Monetary Policy for the Energy Transition

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Abstract

In this paper, we explore the trade-offs that monetary policy faces during the green energy transition. We propose a New-Keynesian model with clean and dirty technologies. We model the energy transition as a progressive tightening of regulatory constraints on the use of dirty technologies, coupled with endogenous technological progress in the clean sector. We show that some transitory inflation is the natural symptom of the reallocation of production and investment out of dirty technologies and towards clean ones, needed to attain a greener economy. A narrow focus on price stability, in fact, leads to persistent output losses during the energy transition. We also document empirically that innovation, particularly in green technologies, is penalized by tight credit.

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1 Introduction

Climate change is one of the most pressing challenges of the world economy, highlighting the urgent need to restructure production away from fossil fuels toward renewable energy sources. This green energy transition has started in advanced economies in the last ten years, but there is still a long way to go. While the long term objective of living in a energy-efficient green economy is essential for the survival of the planet and to achieve sustainable economic growth, the transition will naturally be associated with costs for some segments of the economy, influenced also by policy decisions. In this paper, we explore how the green transition will impact the primary trade-offs for monetary policy.

By definition, the green transition aims to reduce production by emission-intensive firms, while supporting the use of clean technologies. In fact, various national governments and supranational institutions have imposed different types of regulatory constraints, with the explicit objective of reducing greenhouse gas emissions. Examples include regulating emissions by pollutants through measures like the Clean Air Act in the US or the Emissions Trading System in the EU. These and other types of regulatory interventions have constrained the production of "dirty firms," i.e. firms with high usage of fossil fuels, either by imposing direct limit on emissions or by increasing their costs of production.[1]

To account for this aspect of the energy transition, we build a New-Keynesian model where production requires, together with labor, intermediate inputs supplied by clean and dirty firms. Dirty firms face supply constraints, that limit their production capacity. When these constraints bind dirty goods become in scarce supply, triggering a rise in their price.[2] This effect introduces a non-linearity in the aggregate Phillips curve, which steepens up substantially when high demand makes supply constraints on dirty goods bind. The reason is that dirty firms, once they become supply-constrained, react to increases in demand fully through price rises.

We think of the green energy transition as a progressive tightening of the supply constraints on dirty firms, inducing a gradual increase in their price. This amounts to a cost-push shock, that is a left-ward shift of the steep portion of the Phillips curve, worsening

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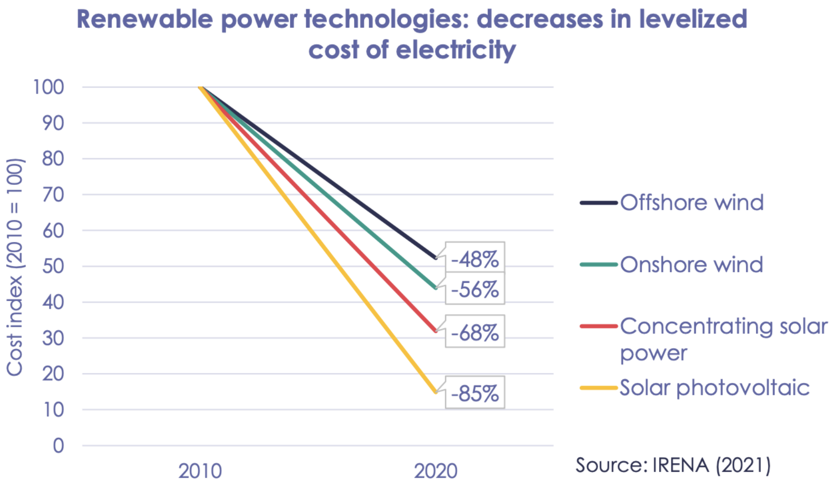
[1] Other factors are constraining the supply of dirty goods. Recent geopolitical events, such as the Russian invasion of Ukraine and the tensions in the Middle East, have have driven up the cost of oil and natural gas. This has imposed higher production costs especially for firms that heavily rely on fossil fuels. Additionally, the anticipation of the green transition has also had the effect of reducing investment in emission-intensive technologies.

[2] Our model is thus consistent with the empirical evidence provided by Boehm and Pandalai-Nayar (2022), who show that sectoral supply curves are convex, i.e. that prices become more sensitive to changes in output as capacity utilization increases. It is also in line with the empirical evidence provided by Balleer and Noeller (2023), who show that supply curves get steeper when intermediate inputs are in short supply.



Source: IRENA (2021)

Figure 1: Rapid advances in renewable power technologies. Notes: this figure shows that dramatic reduction in the cost of producing electricity using clean sources, occurred between 2010 and 2020.

the inflation/employment trade-off faced by the central bank.[3] Our model shows that during the green transition some degree of inflation is necessary to obtain an increase in the relative price of dirty goods, and to reallocate production towards the clean sector. As a result, the central bank may decide to accept a temporary rise in inflation during the energy transition, while a monetary policy purely focused on combating inflation might have large costs in terms of economic activity and slow down the transtion to a green economy.

Tighter supply constraints on emission-intensive firms is only one aspect of the green transition. Rapid advances in renewable power technologies are also playing a key role (Figure 1), and fighting climate change will require a substantial scaling up of green investments. Interestingly, green investments seem to be particularly reliant on external financing, and highly sensitive to changes in financing conditions (Martin et al., 2024; Gormsen et al., 2023). To understand how monetary policy will shape the energy transition, it is then crucial to take its impact on green investment into account.

We thus enrich the model by introducing endogenous technological change in the clean sector. This feature creates an intertemporal inflation trade-off for monetary authorities. As it is standard, engineering a monetary contraction lowers inflation in the short run. But it also depresses clean investment, because it leads to a higher cost of capital and lower demand for clean goods. The result is a slowdown in productivity growth in the clean

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[3] Känzig and Konradt (2023) provide some empirical evidence consistent with this interpretation. They show that tightenings in the carbon emissions allowed by the European Union Trading System lead to higher inflation and lower economic activity in the EU.

sector, which generates inflationary pressures over the medium run.

This effect amplifies the economic costs of maintaining a hawkish monetary stance during the green transition. To contain inflation, indeed, the central banks has to keep the cost of credit high, which depresses investment and productivity growth in the clean sector. Replacing dirty goods with clean ones then takes longer, and the energy transition is associated with persistent output losses. Some transitory inflation may thus be the natural symptom of the reallocation of production and investment out of dirty sectors and towards clean ones, needed to attain our climate goals.

We then turn to an empirical analysis, to understand how changes in financing conditions affect green investments, especially in R&D. As a measure of financing conditions, we consider shocks to the Chicago Fed Financial Condition index, identified using a Choleski approach. Using a sample of US Compustat firms, we find that tighter financial conditions lead to a drop in R&D investment.[4] We then focus on R&D investment by firms characterized by a high share of green patents, which we interpret as a proxy for innovation activities in clean technologies. We show that investments in green R&D are particularly sensitive to financial conditions. These results point to a role for policies that facilitate capital access to green firms. Moreover, given the link between interest rates and financial conditions, these results also point to an additional role for monetary policy in shaping green investments during the energy transition.

Taking stock, our analysis suggests that central banks will face difficult trade-offs during the energy transition. On the one hand, an excessively narrow focus on price stability may generate substantial output losses, and slow down the transition. On the other hand, letting inflation overshoot its target for too long may dis-anchor inflation expectations. Central banks will then have to carefully calibrate the horizon at which inflation should converge back to target. Moreover, though this is not the focus of this paper, appropriate fiscal policy interventions are going to be crucial to ensure a smooth energy transition. In particular, subsidies to green investment may reconcile price stability with a rapid energy transition, and mitigate its economic costs.

