary Economics*, 46(2):281–313.

Faccia, D., Parker, M., and Stracca, L. (2021). Feeling the heat: extreme temperatures and price stability. ECB Working Paper, 2626.

Ferrari, A. and Nispi Landi, V. (2025). Will the green transition be inflationary? expectations matter. *IMF Economic Review*, 73(4):1195–1258.

Ferrari, M. and Pagliari, M. S. (2023). No country is an island. International cooperation and climate change. *Journal of International Economics*, 145:103816.

Giovanardi, F. and Kaldorf, M. (2025). Pro-cyclical emissions, real externalities, and optimal monetary policy. *European Economic Review*, page 105124.

Golosov, M., Hassler, J., Krusell, P., and Tsyvinski, A. (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88.

Guerrieri, V., Lorenzoni, G., Straub, L., and Werning, I. (2022). Macroeconomic implications of covid-19: Can negative supply shocks cause demand shortages? *American Economic Review*, 112(5):1437–1474.

Holtemöller, O. and Sardone, A. (2024). Optimal monetary policy in a two-sector environmental DSGE model. IWH Discussion Papers, 18/2024.

IPCC (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Khan, H., Metaxoglou, K., Knittel, C. R., and Papineau, M. (2019). Carbon emissions and business cycles. *Journal of Macroeconomics*, 60:1–19.

Kim, H. S., Matthes, C., and Phan, T. (2025). Severe weather and the macroeconomy. *American Economic Journal: Macroeconomics (forthcoming).*

Känzig, D. R. (2023). The Unequal Economic Consequences of Carbon Pricing. NBER Working Papers, 31221.

La'O, J. and Tahbaz-Salehi, A. (2022). Optimal Monetary Policy in Production Networks. *Econometrica*, 90(3):1295–1336.

Levine, P., Lotti, E., Pearlman, J., and Pierse, R. (2010). Growth and welfare effects of world migration. *Scottish Journal of Political Economy*, 57(5):615–643.

Levine, P., McAdam, P., and Pearlman, J. (2008). Quantifying and sustaining welfare gains from monetary commitment. *Journal of Monetary Economics*, 55(7):1253–1276.

Monacelli, T. (2025). Tariffs and monetary policy. CEPR Discussion Paper No. 20142.

Montoro, C. (2012). Oil Shocks And Optimal Monetary Policy. *Macroeconomic Dynamics*, 16(2):240–277.

Nakov, A. and Thomas, C. (2023). Climate-conscious monetary policy. Banco de Espana Working Paper, 2334.

Natal, J.-M. (2012). Monetary policy response to oil price shocks. *Journal of Money, Credit and Banking*, 44(1):53–101.

Nordhaus, W. D. (2018). Evolution of modeling of the economics of global warming: changes in the dice model, 1992–2017. *Climatic Change*, 148(4):623–640.

Olovsson, C. and Vestin, D. (2025). Greenflation? *European Economic Review*, page 105237.

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

Reilly, J. M. and Richards, K. R. (1993). Climate change damage and the trace gas index issue. *Environmental and Resource Economics*, 3(1):41–61.

Rubbo, E. (2023). Networks, Phillips Curves, and Monetary Policy. *Econometrica*, 91(4):1417–1455.

Sahuc, J.-G., Smets, F., and Vermandel, G. (2024). The New Keynesian Climate Model. Available at SSRN: 5035207(2024).

Semik, S. (2025). Carbon pricing and monetary policy in an estimated macro-climate model. Mimeo.

United Nations Environment Programme (2023). Emissions gap report 2023: broken record—temperatures hit new highs, yet world fails to cut emissions (again). United Nations Environment Programme Nairobi.

Varga, J., Roeger, W., et al. (2022). E-QUEST: A multisector dynamic general equilibrium model with energy and a model-based assessment to reach the EU climate targets. *Economic Modelling*, 114:105911.

Werning, I., Lorenzoni, G., and Guerrieri, V. (2025). Tariffs as cost-push shocks: Implications for optimal monetary policy. NBER Working Paper No. 33772.