Our paper belongs to a growing literature studying monetary policy in the context of the green transition.[5] Among the others, two papers that are closer to ours are Del Negro et al. (2023) and Aghion et al. (2024). Del Negro et al. (2023) propose a two-sector New-Keynesian model where the trade-off for monetary policy depends on how flexible prices in the dirty

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[4] This result echoes the empirical findings of Moran and Queraltó (2018a) and Ma and Zimmermann (2023), who show that monetary contractions cause declines in R&D spending.

[5] A non-exhaustive list of contributions include Campiglio (2016), Airaudo et al. (2022), Nakov and Thomas (2023), Bartocci et al. (2024) and Olovsson and Vestin (2023).

and green sector are relative to the rest of the economy. Aghion et al. (2024) build a model where tightening in financial conditions dampen innovation in green technology. Our paper is also connected to Campiglio et al. (2022) and Mehrotra (2024), which emphasize how the green transition is going to involve a reallocation of investment out of dirty technologies and towards clean ones.

We also build on the literature studying the role of supply constraints in the recent surge in inflation, including Comin et al. (2023), Fornaro and Wolf (2023), and Lorenzoni and Werning (2023). They all introduce supply constraints on non-labor inputs in New-Keynesian models and explore their role in affecting inflation dynamics. In particular, our model builds on Fornaro and Wolf (2023) who provide a Keynesian model with endogenous productivity growth.[6] The authors show that contractionary monetary policy might be able to fight inflation in the short run, but at the cost of persistent output losses and higher inflationary pressures in the medium run. Our model exhibits a similar intertemporal trade-off, although in the context of the green transition.

More broadly, the paper is related to the literature studying monetary policy in multi-sector New-Keynesian models, that emphasizes the allocative role of relative price movements. This literature goes back to Aoki (2001) and Woodford (1999) and include more recent work by Guerrieri et al. (2021), Rubbo (2023), Fornaro and Romei (2022), and Guerrieri et al. (2023) to cite a few.

The rest of the paper is composed by five sections. Section 2 introduces our baseline model. In Section 3, we derive the macroeconomic implications of tighter supply constrains on dirty goods. Section 4 enriches the model with endogenous technological change in the clean sector. Our empirical analysis is contained in Section 5. Finally, Section 6 concludes the paper by providing some policy implications for monetary and fiscal policy.

2 Model

We now propose a simple model with constraints on the use of dirty technologies, and show how this generates a non-linear Phillips curve. We then model the energy transition as a progressive tightening of these constraints, and explore the effects of different types of monetary policy.

Consider an infinite-horizon closed economy. Time is discrete and indexed by $t \in \{0, 1, 2, ...\}$. The economy is inhabited by households, firms, and by a central bank that

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[6] Other contributions considering Keynesian growth frameworks include Benigno and Fornaro (2018), Anzoategui et al. (2019), Garga and Singh (2020) and Queraltó (2022).

sets monetary policy. For simplicity, we abstract from uncertainty and focus on perfect foresight.

2.1 Households

There is a continuum of measure one of identical households with utility

$$\sum_{t=0}^{\infty} \beta^t \log C_t, \tag{1}$$

where $0 < \beta < 1$ is the subjective discount factor and C_t denotes consumption of a homogenous final good. The households' budget constraint is

$$P_t C_t + B_{t+1} = W_t L_t + D_t + (1 + i_{t-1}) B_t, \tag{2}$$

where P_t denotes the nominal price of the final good, B_t one-period nominal bonds, W_t and L_t the nominal wage and employment respectively, D_t the firms' dividends that are distributed to the households, and i_t the nominal interest rate.

At each time t, households allocate their total income between consumption expenditures and bonds purchase. Optimal saving behavior implies

$$C_t = \frac{C_{t+1}}{\beta} \frac{1 + \pi_{t+1}}{1 + i_t} = \frac{C_{t+1}}{\beta(1 + r_t)}, \tag{3}$$

where $\pi_t \equiv P_t / P_{t-1} - 1$ denotes the inflation rate, and r_t the real interest rate.

Households would like to work $\bar{L}$ units of labor every period. Due to wage rigidities, however, employment L_t is determined by firms' labor demand and may deviate from $\bar{L}$. Inspired by the empirical literature on wage Phillips curves (Galí, 2011) , we assume that nominal wages evolve according to

$$\frac{W_t}{W_{t-1}} = \left(\frac{L_t}{\bar{L}} \right)^{\xi} \pi_{t-1}^{\lambda}, \tag{4}$$

where $\xi > 0$ and $0 \leq \lambda < 1$. According to this equation, as in a standard Phillips curve, an increase in employment puts upward pressure on wage growth. Moreover, when $\lambda > 0$ wages are partially indexed to past price inflation. While not crucial for our results, this feature is helpful to obtain reasonable inflation dynamics.

2.2 Final good production

The final good is produced by competitive firms using labor and a continuum of measure one of intermediate inputs $x_{j,t}$, indexed by $j \in [0,1]$. Denoting by Y_t the output of the final good, the production function is

$$Y_t = L_t^{1-\alpha} \int_0^1 A_j^{1-\alpha} x_{j,t}^{\alpha} dj, \tag{5}$$

where $0 < \alpha < 1$, while A_j denotes the productivity of input j.

Profit maximization implies that the demand for labor and for a generic intermediate good j are given respectively by

$$P_t(1-\alpha)L_t^{-\alpha} \int_0^1 A_j^{1-\alpha} x_{j,t}^{\alpha} dj = W_t, \tag{6}$$

and

$$P_t \alpha L_t^{1-\alpha} A_j^{1-\alpha} x_{j,t}^{\alpha-1} = P_{j,t}, \tag{7}$$

where $P_{j,t}$ is the nominal price of intermediate input j. Combining expressions (6) and (7) gives that

$$P_t = \left(\frac{W_t}{\int_0^1 \frac{A_j}{P_{j,t}^{\frac{\alpha}{1-\alpha}}} dj} \right)^{1-\alpha} \frac{1}{(1-\alpha)^{1-\alpha}\alpha^{\alpha}}. \tag{8}$$

Intuitively, the price of the final good is equal to its marginal production cost. This explains why P_t is increasing in the wage and in the prices of the intermediate inputs. A higher productivity of the intermediate inputs, instead, is associated with a lower price of the final good. Due to perfect competition, firms in the final good sector do not make any profit in equilibrium.

2.3 Intermediate goods

Each intermediate good j is produced by a single monopolist, and all the profits are redistributed to the households as dividends. There are two types of intermediate goods: a measure χ of clean goods with productivity A_c and a measure $1-\chi$ of dirty goods with productivity A_d. Since within each class the intermediate goods are identical, with a slight abuse of notation we will denote clean and dirty goods respectively with the subscripts c

and d. We define the share of clean goods in intermediates as

$$\frac{\chi A_c^{1-\alpha} x_{c,t}^{\alpha}}{\chi A_c^{1-\alpha} x_{c,t}^{\alpha} + (1-\chi) A_d^{1-\alpha} x_{d,t}^{\alpha}}. \tag{9}$$

We will use this variable as a measure of the speed of the energy transition out of dirty goods and toward clean ones.

All intermediate goods are produced one-for-one with the final good, but dirty goods face a supply constraint

$$x_{d,t} \leq \bar{x}_t, \tag{10}$$

where $\bar{x}_t$ denotes the upper bound for dirty intermediate good at time t. Such constraint creates bottlenecks in the production process and captures a variety of factors that limit firms' use of polluting sources of energy. For instance, it may capture regulation restricting the use of polluting technologies, such as the Emission Trading System operating in the European Union, or a reduction in the access to foreign oil and gas due to geopolitical factors, but it could also be the result of past under-investment in production capacity by firms operating in the dirty energy sector.[7]

A monopolist producing a clean intermediate good maximizes profits by charging a markup $1/\alpha$ over its marginal cost, that is,

$$P_{c,t} = \frac{P_t}{\alpha}. \tag{11}$$

Equations (7) and (11) then imply that

$$x_{c,t} = \alpha^{\frac{2}{1-\alpha}} A_c L_t \equiv x_{c,t}^{*}, \tag{12}$$

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[7] Sometimes governments implement environmental regulation through taxes, rather than quantity restrictions. But it turns out that this difference is not important for our purposes. To see this point, imagine that dirty firms face no supply constraints, but that for each unit of dirty good produced they have to pay a tax τ_t, whose revenue is rebated to households through lump-sum transfers. The price of dirty goods then satisfies

$$P_{d,t} = (1+\tau_t)\frac{P_t}{\alpha}.$$

Now imagine that the government sets the tax according to

$$\tau_t = \max\left(0, \alpha^2 \left(\frac{A_d L_t}{\bar{x}_t}\right)^{1-\alpha} - 1\right).$$

It is easy to see that this version of the model is isomorphic to the one considered in the main text.

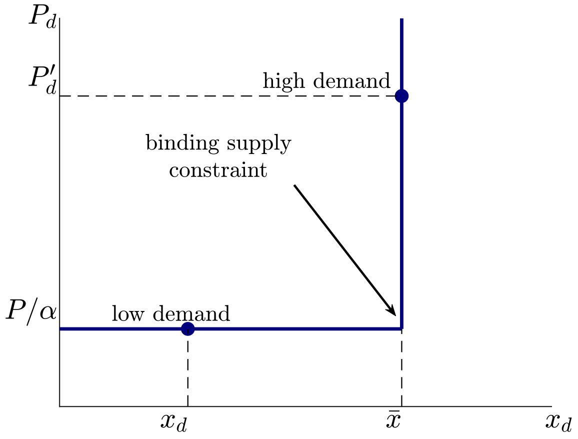

Figure 2: Convex supply curves in the dirty sector.

where x_c^* denotes the desired production of clean intermediate goods.

Similarly, a monopolist producing a dirty intermediate good would produce

$$x_{d,t} = \alpha^{\frac{2}{1-\alpha}} A_d L_t \equiv x_{d,t}^*,$$

absent the supply constraint. This implies that the quantity of dirty goods produced is equal to

$$x_{d,t} = \min\left(x_{d,t}^*, \bar{x}_t\right). \tag{13}$$

So, from condition (7), the price of dirty goods satisfies

$$P_{d,t} = \max\left(1, \left(\frac{x_{d,t}^*}{\bar{x}_t}\right)^{1-\alpha}\right)\frac{P_t}{\alpha}. \tag{14}$$

When the supply constraint does not bind, therefore, firms producing dirty goods react to changes in demand by leaving their price unchanged and adjusting output. When the supply constraint binds, instead, firms respond to variations in demand only by changing prices. Our model thus features convex supply curves for dirty intermediate goods. As illustrated by Figure 2, in fact, the relationship between price and quantity produced is horizontal when the supply constraint does not bind, and becomes vertical thereafter.[8]

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[8] This behavior is consistent with the empirical evidence provided by Boehm and Pandalai-Nayar (2022). They show that, under normal conditions, firms barely adjust their price in response to variations in demand. But prices are extremely sensitive to changes in demand in sectors operating at high levels of capacity utilization.

These bottlenecks in the production process negatively affect labor productivity. Notice that the production constraint on dirty goods binds when employment is high enough, that is, when

$$L_t > \frac{\bar{x}_t}{\alpha^{\frac{2}{1-\alpha}} A_d}. \tag{15}$$

Higher employment is associated with higher demand for dirty intermediates from the final sector, making it more likely that the supply constraint on dirty goods binds. Using this result, and combining equations (5) and (12), total production of the final good is given by

$$Y_t = \begin{cases} \alpha^{\frac{2\alpha}{1-\alpha}} (\chi A_c + (1-\chi) A_d) L_t & \text{if } L_t \leq \frac{\bar{x}_t}{\alpha^{\frac{2}{1-\alpha}} A_d} \\ \chi \alpha^{\frac{2\alpha}{1-\alpha}} A_c L_t + (1-\chi)\, \bar{x}_t^{\alpha} \left(A_d L_t\right)^{1-\alpha} & \text{if } L_t > \frac{\bar{x}_t}{\alpha^{\frac{2}{1-\alpha}} A_d}. \end{cases} \tag{16}$$

This expression shows that binding supply constraints on the dirty goods introduce concavity in the production function, leading to decreasing labor productivity when employment is above the level at which the supply constraint binds. As we will see, this effect is crucial to understand the impact of the energy transition on inflation.

2.4 Monetary policy

Due to the presence of nominal rigidities, by setting the nominal rate i_t the central bank effectively controls the real rate r_t. By equation (3), it follows that monetary policy determines households' demand for consumption, i.e. the economy's aggregate demand.

We frame our monetary policy analysis in terms of two targets: one for inflation that corresponds to the price stability mandate, and one for employment that corresponds to the full employment mandate. In particular, we normalize the inflation target to zero, and we assume that the employment target is the households' desired labor supply $\bar{L}$.

2.5 Market clearing

Market clearing for the final good implies

$$Y_t - \int_0^1 x_{j,t} dj = C_t. \tag{17}$$

The left-hand side of this expression is the GDP of the economy, that is $GDP_t \equiv Y_t - \int_0^1 x_{j,t} dj$, which in the baseline model is fully consumed. Using equations (12) and (16) we can write GDP as

$$GDP_t = \begin{cases} \Psi(\chi A_c + (1-\chi)A_d)L_t & \text{if } L_t \leq \frac{\bar{x}_t}{\alpha^{\frac{2}{1-\alpha}} A_d} \\ \chi \Psi A_c L_t + (1-\chi)\left(\bar{x}_t^{\alpha}\left(A_d L_t\right)^{1-\alpha} - \bar{x}_t\right) & \text{if } L_t > \frac{\bar{x}_t}{\alpha^{\frac{2}{1-\alpha}} A_d}, \end{cases} \tag{18}$$

where $\Psi \equiv \alpha^{2\alpha/(1-\alpha)}(1-\alpha^2)$. As in the case of gross output, supply constraints on dirty goods introduce concavity in the relationship between employment and GDP.

2.6 The Phillips Curve

We start the analysis by deriving the Phillips curve implied by our model, that is the relationship between price inflation and aggregate employment.