Appendix A: The cyclical evolution of carbon prices

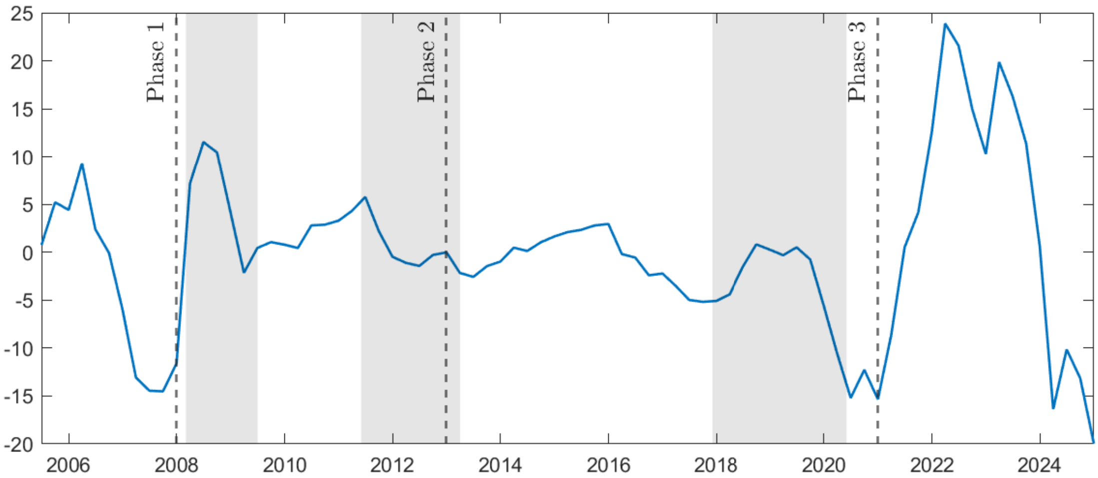

Figure A-1: Cyclical fluctuations in carbon price under the EU ETS

Note: The figure reports the cyclical component of the series of the price of EUA futures contracts (converted to quarterly frequency) derived via HP filtering. Vertical dashed lines show the end of each phase of the ETS (Phase 4 ongoing). Grey bars indicate periods of recessions for the Euro Area according to OECD indicators.

Appendix B: Analytical derivations

Appendix B.1: Optimal price setting

We assume that each period only a fraction $1-\theta_Y$ of firms j, drawn randomly from the firms' population, re-optimize their price to choose the price $P^*_{CY,j,t}$ that maximizes the current market value of the profits generated while that price remains effective. Formally, the maximization problem is the following:

$$\max_{P^*_{CY,j,t}} \quad \mathbb{E}_t \sum_{k=0}^{\infty} (\theta_Y)^k \left[Q_{t,t+k} \left(\frac{P^*_{CY,j,t}}{P_{CY,t+k}} Y_{t+k|t} - \Psi\left(Y_{t+k,t}\right) \right) \right], \tag{B-1}$$

subject to the sequence of demand constraints:

$$Y_{j,t+k,t} = \left(\frac{P^*_{CY,j,t}}{P_{CY,t+k}} \right)^{-\sigma} Y_{t+k}, \tag{B-2}$$

for $k = 0, 1, 2, ...$ The firm will discount future profits by the gross nominal interest rate between today, t, and any future date, $t+k$. The real stochastic discount factor for the nominal pay-offs is:

$$Q_{t,t+k} \equiv \beta^k \left(\frac{\lambda_{t+k}}{\lambda_t} \right). \tag{B-3}$$

$Y_{t+k|t}$ is the output in period $t+k$ for a firm resetting its price at time t and $\Psi\left(Y_{t+k,t}\right)$ is the cost function depending on output set in period t. At the optimum, the firm able to reset its price at time t will choose to equate the expected discounted value of real marginal revenues to that of real marginal costs. The expected discounted value of real marginal revenues associated with a price changed in period t is:

$$(1-\sigma)\mathbb{E}_t \sum_{k=0}^{\infty} \theta_Y^k Q_{t,t+k} \left(\frac{P^*_{CY,j,t}}{P_{CY,t+k}} \right)^{-\sigma} \frac{Y_{t+k}}{P_{CY,t+k}}, \tag{B-4}$$

while the expected discounted value of real marginal costs stemming from a price change occurring at time t is:

$$-\sigma\mathbb{E}_t \sum_{k=0}^{\infty} \theta_Y^k Q_{t,t+k} \frac{MC_{t+k,t}}{P_{CY,t+k}} \left(\frac{P^*_{CY,j,t}}{P_{CY,t+k}} \right)^{-\sigma-1} \frac{Y_{t+k}}{P_{CY,t+k}}, \tag{B-5}$$

By equating the dynamic marginal revenues to the dynamic marginal costs, we have the following optimal pricing condition:

$$P^*_{CY,t}\mathbb{E}_t \sum_{k=0}^{\infty} \theta_Y^k Q_{t,t+k} P^{\sigma-1}_{CY,t+k} Y_{t+k} = \mathbb{E}_t \sum_{k=0}^{\infty} \theta_Y^k Q_{t,t+k} \frac{\sigma}{\sigma-1} \frac{MC_{t+k,t}}{P_{CY,t+k}} P^{\sigma}_{CY,t+k} Y_{t+k}, \tag{B-6}$$

where we have dropped the j-index, since all firms able to set their price optimally at time t will make the same decisions. We can rewrite the above equation as follows:

$$\frac{P^*_{CY,t}}{P_{CY,t}} = \frac{\sigma}{\sigma-1} \left(\frac{\mathbb{E}_t \sum_{k=0}^{\infty} \theta_Y^k Q_{t,t+k} \frac{MC_{t+k,t}}{P_{CY,t+k}} \left(\frac{P_{CY,t+k}}{P_{CY,t}} \right)^{\sigma} Y_{t+k}}{\mathbb{E}_t \sum_{k=0}^{\infty} \theta_Y^k Q_{t,t+k} \left(\frac{P_{CY,t+k}}{P_{CY,t}} \right)^{\sigma-1} Y_{t+k}} \right). \tag{B-7}$$