Let us denote by $p_{d,t} \equiv P_{d,t}/P_t$ the relative price of dirty intermediate goods in terms of the final good. Using expression (8), inflation can then be written as

$$1 + \pi_t = \frac{W_t}{W_{t-1}} \frac{\chi A_c + (1-\chi)A_d\left(\alpha p_{d,t-1}\right)^{-\frac{\alpha}{1-\alpha}}}{\chi A_c + (1-\chi)A_d\left(\alpha p_{d,t}\right)^{-\frac{\alpha}{1-\alpha}}}, \tag{19}$$

with the relative price of dirty intermediates defined by

$$p_{d,t} = \max\left(\frac{1}{\alpha}, \alpha\left(\frac{L_t A_d}{\bar{x}_t}\right)^{1-\alpha}\right). \tag{20}$$

Hence, when the supply constraint on dirty goods binds their price increases, creating upward pressure on the inflation rate. Equivalently, when the supply constraint on dirty goods binds labor productivity declines, because access to some intermediate goods is curtailed. In turn, lower labor productivity increases production costs and inflation.[9]

We are now ready to trace the Phillips curve. Imagine that the economy starts from a

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[9] More formally, using (5) and (6) gives the expression for price inflation

$$1 + \pi_t = \frac{W_t}{W_{t-1}} \frac{L_t}{Y_t} \frac{Y_{t-1}}{L_{t-1}}, \tag{21}$$

which captures the fact that firms producing the final good set prices equal to their marginal cost. Higher wage inflation puts upward pressure on marginal costs and leads to higher price inflation, while faster productivity growth reduces marginal costs and lowers price inflation.

steady state in which supply constraints do not bind. Then inflation in period 0 is

$$1+\pi_0 = \left(\frac{L_0}{\bar{L}}\right)^{\xi} \frac{\chi A_c + (1-\chi)A_d}{\chi A_c + (1-\chi)A_d\left(\alpha p_{d,0}\right)^{-\frac{\alpha}{1-\alpha}}}, \tag{22}$$

where

$$p_{d,0} = \max\left(\frac{1}{\alpha}, \alpha\left(\frac{L_0 A_d}{\bar{x}_0}\right)^{1-\alpha}\right). \tag{23}$$

The first term in expression (22) is the usual wage Phillips curve component, while the second term captures the effect of supply constraints on dirty goods. As shown in Figure 3, the Phillips curve inherits the non-linearity characterizing the supply curves for dirty goods. The kink in the Phillips curve corresponds to the employment cut-off $\hat{L}_0$ above which the supply constraint on dirty goods becomes binding. Below that employment cut-off wages do not react much to labor market conditions and the Phillips curve is relatively flat. As employment increases above $\hat{L}_0$, the price of dirty goods starts rising, increasing the implied level of inflation. This explains why the Phillips curve steepens up when employment exceeds $\hat{L}_0$.

The first implication is that fluctuations in employment, perhaps driven by demand shocks, are likely to cause high inflation volatility. This happens when positive demand shocks push the economy on the steep part of the Phillips curve, where the sensitivity of inflation to changes in employment is high. The left panel of Figure 3 shows this result, by illustrating how symmetric fluctuations in employments around the kink translate into a highly volatile inflation rate.

The right panel of Figure 3 shows how the Phillips curve responds to a tightening of the supply constraint on dirty goods, i.e. a drop in $\bar{x}_0$. Then, the steep portion of the Phillips curve shifts to the left, because supply constraints on dirty goods start binding at a lower level of employment. As a result, the central bank faces a worse inflation/employment trade off. For instance, suppose that the economy starts from an equilibrium with full employment and inflation on target (point $(\bar{L}, 0)$). Now imagine that $\bar{x}_0$ drops. To maintain inflation on target, monetary policy has to generate slack on the labor market (point $(L_0^l, 0)$) in order to contain the rise in the price of dirty goods, and to compensate it with a drop in nominal wages. Instead, if monetary policy focuses on maintaining full employment, inflation rises sharply (point $(\bar{L}, \pi_0^h)$). Once again, the reason is that a binding constraint on dirty goods triggers a rise in their price, as well as production bottlenecks and lower labor productivity, which are accommodated through higher price inflation.

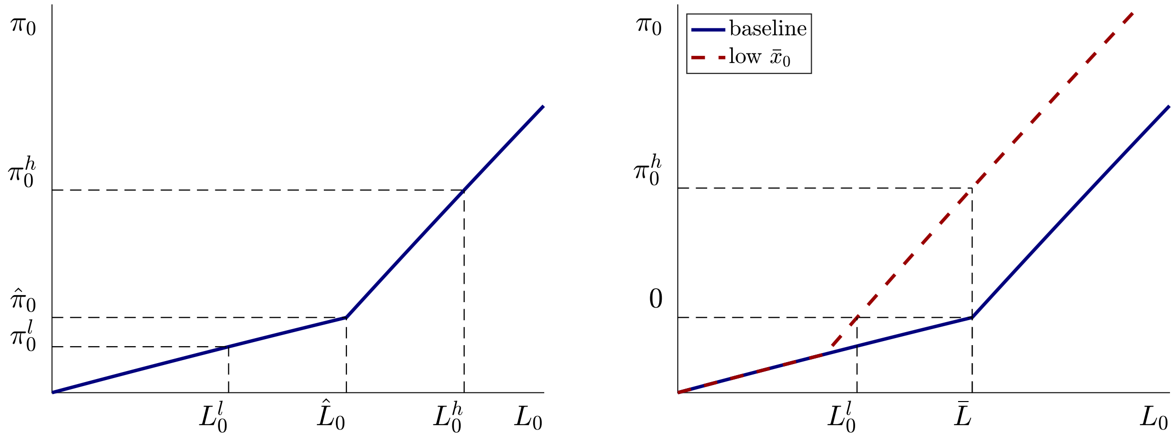

Figure 3: Non-linear Phillips curve.

How do these results relate to the macroeconomic impact of the energy transition? We anticipate that in the coming years, due to tighter regulations on polluting energy sources and geopolitical shocks, production bottlenecks in dirty sectors will become particularly salient. Through the lens of our model, this means that our economies will often end up on the steep portion of the Phillips curve. If so, busyness cycles driven by demand shocks will likely lead to high inflation volatility. Moreover, the employment cost of containing inflation will likely be high. These considerations suggest that the energy transition may trigger an increase in both the volatility and the average level of inflation. We elaborate on this point below, by using the model to study different macroeconomic scenarios related to the energy transition.

3 The macroeconomic impact of dirty energy shortages

We now turn to the macroeconomic impact of dirty energy shortages. In particular, we highlight that tighter supply constraints on dirty goods put upward pressure on their price, inducing a reallocation of resources toward clean goods. Some degree of transitory inflation is thus a natural symptom of an efficient reallocation of productive activities and a monetary authority narrowly focused on containing inflation can generate large output and employment losses.

3.1 Temporary dirty energy shortages

We start by considering temporary dirty energy shortages. These could be caused by geopolitical shocks, temporarily disrupting access to imports of oil and gas. We study this scenario using a numerical simulation. While performing a full-blown quantitative analysis is not our objective, we try to pick reasonable values for the parameters. We calibrate the model at quarterly frequency. We set $\beta = .9938$, so that the steady state (annualized) real interest rate is 2.5%. We set $\alpha = .5$, in line with the share of intermediates in gross output in the United States. We choose $\chi = .5$ and $A_c/A_d = .43$, so that in the initial steady state the share of clean goods in total intermediates is 30%. According to data from the World Bank, 30% is the share of energy produced using renewables in 2022 for the world as a whole.[10] Turning to the wage Phillips curve, we set $\xi = .1$ and $\lambda = .5$, in line with the empirical estimates provided by Galí (2011) and Galí and Gambetti (2020).

We study the economy's response to a temporary drop in $\bar{x}_t$. More precisely, the cap on the production of dirty goods drops below its steady state value in period $t = 0$, that is, to $\bar{x}_0 < \bar{x}_{ss}$. From then on, $\bar{x}_t$ evolves according to

$$\bar{x}_t = \rho \bar{x}_{t-1} + (1-\rho)\bar{x}_{ss}, \tag{24}$$

where $\bar{x}_{ss}$ denotes the value of $\bar{x}_t$ in steady state. The initial shock is unanticipated, but then agents forecast correctly the path of $\bar{x}_t$. We set $\bar{x}_{ss} = \alpha^{\frac{2}{1-\alpha}} A_d \bar{L}$, so that the constraint on dirty energy production is marginally binding in steady state, and $\bar{x}_0 = .83 * \bar{x}_{ss}$, so that under full employment $p_{d,0}$ rises by 10% above its steady state value. Finally, we set $\rho = .75$ so that the bulk of the shock has disappeared after one year. This corresponds to a large, but short-lived, energy shock, similar to the one experienced by the euro area in 2022.

The results are shown in Figure 4. Start by considering the solid lines, which correspond to a central bank that targets full employment $(L_t = \bar{L})$. Under this policy, the dirty energy shortage causes a recession, accompanied by a sharp transitory rise in inflation. The drop in GDP happens because tighter access to dirty goods reduces productivity. Lower productivity, moreover, depresses real wages. Since under full employment nominal wages are slow to adjust, the cut in real wages is attained through a burst of inflation. Inflation is particularly acute in the dirty sector, which induces producers of the final good to rely more on clean intermediate inputs.

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[10] For details, see https://ourworldindata.org/grapher/share-of-electricity-production-from-renewable-sources.

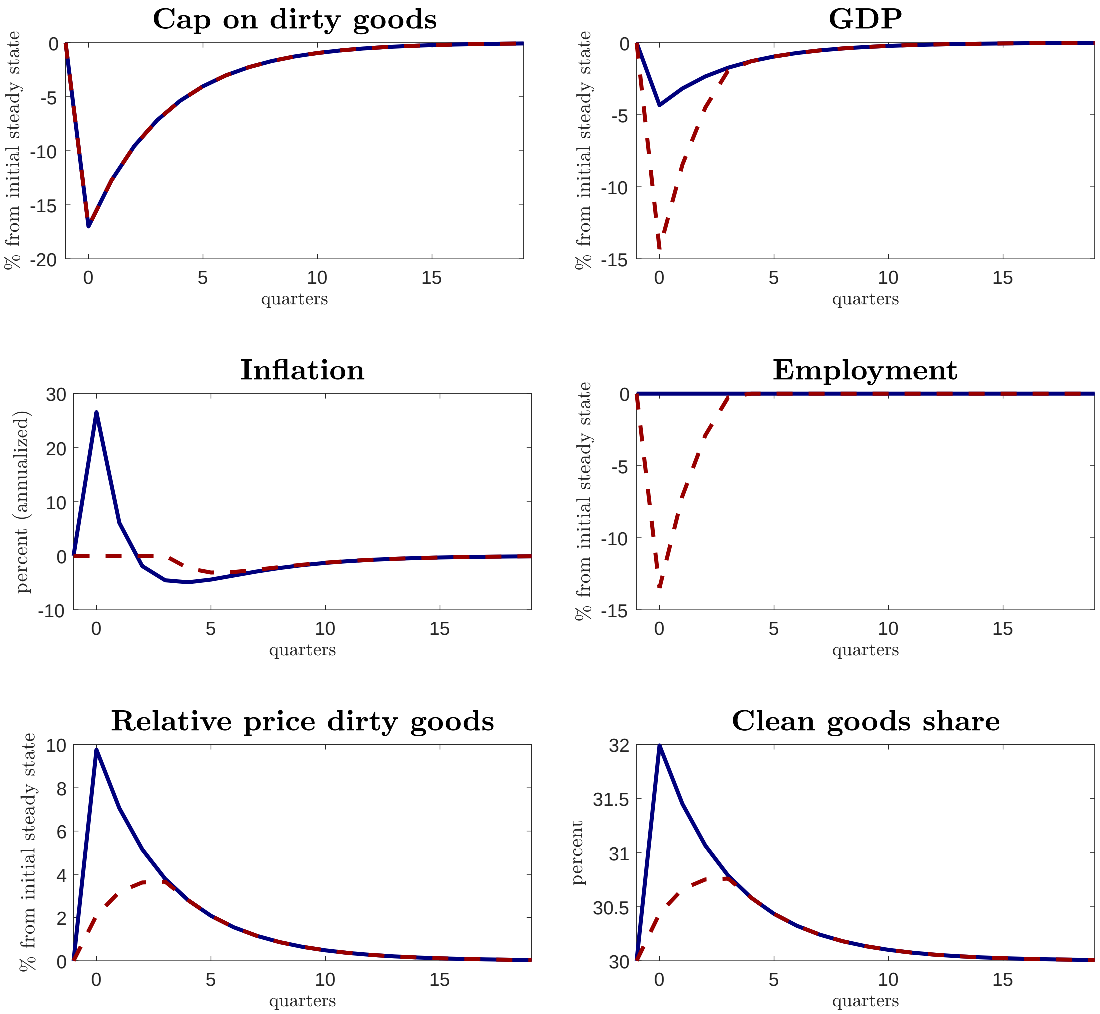

Figure 4: Temporary dirty-energy shortages. Notes: solid lines refer to a central bank that targets full employment ($L_t = \bar{L}$), dashed lines refer to a hawkish monetary stance, which does not allow inflation to rise above target ($\pi_t \leq 0$).

What if the central bank chooses to counteract the inflationary pressures? Consider a hawkish monetary stance, which prevents inflation from rising above target.[11] This hawkish stance, illustrated by the dashed lines, amplifies substantially the recession caused by the shock. Substantial slack on the labor market, in fact, is needed to contain the inflationary pressures caused by the dirty energy shortage. Moreover, a hawkish monetary response - by dampening the rise in the relative price of dirty goods - reduces the temporary

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[11] More precisely, under this hawkish monetary stance the central bank follows the rule

$$\pi_t \left(L_t - \bar{L}\right) = 0 \quad \text{with} \quad \pi_t \leq 0.$$

In words, the central bank is willing to sacrifice full employment to prevent inflation from rising above target.

reallocation of production toward clean intermediate inputs, creating efficiency losses. This effect constitutes a further drag on productivity, which contributes to the severity of the recession.

Tighter access to dirty goods thus acts as a cost-push shock, worsening the trade-off between inflation and economic activity faced by the central bank. This implication of the model is consistent with the empirical evidence provided by Känzig and Konradt (2023). Using data from the European Union, they show that increases in energy prices caused by stricter regulation on carbon emissions lead to higher inflation and lower economic activity. In the model, the inflation response is mainly driven by the firms that rely more on fossil fuels to produce, which is consistent with the empirical findings of Balleer and Noeller (2023). Using German firm-level data, they document that firms increase prices when their access to some key production input is constrained.

3.2 Phasing out of dirty goods

Our model can also be used to study the macroeconomic impact of a gradual phasing out of dirty goods, driven by regulations aiming at combating climate change. A good example is the Emission Trading System enacted by the European Union, which is progressively reducing firms' use of fossil fuels. We do so by considering a smooth permanent reduction in $\bar{x}$. We calibrate the shock so that the share of green goods rises from 30% to 45%, and assume that the phase out of dirty goods is spanned over a decade. Figure 5 shows the response of the economy to such a shock under the two alternative monetary policies considered above.

The solid lines refer to a central bank committed to full employment ($L_t = \bar{L}$). The tightening of regulation on dirty goods leads to bottlenecks in the production process, explaining the gradual decline in GDP. Moreover, as the supply constraints on dirty goods become more binding, the price of dirty goods rises, putting upward pressures on firms' marginal costs. This is the reason why the phasing out of dirty goods is accompanied by a transitory rise in inflation.