To solve the model we now re-write each of the expected values of the infinite sums in the above equation recursively, in terms of two artificial variables namely, $\Omega_{1,t}$ and $\Omega_{2,t}$:

$$\Omega_{1,t} = E_t \sum_{k=0}^{\infty} \theta_Y^k Q_{t,t+k} \frac{MC_{t+k,t}}{P_{C,t+k}} \frac{P_{C,t+k}}{P_{CY,t+k}} \left(\frac{P_{CY,t+k}}{P_{CY,t}} \right)^{\sigma} Y_{t+k}, \tag{B-8}$$

$$\Omega_{2,t} = E_t \sum_{k=0}^{\infty} \theta_Y^k Q_{t,t+k} \left(\frac{P_{CY,t+k}}{P_{CY,t}} \right)^{\sigma-1} Y_{t+k}. \tag{B-9}$$

The optimal pricing equation can then be expressed as:

$$\frac{P^*_{CY,t}}{P_{C,t}} \frac{P_{C,t}}{P_{CY,t}} = \frac{\sigma}{\sigma - 1} \frac{\Omega_{1,t}}{\Omega_{2,t}}, \tag{B-10}$$

with

$$\Omega_{1,t} = \frac{MC_t}{P_{C,t}} \frac{P_{C,t}}{P_{CY,t}} Y_t + \theta_Y E_t Q_{t,t+1} \Pi^{R\sigma}_{CY,t+1} \Omega_{1,t+1}, \tag{B-11}$$

$$\Omega_{2,t} = Y_t + \theta_Y E_t Q_{t,t+1} \Pi^{R\sigma-1}_{CY,t+1} \Omega_{2,t+1}, \tag{B-12}$$

where $\Pi^R_{CY,t} = \frac{P_{CY,t}}{P_{C,t}} \frac{P_{C,t-1}}{P_{CY,t-1}}$.
The aggregate price level evolves according to:

$$P_{CY,t} = \left(\theta_Y P^{1-\sigma}_{CY,t-1} + (1 - \theta_Y) P^{*1-\sigma}_{CY,t} \right)^{1/(1-\sigma)} \tag{B-13}$$

that is to say that the price level is just a weighted average of the last period's price level and the price set by firms adjusting in the current period. This equation can be rewritten in real terms as:

$$\frac{P_{CY,t}}{P_{C,t}}^{1-\sigma} = \theta_Y \Pi^{\sigma_t - 1}_{C,t} \left(\frac{P_{CY,t-1}}{P_{C,t-1}} \right)^{1-\sigma} + (1 - \theta_Y) \left(\frac{P^*_{CY,t}}{P_{C,t}} \right)^{1-\sigma}. \tag{B-14}$$

Appendix B.2: Optimal wage setting

Consider a household resetting its wage in period t, and let W_t^* denote the newly set wage. The household will choose W_t^* in order to maximize:

$$\max_{W_t^*} \quad \mathbb{E}_0 \sum_{k=0}^{\infty} (\theta_W \beta)^k \left(\frac{1}{1 - \zeta} C^{1-\zeta}_{t+k,t} - \chi \frac{N^{1+\varphi}_{t+k,t}}{1 + \varphi} \right), \tag{B-15}$$

with $C_{t+k,t}$ and $N_{t+,t}$ denote the consumption and labor supply in period $t + k$ of a household that last reset its wage in period t. The above expression can be interpreted as the expected discounted sum of utilities generated over the (uncertain) period during which the wage remains unchanged at the level W_t^* set in the current period. Maximizing the expected utility subject to the flow households budget constraint (5) and the sequence of labor supply schedules (expressed in real terms) that are effective while W_t^* remains in place, $N_{t+k,t} = \left(\frac{W_t^*}{P_{C,t}} \frac{P_{C,t+k}}{W_{t+k}} \frac{P_{C,t}}{P_{C,t+k}}\right)^{-\sigma_W} N_{t+k}$, at the optimum we have that:

$$\frac{W_t^*}{P_{C,t}}^{1+\sigma_W \varphi} = \frac{\sigma_W}{\sigma_W - 1} \frac{\mathbb{E}_0 \sum_{k=0}^{\infty} (\theta_W \beta)^k \chi \left(\frac{W_{t+k}}{P_{C,t+k}}\right)^{\sigma_W (1+\varphi)} \Pi_{C,t+k}^{\sigma_W (1+\varphi)} N_{t+s}^{(1+\varphi)}}{\mathbb{E}_0 \sum_{k=0}^{\infty} (\theta_W \beta)^k \lambda_{t+k} \left(\frac{W_{t+k}}{P_{C,t+k}}\right)^{\sigma_W} \Pi_{C,t+k}^{\sigma_W - 1} N_{t+s}}. \tag{B-16}$$

Rewriting the above equation in recursive terms we obtain:

$$\frac{W_t^*}{P_{C,t}}^{1+\sigma_W \varphi} = \frac{\sigma_W}{\sigma_W - 1} \frac{H_{1,t}}{H_{2,t}}, \tag{B-17}$$

$$H_{1,t} = \chi \left(\frac{W_t}{P_{C,t}}\right)^{\sigma_W (1+\varphi)} N_t^{(1+\varphi)} + \theta_W \beta \Pi_{C,t+1}^{\sigma_W (1+\varphi)} H_{1,t+1}, \tag{B-18}$$

$$H_{2,t} = \lambda_t \left(\frac{W_t}{P_{C,t}}\right)^{\sigma_W} N_t + \theta_W \beta \Pi_{C,t+1}^{\sigma_W - 1} H_{2,t+1}. \tag{B-19}$$

The aggregate wage index equals:

$$W_t = \left(\theta_W W_{t-1}^{1-\theta_W} + (1-\theta_W) W_t^{*1-\theta_W}\right)^{\frac{1}{1-\theta_W}}. \tag{B-20}$$

The equation can be rewritten in real terms as:

$$\frac{W_t}{P_{C,t}}^{1-\sigma_W} = \theta_W \Pi_{C,t}^{\sigma_W - 1} \left(\frac{W_{t-1}}{P_{C,t-1}}\right)^{1-\sigma_W} + (1-\theta_W) \left(\frac{W_t^*}{P_{C,t}}\right)^{1-\sigma_W}. \tag{B-21}$$

Appendix C: Equilibrium conditions

This appendix reports the equilibrium conditions of the economy. The model is expressed in real terms, using $P_{C,t}$ as numeraire. Lower case letters denote relative prices (i.e. prices divided by $P_{C,t}$).

Households

$$C_t^{-\zeta} = \lambda_t \tag{C-1}$$

$$\frac{1}{R_t} = \frac{Q_t}{\Pi_{C,t+1}} \tag{C-2}$$

$$Q_t = \beta \mathbb{E}_t \left(\frac{\lambda_{t+1}}{\lambda_t} \right) \tag{C-3}$$

$$C_{Y,t} = (1 - \varpi_{CE})(p_{CY,t})^{-\sigma_C} C_t \tag{C-4}$$

$$C_{E,t} = \varpi_{CE}(p_{CE,t})^{-\sigma_C} C_t \tag{C-5}$$

$$C_{EF,t} = \varpi_{CF} \left(\frac{p_{F,t}}{p_{CE,t}} \right)^{-\sigma_E} C_{E,t} \tag{C-6}$$

$$C_{EG,t} = (1 - \varpi_{CF}) \left(\frac{\tau_{g,t} p_{G,t}}{p_{CE,t}} \right)^{-\sigma_E} C_{E,t} \tag{C-7}$$

$$p_{CE,t} = \left[\varpi_{CF} \left(p_{F,t} \right)^{1-\sigma_E} + (1 - \varpi_{CF}) \left(p_{G,t} \right)^{1-\sigma_E} \right]^{\frac{1}{1-\sigma_E}} \tag{C-8}$$

$$\Pi_{C,t} = \left[\varpi_{CE} \left(\Pi_{CE,t} p_{CE,t-1} \right)^{1-\sigma_C} + (1 - \varpi_{CE}) \left(\Pi_{CY,t} p_{CY,t-1} \right)^{1-\sigma_C} \right]^{\frac{1}{1-\sigma_C}} \tag{C-9}$$

$$\Pi_{CE,t} = \frac{p_{CE,t}}{p_{CE,t-1}} \Pi_{C,t} \tag{C-10}$$

$$\Pi_{CY,t} = \frac{p_{CY,t}}{p_{CY,t-1}} \Pi_{C,t} \tag{C-11}$$

Firms

Intermediate goods sector

$$p_{ME,t} = (1 - \varpi_Y)^{1/\varepsilon_Y} \left(\frac{M_{E,t}}{Y_t} \right)^{-\frac{1}{\varepsilon_Y}} mc_t \tag{C-12}$$

$$w_t = \varpi_Y^{1/\varepsilon_Y} \left(\frac{N_{Y,t}}{VA_{Y,t}} \right)^{-1} \left(\frac{VA_{Y,t}}{Y_t} \right)^{-1/\varepsilon_Y} mc_t \tag{C-13}$$

$$\frac{VA_{Y,t}}{Y_t} = \frac{A_{Y,t} N_{Y,t}}{Y_t} \tag{C-14}$$

$$mc_t = \varpi_Y^{1/(1-\varepsilon_Y)} \frac{w_t}{\frac{VA_{Yt}}{N_{Yt}}} + (1 - \varpi_Y)^{1/(1-\varepsilon_Y)} p_{ME,t} \tag{C-15}$$

$$\frac{M_{E,t}}{Y_t} = \left[\varpi_{MG}^{1/\varepsilon_E} \left(\frac{M_{EG,t}}{Y_t}\right)^{(\varepsilon_E-1)/\varepsilon_E} + (1-\varpi_{MG})^{1/\varepsilon_E} \left(\frac{M_{EF,t}}{Y_t}\right)^{(\varepsilon_E-1)/\varepsilon_E}\right]^{\varepsilon_E/(\varepsilon_E-1)} \tag{C-16}$$

$$\frac{M_{EF,t}}{Y_t} = (1-\varpi_{MG}) \left(\frac{p_{F,t}}{p_{ME,t}}\right)^{-\varepsilon_E} \frac{M_{E,t}}{Y_t} \tag{C-17}$$

$$\frac{M_{EG,t}}{Y_t} = \varpi_{MG} \left(\frac{\tau_{g,t} p_{G,t}}{p_{ME,t}}\right)^{-\varepsilon_E} \frac{M_{E,t}}{Y_t} \tag{C-18}$$