Of course, the central bank can prevent inflation from rising by running a sufficiently tight monetary policy. This is the case shown by the dashed lines. However, substantial slack on the labor market is needed to dampen the inflationary pressures during the transition to a greener economy. As a result, the cost in terms of economic activity of moving out of dirty goods is greatly amplified. Moreover, under this policy the central bank slows down the rise in the relative price of dirty goods. The result is a slower

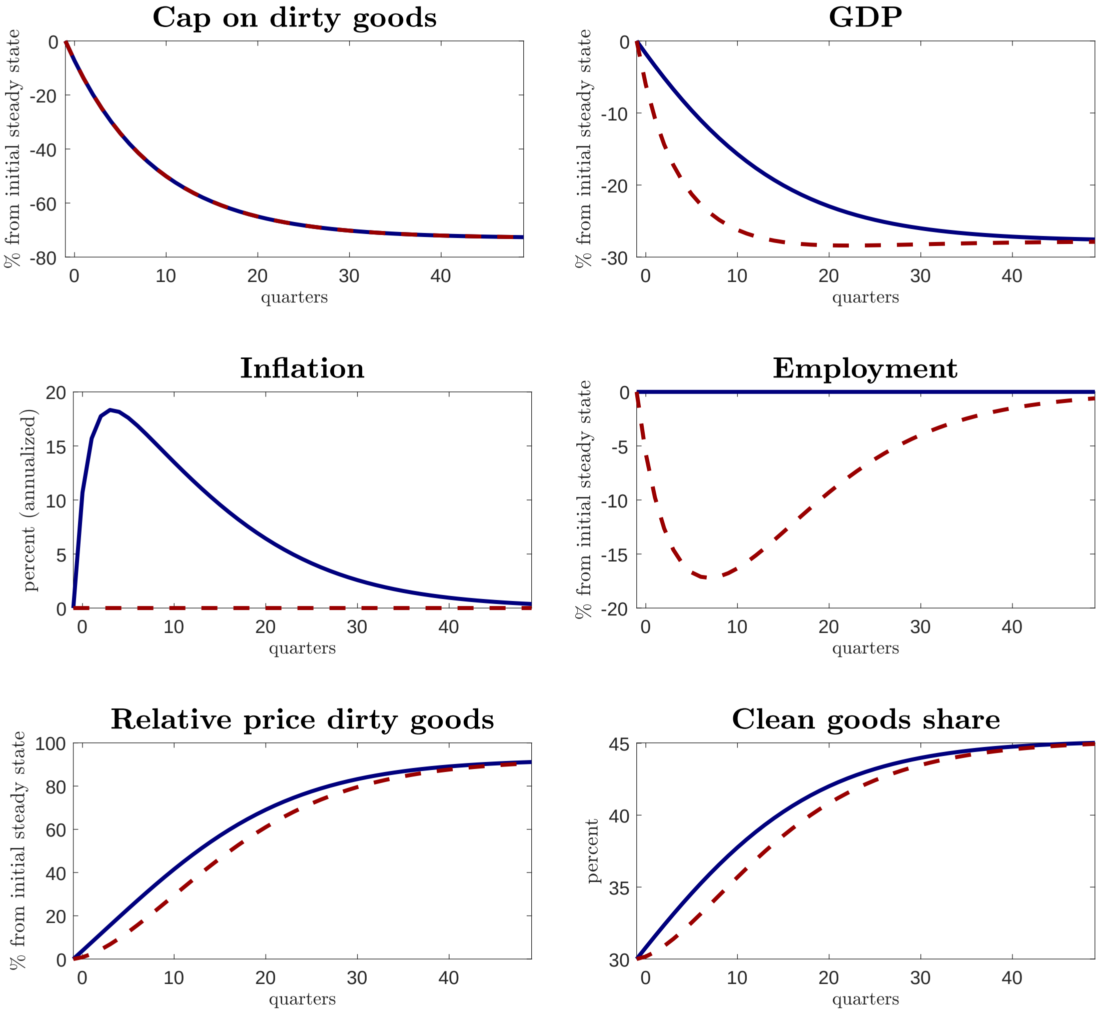

Figure 5: Phasing out of dirty energy sources. Notes: solid lines refer to a central bank that targets full employment ($L_t = \bar{L}$), dashed lines refer to a hawkish monetary stance, which does not allow inflation to rise above target ($\pi_t \leq 0$).

reallocation toward clean inputs.

Taking stock, these two experiments show how some degree of transitory inflation is a natural symptom of the reallocation of economic activity toward clean goods. However, they also offer a rather gloomy vision of the energy transition, which is characterized by a long-run drop in GDP. What is missing is the notion that advances in green technologies can reconcile a cleaner economy with robust productivity growth. We explore the implications of green innovations for monetary policy next.

4 Endogenous green innovation

We have abstracted from technological change so far, but - when we think about the transition to a green economy - it is key to consider the effect of different policies on innovation in clean technologies. With this in mind, we now introduce endogenous technical change in the clean sector, by allowing firms producing clean intermediate goods to increase their productivity through investment. More precisely, the productivity of a generic clean intermediate good now evolves according to

$$A_{c,t+1} = (1-\delta)A_{c,t} + \frac{\psi_t}{\phi} I_{c,t}^{\phi}, \tag{25}$$

where $I_{c,t}$ denotes investment in units of the final good. Investment is subject to diminishing returns, captured by the parameter $0 < \phi < 1$, and productivity depreciates at rate δ. The exogenous variable ψ_t determines the productivity of investment in clean technologies. An increase in ψ_t, for instance, can be the result of scientific discoveries that facilitate the development of new technologies in the clean sector.

To understand why a firm in the clean sector would want to invest in innovation, consider that firms producing clean goods earn profits $P_t \varpi A_{c,t} L_t$ where $\varpi \equiv (1/\alpha - 1)\alpha^{2/(1-\alpha)}$. So technology upgrades are associated with higher profits. In fact, optimal investment by firms producing clean intermediates implies[12]

$$I_{c,t}^{1-\phi}/\psi_t = \frac{\varpi L_{t+1} + (1-\delta) I_{c,t+1}^{1-\phi}/\psi_{t+1}}{1 + r_t + \eta_t}. \tag{26}$$

Intuitively, firms equalize the marginal investment cost $(I_{c,t})^{1-\phi}/\psi_t$ to its discounted marginal benefit. The marginal benefit is given by the increase in next period profits ϖL_{t+1} plus the savings on future investment costs $(I_{c,t+1})^{1-\phi}/\psi_{t+1}$. Following Fornaro and Wolf (2023), we introduce a spread η_t between the policy rate and the discount factor used by firms. This is the reason why firms discount the future return to investment at rate $1 + r_t + \eta_t$.

We introduce this wedge for three reasons. First, for empirical realism. In fact, recent

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[12] Firms producing intermediate goods choose investment in innovation to maximize

$$\sum_{t=0}^{\infty} \left(\prod_{\tau=1}^{t} \frac{1}{1 + r_{\tau-1} + \eta_{\tau-1}} \right) (\varpi A_{c,t} L_t - I_{c,t}),$$

subject to (25), given the initial condition $A_{c,0}$.

work by Gormsen and Huber (2022) shows that the discount rates used by firms to evaluate investment projects are substantially higher than the financial cost of capital, and only partly responsive to changes in market interest rates. Second, in innovation-based endogenous growth models the social return from investing in innovation is typically higher than the private one (Romer, 1990; Aghion and Howitt, 1992). For instance, this happens if knowledge is only partly excludable, and so inventors cannot prevent others from drawing on their ideas to innovate. The wedge η_t captures in reduced form these effects, because it leads firms to underestimate the positive impact of their investments on social welfare. Third, this wedge captures changes in financial conditions not directly related to variations in the risk-free rate. This feature of the model will help us connect it to the empirical analysis developed in Section 5.