Fossil energy sector

$$w_t = \varpi_O^{1/\varepsilon_F} \left(\frac{N_{F,t}}{VA_{F,t}}\right)^{-1} \left(\frac{VA_{F,t}}{E_{F,t}}\right)^{-1/\varepsilon_F} p_{F,t} \tag{C-19}$$

$$p_{O,t} = (1-\varpi_O)^{1/\varepsilon_F} \left(\frac{O_{,t}}{E_{F,t}}\right)^{-\frac{1}{\varepsilon_F}} p_{F,t} \tag{C-20}$$

$$p_{O,t} = \tau_{o,t} p_O \tag{C-21}$$

$$\frac{VA_{F,t}}{E_{F,t}} = \frac{A_{F,t} N_{F,t}}{E_{F,t}} \tag{C-22}$$

$$E_{F,t} = \left[\varpi_O^{1/\varepsilon_F} (VA_{F,t})^{(\varepsilon_F-1)/\varepsilon_F} + (1-\varpi_O)^{1/\varepsilon_F} O_t^{(\varepsilon_F-1)/\varepsilon_F}\right]^{\varepsilon_F/(\varepsilon_F-1)} \tag{C-23}$$

$$X_t = \xi O_t \tag{C-24}$$

Green energy sector

$$w_t = \frac{E_{G,t}}{N_{G,t}} p_{G,t} \tag{C-25}$$

$$p_{G,t} = \frac{w_t}{A_{G,t}} \tag{C-26}$$

Price and wage setting

$$p_{CY,t}^{1-\sigma} = \theta_Y \Pi_{C,t}^{\sigma-1} (p_{CY,t-1})^{1-\sigma} + (1-\theta_Y) \left(p_{CY,t}^*\right)^{1-\sigma} \tag{C-27}$$

$$\frac{p_{CY,t}^*}{p_{CY,t}} = \frac{\sigma}{\sigma-1} \frac{\Omega_{1,t}}{\Omega_{2,t}} \tag{C-28}$$

$$\Omega_{1,t} = \frac{mc_t}{p_{CY,t}} \frac{Y_t}{\Delta_{p,t}} + \theta_Y E_t Q_{t,t+1} \Pi_{CY,t+1}^{R,\sigma} \Omega_{1,t+1} \tag{C-29}$$

$$\Omega_{2,t} = \frac{Y_t}{\Delta_{p,t}} + \theta_Y E_t Q_{t,t+1} \Pi_{CY,t+1}^{R,\sigma-1} \Omega_{2,t+1} \tag{C-30}$$

$$\Pi_{CY,t}^R = \frac{p_{CY,t}}{p_{CY,t-1}} \tag{C-31}$$

$$D_p = (1-\theta_Y)\left(\frac{p^*_{CY,t}}{p_{CY,t}}\right)^{-\sigma} + \theta_Y \Pi^{\sigma}_{CY,t} D_{p,t-1} \tag{C-32}$$

$$w_t^{1-\sigma_W} = \theta_W \Pi^{\sigma_W - 1}_{C,t} (w_{t-1})^{1-\sigma_W} + (1-\theta_W)(w^*_t)^{1-\sigma_W} \tag{C-33}$$

$$\Pi_{W,t} = \frac{w_t}{w_{t-1}} \Pi_{C,t} \tag{C-34}$$

$$w_t^{*1+\sigma_W \varphi} = \frac{\sigma_W}{\sigma_W - 1} \frac{H_{1,t}}{H_{2,t}} \tag{C-35}$$

$$H_{1,t} = \chi w_t^{\sigma_W(1+\varphi)} N_t^{(1+\varphi)} + \theta_W \beta \Pi^{\sigma_W(1+\varphi)}_{C,t+1} H_{1,t+1} \tag{C-36}$$

$$H_{2,t} = \lambda_t w_t^{\sigma_W} N_t + \theta_W \beta \Pi^{\sigma_W - 1}_{C,t+1} H_{2,t+1} \tag{C-37}$$

$$D_W = (1-\theta_W)\left(\frac{w^*_t}{w_t}\right)^{-\sigma_W} + \theta_W \Pi^{\sigma_W}_{W,t} D_{W,t-1} \tag{C-38}$$

Monetary and fiscal policy

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\iota_R} \left[\left(\frac{\Pi_{C,t}}{\Pi_C}\right)^{\iota_\pi} \left(\frac{GDP_t}{GDP^*_t}\right)^{\iota_y}\right]^{1-\iota_R} \tag{C-39}$$

$$T_t = \tau_{o,t} p_O O_t - \tau_{g,t} p_{G,t} E_{G,t} \tag{C-40}$$

Market clearing conditions

$$N_t = N_{Y,t} + N_{G,t} + N_{F,t} \tag{C-41}$$

$$N_t = \frac{N^s_t}{D_{W,t}} \tag{C-42}$$

$$C_{Y,t} = \frac{Y_t}{D_{p,t}} \tag{C-43}$$

$$E_{G,t} = C_{EG,t} + M_{EG,t} \tag{C-44}$$

$$E_{F,t} = C_{EF,t} + M_{EF,t} \tag{C-45}$$

$$GDP_t = p_{CY,t} C_{Y,t} + p_{CE,t} C_{E,t} \tag{C-46}$$

Exogenous processes

$$\log \tau_{o,t} = \rho_o \log \tau_{o,t-1} + \eta_{o,t} \tag{C-47}$$

$$\log \tau_{g,t} = \rho_g \log \tau_{g,t-1} + \eta_{g,t} \tag{C-48}$$

Appendix D: Optimal monetary policy

Appendix D.1: Analytical details

This section of the Appendix enriches the discussion on the carbon pricing shock in the main text by providing analytical insights from the first-order approximation of some equations of the model. The definition of real marginal costs is:

$$\begin{aligned}\hat{mc}_t - \hat{p}_{CY,t} = {} & [(1-\tilde{\alpha}_Y) + \tilde{\alpha}_Y(1-\tilde{\alpha}_{MG}) + \tilde{\alpha}_Y\tilde{\alpha}_{MG}(1-\tilde{\alpha}_O)](\hat{w}_t - \hat{p}_{CY,t}) \\ & + \tilde{\alpha}_Y\tilde{\alpha}_{MG}\tilde{\alpha}_O(\hat{p}_{O,t} - \hat{p}_{CY,t}),\end{aligned} \tag{D-1}$$

where

$$\tilde{\alpha}_Y \equiv (1-\varpi_Y)\left(\frac{P_{ME}}{MC}\right)^{1-\varepsilon_Y}, \quad \tilde{\alpha}_{MG} \equiv (1-\varpi_{MG})\left(\frac{P_F}{P_{ME}}\right)^{1-\varepsilon_E}, \quad \tilde{\alpha}_O \equiv (1-\varpi_O)\left(\frac{P_O}{P_F}\right)^{1-\varepsilon_F}.$$

The weight of the price of the fossil resource $\hat{p}_{O,t}$ in the definition of the real marginal costs depends therefore on three components. As the two types of energy are considered to be substitute in production and $\varepsilon_E > 1$, a higher share of fossil energy used in overall energy production implies more substitution, thus making real marginal costs less sensitive to increases in fossil resource prices. On the other hand, as the fossil resource is a complement to labor in fossil energy production and $\varepsilon_F < 1$, an increase in $\hat{p}_{O,t}$ has greater impact on real marginal costs when the economy depends more on fossil resources. More notably, as energy is a complement to labor in the production of the core good and $\varepsilon_Y < 1$, real marginal costs are more sensitive to changes in the price of the fossil resource when the economy is less competitive, or the degree of monopolistic competition MC^{-1} is greater. A planner concerned with price stabilization is then faced with a bigger trade-off when the economy is on a more distorted steady state[1] and depends more on fossil resources, although the fossil resource price elasticity of marginal costs is also partially reduced by the possibility to substitute fossil with green energy. Under these conditions and when the production of core goods relies heavily on the labor input factor, keeping real marginal costs constant would indeed entail a bigger drop in the real wage, with employment and output falling correspondingly. Note that the inflation-output trade-off stems also from the input-output structure of the economy, which makes marginal costs in the core sector dependent on the price of fossil fuels both directly and indirectly via the product wage.

Investigating the definition of consumption, it is possible to appreciate how an increase in the price of fossil resources induced by a carbon price hike acts as a tax on labor income when core good and energy consumption are complement:

$$\begin{aligned}\hat{c}_t = {} & (1-\tilde{\alpha}_{CE})\hat{y}_t \\ & - \sigma_E\tilde{\alpha}_{CE}\left\{[\tilde{\alpha}_{CF}\tilde{(}1-\alpha_O) + (1-\tilde{\alpha}_{CF})](\hat{w}_t - \hat{p}_{CE,t}) + \tilde{\alpha}_{CF}\tilde{\alpha}_O(\hat{p}_{O,t} - \hat{p}_{CE,t})\right\},\end{aligned} \tag{D-2}$$

[1] Assuming away steady-state distortions does not alter significantly the dynamics of the optimal monetary response, especially when they are removed separately. Reducing the sensitivity of marginal costs to the price of the fossil resource can anyway affect computationally the reaction on impact of the policy rate in the face of a carbon pricing shock.

where

$$\tilde{\alpha}_{CE} \equiv \varpi_{CE} \left(P_{CE}\right)^{1-\sigma_C}, \quad \tilde{\alpha}_{CF} \equiv \varpi_{CF} \left(\frac{P_F}{P_{CE}}\right)^{1-\sigma_E}.$$

The impact of an increase in $\hat{p}_{O,t}$ on total consumption is again magnified by the economy being more dependent on fossil resources for the production of energy, while on the other hand is attenuated by the possibility to substitute for green energy in consumption. More notably, an increase in $\hat{p}_{O,t}$ has a negative effect on total consumption which is larger when the latter depends more on energy, and core goods and energy consumption are complement, with $\sigma_C < 1$.

On a final note, recall that full price stabilization would be anyway unfeasible for a planner because of wage rigidities that would limit the response of salaries required to keep marginal costs constant. As households do not all immediately adjust their salary, wage inflation is defined according to:

$$\hat{\pi}_{W,t} = \beta \mathbb{E}_t \hat{\pi}_{W,t+1} - \beta(1-\theta_W)\mathbb{E}_t \hat{\pi}_{C,t+1} - \frac{(1-\theta_W)(1-\beta\theta_W)}{\theta_W(1+\sigma_W\phi)}(\hat{w}_t - \hat{mrs}_t), \tag{D-3}$$

where

$$\hat{mrs}_t = \phi \hat{n}_t + \zeta \hat{c}_t. \tag{D-4}$$

Thus, a planner is also faced with the problem of reducing wage dispersion across households and can end up prioritizing wage inflation and output stabilization, while tolerating fluctuations in real marginal costs on impact.