To understand how monetary policy affects investment in clean technologies, it is useful to iterate equation (27) forward to obtain

$$I_{c,t}^{1-\phi} = \psi_t \sum_{\tau=t}^{\infty} \left(\prod_{\hat{\tau}=t}^{\tau} \frac{1}{1 + r_{\hat{\tau}} + \eta_{\hat{\tau}}} \right) \left((1-\delta)^{\tau-t} \varpi L_{\tau+1} \right). \tag{27}$$

First, monetary policy has a direct impact on investment, because it determines the stream of real rates r. As it is intuitive, a higher interest rate induces firms to decrease their investment in green technologies. Moreover, since investment is a forward-looking variable, what matters for this effect is the whole term structure of interest rates. This means that monetary interventions affecting interest rates over the medium run have a particularly strong impact on investment.

In addition, monetary policy affects investment through a general equilibrium effect, that is by influencing aggregate demand and profits. This effect is captured by the term ϖL. For instance, a monetary contraction depresses economic activity and employment L, leading to a fall in profits. In turn, lower profits reduce firms' incentives to invest. The opposite applies to monetary expansions, which instead boost firms' profits and investment. Once again, since investment decisions are forward looking, monetary interventions persistently affecting aggregate demand have a bigger impact on investment.

To close the model, we have to replace the market clearing condition (17) with

$$GDP_t = C_t + \chi I_{c,t}, \tag{28}$$

where we are focusing on a symmetric equilibrium in which all the firms are identical, and so aggregate investment is equal to $\chi I_{c,t}$.

Before turning to monetary policy and the energy transition, it is useful to have a look at the steady state of the model. In steady state the real rate is constant an equal to $r = 1/\beta - 1$. Moreover, we assume that in steady state the economy operates at full employment and so $L = \bar{L}$. Steady state investment is then equal to

$$I_c = \left(\frac{\varpi \psi \bar{L}}{r + \eta + \delta} \right)^{\frac{1}{1-\phi}}, \tag{29}$$

while the productivity of clean inputs is

$$A_c = \frac{\psi}{\delta \phi} \left(\frac{\varpi \psi \bar{L}}{r + \eta + \delta} \right)^{\frac{\phi}{1-\phi}}. \tag{30}$$

Hence, as it is natural, higher profits or a lower interest rate boost investment and the productivity of clean intermediates in steady state. Notice that, in line with the empirical evidence provided by Gormsen and Huber (2022), the presence of the discount factor wedge η dampens the investment response to changes in their cost of capital r.

4.1 An intertemporal inflation trade-off

We now consider the macroeconomic impact of a monetary contraction. To anticipate the main messages, a monetary tightening hurts green investment and slows down productivity growth in the clean sector. Moreover, the endogenous drop in productivity generates inflationary pressures in the medium run, effectively creating an intertemporal inflation trade-off for the central bank.

Our simple model does not differentiate between investment in physical capital and intangible investment in innovation. However, we interpret the green energy transition as the result of investment in new technologies, and so we calibrate the investment side of the model inspired by the endogenous growth literature. We thus set $\delta = 0.15/4$, to match the yearly depreciation rate of 15% used by the Bureau of Labor Statistics to estimate the R&D stock. For simplicity, we assume that η is constant, and set its value to match a yearly discount rate of 10%, in line with the discount factors used by firms to evaluate green investments (Gormsen et al., 2023).[13] Hence, recalling that the steady state yearly real rate is 2.5%, we set $\eta = 7.5\%/4$. The parameter ϕ, which governs the curvature of

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[13] More precisely, Gormsen and Huber (2022) estimate an average nominal discount factor of 16%. Subtracting 2% expected inflation, we are left with a real discount factor of 14%. Moreover, Gormsen et al. (2023) show that the discount factor applied by firms to green investments is 4% lower than on other types of investment. This implies that the real discount factor used to evaluate green investments is around 10%.

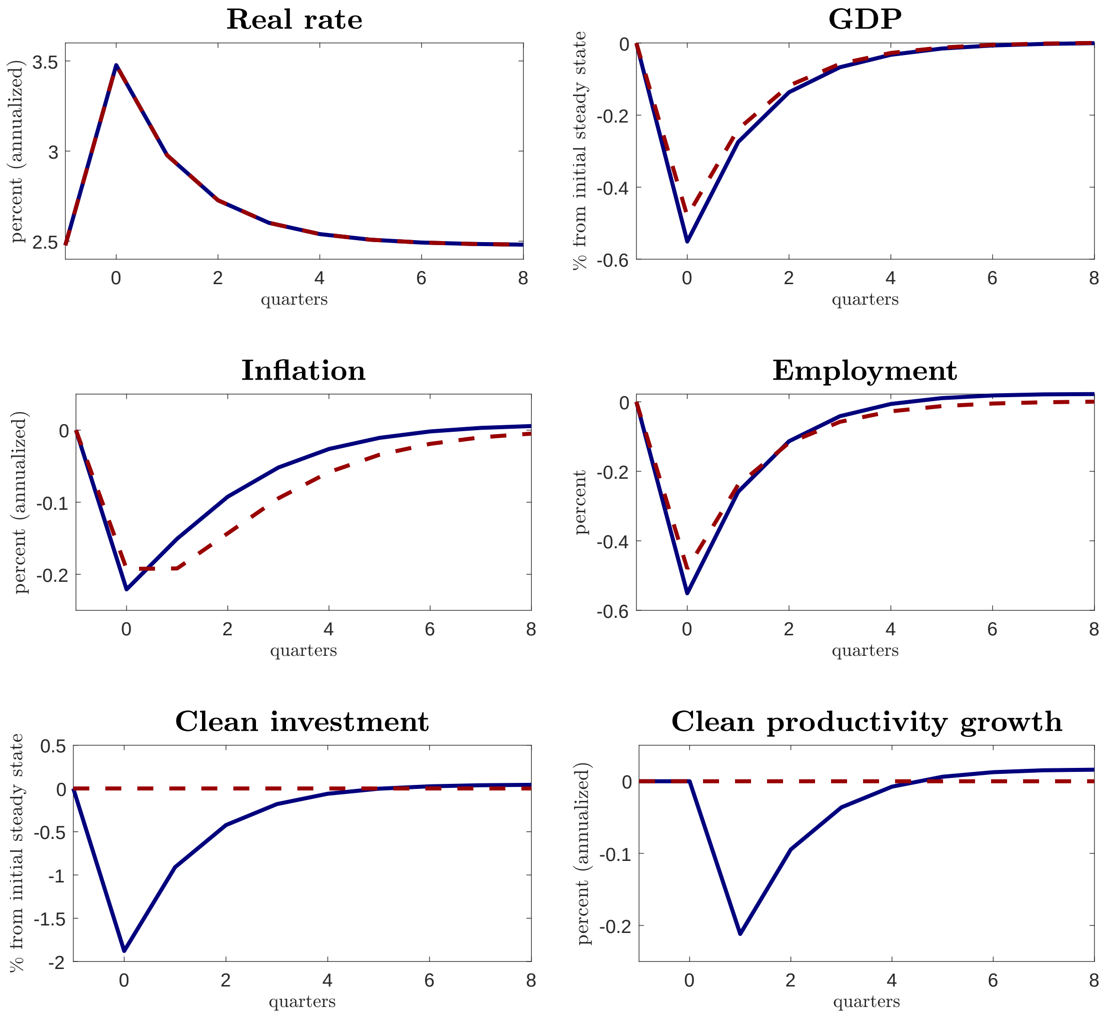

Figure 6: Impact of a monetary contraction. Notes: solid lines refer to the baseline model with endogenous investment, dashed lines refer to a counterfactual economy in which investment is fixed to its steady state value.

the innovation investment function, is hard to calibrate, given the lack of consensus in the literature. We set it equal to $\phi = 0.75$, to roughly match the peak response of investment relative to the peak response of output to monetary shocks, as estimated in Christiano et al. (2005). We then assume that ψ is constant and such that in steady state the share of clean goods in total intermediates is 30%.