Appendix D.2: Inspecting the welfare mechanism

In this subsection, we examine more in detail the economy's welfare function. To do so, we take a second-order approximation of household h's utility $\int_0^1 \left(U_t(h) - U\right) dh/(U_C C)$, which yields:

$$\left(\widehat{c}_t - (\zeta-1)\frac{\widehat{c}_t^{\,2}}{2}\right) - \chi\frac{N^{1+\varphi}}{C^{1-\zeta}}\left(\widehat{n}_t + (1+\varphi)\frac{\widehat{n}_t^{\,2}}{2} + \varphi\sigma_W^2\frac{var(\widehat{w}_t\,(h))}{2}\right)$$

We can define $\widehat{c}_t + \frac{1-\zeta}{2}\widehat{c}_t^{\,2}$ as proportional to

$$\widehat{y}_{C,t} - \frac{\zeta-1}{2}(\widehat{y}_{C,t})^2 - \omega_C\,(1-\omega_C)\,(1-\sigma_C)\,\sigma_C\frac{(\widehat{p}_{CE,t}-\widehat{p}_{CY,t})^2}{2}$$

When the energy share in consumption $\omega_C > 0$ and energy and core goods are complements, i.e. $\sigma_C < 1$, households dislike too much variability in relative price movements of energy and core goods prices. Yet, the term representing this "consumption cost" disappears when either $\omega_C = 0$ or $\sigma_C = 1$.

When considering the labor part of households' utility, we can define $\widehat{n}_t + (1+\varphi)\left(\widehat{n}_t^{\,2}\right)/2$ as proportional to

$$\sigma_W^2\frac{var(\widehat{w}_t\,(h))}{2} + \frac{\sigma^2}{\varpi_Y}\frac{var(\widehat{p}_{CY,t}\,(j))}{2} + \widehat{n}_{Y,t}^{gross} + cov(\widehat{n}_{Y,t}^{gross})$$
$$+\frac{(1-\varepsilon_Y)\,\varepsilon_Y}{\varpi_Y}\frac{(\widehat{p}_{CY,t})^2}{2} + \frac{(1-\varepsilon_F)\,\varepsilon_F}{\varpi_o}\frac{(\widehat{p}_{F,t})^2}{2}$$

Whenever energy and labor are complements in production, i.e. $\varepsilon_F < 1$ and $\varepsilon_Y < 1$, higher variability of relative prices changes in production inputs, $\widehat{p}_{CY,t}$ and $\widehat{p}_{F,t}$, induces higher disutility of labor. Consequently, those terms affect households' utility negatively.

Appendix D.3: Additional figures

This subsection integrates the analysis in the main text with additional figures.

Figure D-1 illustrates the significance of the economic structure for the output gap, marginal cost gap, and the policy rate dynamics. We compare our Baseline economy with an economy without energy in consumption and with a "Cobb-Douglas" economy, in which the elasticities between labor and energy in the intermediate sector, between energy consumption and core consumption, and between labor and fossil fuels are all set to 1. Figures D-2 and D-3 complement Figures 1 and 2 in the main text, showing the behavior of monetary policy under flexible wages.

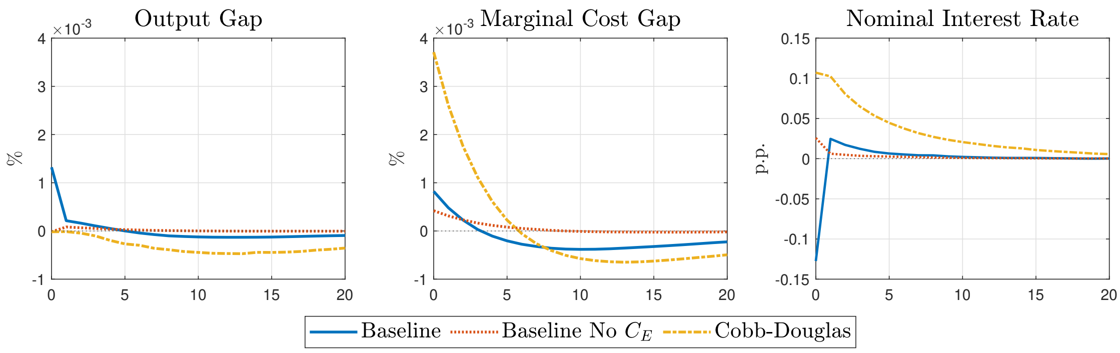

Figure D-1: Dynamic response to a carbon pricing shock under different structures of the economy

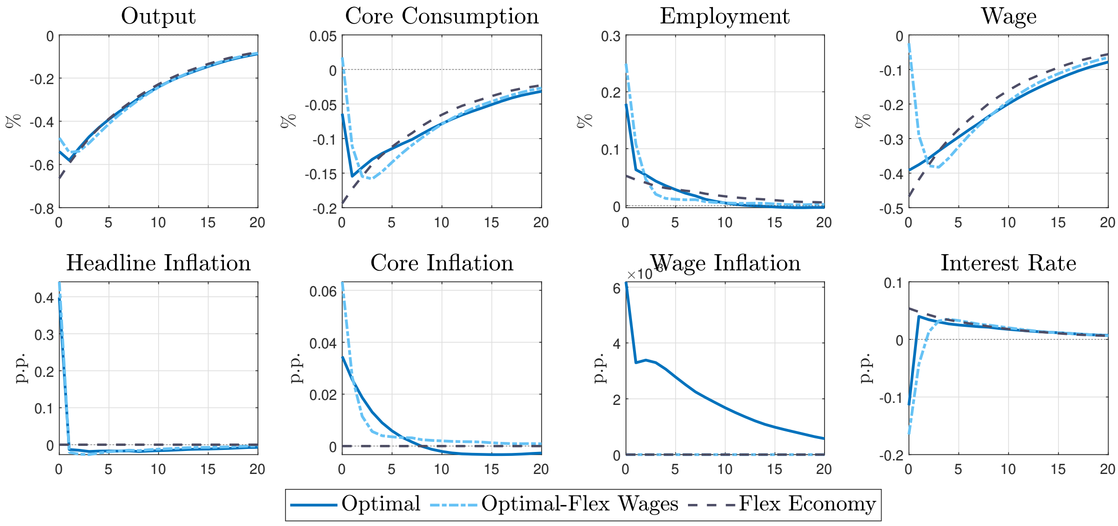

Figure D-2: Dynamic response to a carbon pricing shock - Macroeconomic variables

Note: Results are reported as percentage deviations (%) and percentage point deviations (p.p.) from the steady state. Wage is expressed in real terms with respect to P_C. Time on the horizontal axis is in quarters.

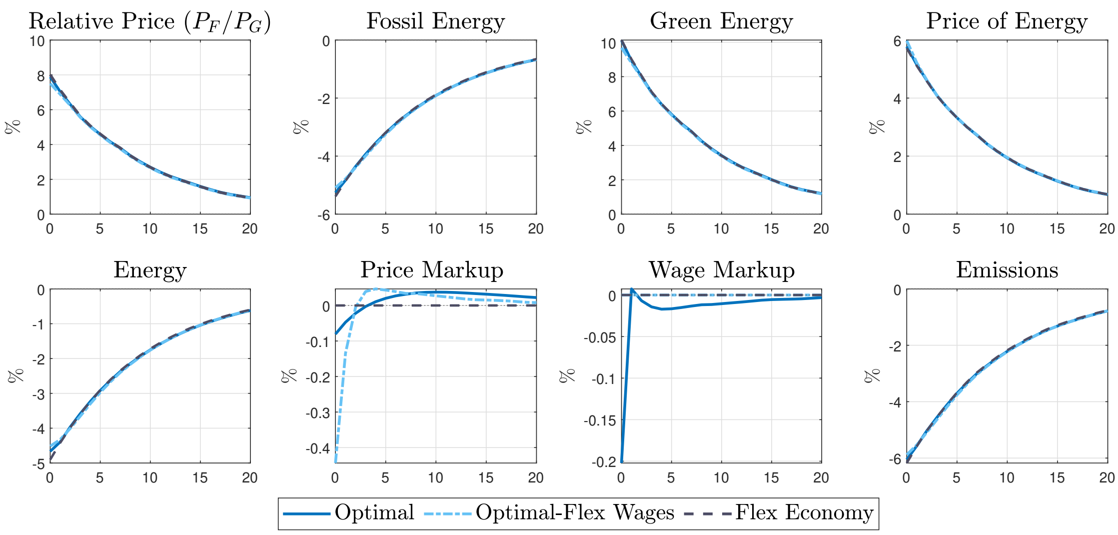

Figure D-3: Dynamic response to a carbon pricing shock - Energy variables, emissions, and markup

Note: Results are reported as percentage deviations (%) and percentage point deviations (p.p.) from the steady state. Prices are expressed in real terms with respect to P_C. Time on the horizontal axis is in quarters.

Appendix D.4: Additional results on Taylor rules

Table D-1: Welfare costs of different Taylor rules

	Carbon Pricing		Green Subsidy	
	Headline	Core	Headline	Core
Cobb-Douglas $\iota_\pi = 1.5, \iota_y = 0$	21.67	18.75	17.06	17.00
Cobb-Douglas - No C_E $\iota_\pi = 1.5, \iota_y = 0$	-	16.90	-	15.69
Baseline $\iota_\pi = 1.5, \iota_y = 0$	11.45	10.30	10.32	10.41
Baseline - No C_E $\iota_\pi = 1.5, \iota_y = 0$	-	7.77	-	7.78
Cobb-Douglas - Dual mandate $\iota_\pi = 1.5, \iota_y = 0.5$	17.73	17.25	16.94	16.91
Baseline - Dual mandate $\iota_\pi = 1.5, \iota_y = 0.5$	10.25	10.01	10.24	10.22

Note: Numbers are computed as percentage deviations of unconditional mean welfare under the two rules from unconditional mean welfare under optimal policy normalized by the increase in welfare obtained from a 1% increase in consumption. See Levine et al. 2008, 2010.