To study the impact of a monetary contraction, we assume that the economy is initially in steady state, and in period $t = 0$ the real rate unexpectedly rises by 1% (annualized). The real rate then reverts to steady state according to $r_t = \rho_r r_{t-1} + (1 - \rho_r) r$, with $\rho_r = .5$. Here we assume that $\bar{x}$ is sufficiently high so that the production constraint on dirty inputs never binds.

Figure 6 shows the results, by comparing our baseline economy (solid lines), with a counterfactual one in which investment is fixed to its steady state value (dashed lines). As it is standard, the monetary contraction depresses aggregate demand, leading to a drop in output and employment. Moreover, the monetary tightening also induces firms to cut back their investment in clean technologies. The result is a temporary drop in productivity growth in the clean sector, which manifests itself with a lag since it takes time for investment to affect productivity.

The inflation response has an interesting feature. The monetary tightening lowers inflation, because it depresses employment and nominal wage growth. However, the endogenous responses of investment and productivity reduce the effectiveness of the monetary tightening as a disinflation tool. In fact, lower productivity growth sustains firms' marginal costs, creating inflationary pressures. This can be seen by the fact that, in the medium run, the economy with endogenous investment features higher inflation, and lower output, compared to the counterfactual fixed-investment economy.

As emphasized by Fornaro and Wolf (2023), endogenous investment in innovation thus creates an intertemporal inflation trade-off for the central bank. That is, a monetary tightening reduces inflation in the short run. But it also leads to lower future productivity growth, creating inflationary pressures in the medium run. This trade-off may be particularly important during the green transition, given that investments in clean technologies seem to be particularly responsive to changes in the cost of capital (Gormsen et al., 2023), and that the green transition will require large investments in renewable sources of energy. We will get back to this discussion in Section 5.

4.1.1 The energy transition

We now study the transition toward clean energy sources. As in Section 3, we assume that during the transition $\bar{x}_t$ declines according to equation (24), to capture tighter regulation on dirty production processes. But now we also assume that the productivity of investment in clean technologies ψ_t gradually rises during the transition. This is meant to capture the development of new clean technologies, which creates scope for firms to adopt cleaner production methods. More precisely, we assume that the rise in ψ_t is such that productivity in the clean sector A_c doubles during the transition. Figure 7 shows the results, again contrasting a policy of full employment (solid lines) against a hawkish monetary stance that prevents inflation from overshooting its target (dashed lines).

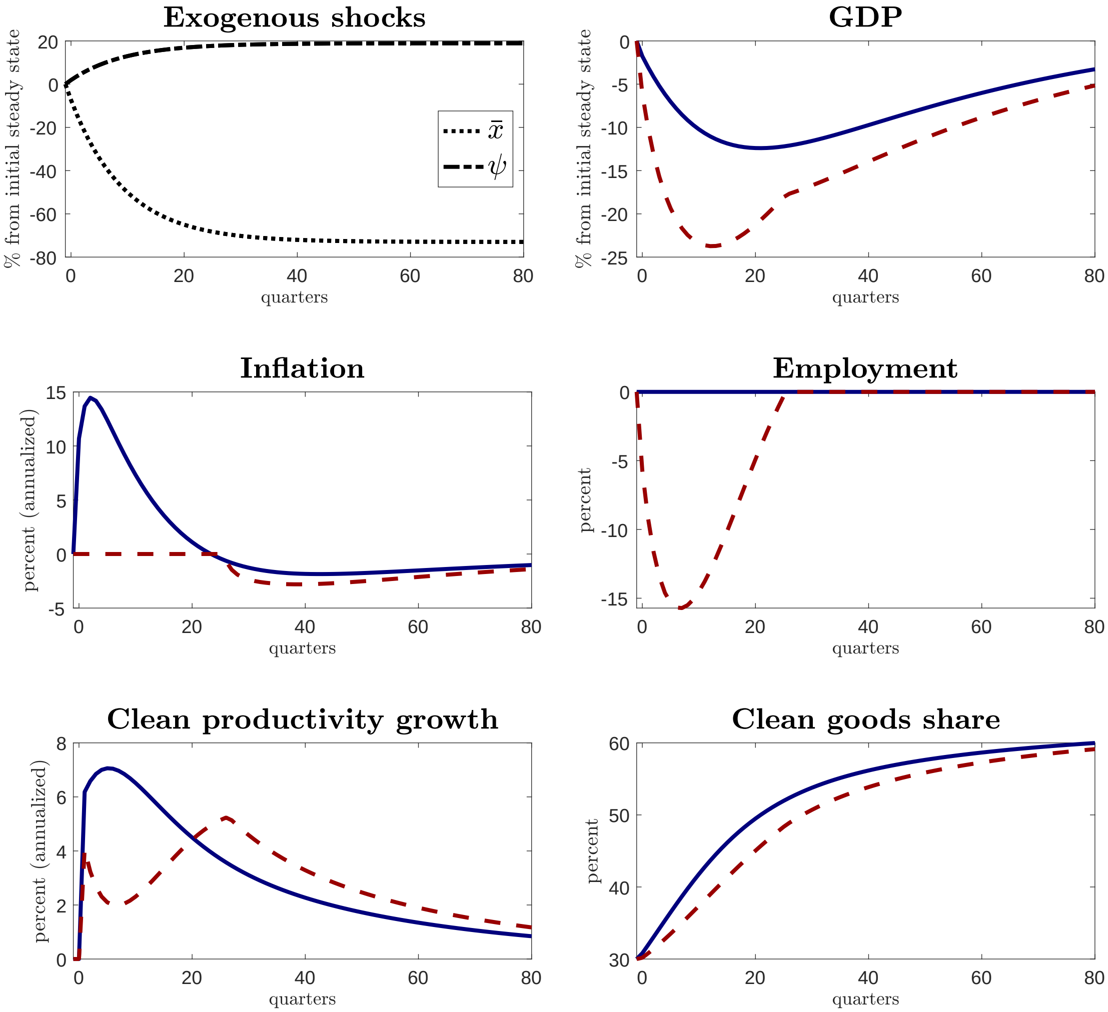

Figure 7: Transition toward a clean economy. Notes: solid lines refer to a central bank that targets full employment ($L_t = \bar{L}$), dashed lines refer to a hawkish monetary stance, which does not allow inflation to rise above target ($\pi_t \leq 0$).

There are a few results worth highlighting. First, the energy transition is now associated with an investment boom in the clean sector, which translates into a spell of fast productivity growth. On the one hand, this productivity boost dampens the negative impact on output coming from the tighter supply constraint in the dirty sector. This is the reason why the transition toward a cleaner economy does not entail output losses in the long run. Moreover, the productivity growth acceleration reduces firms' marginal costs, and so mitigates the inflationary pressures associated with the clean energy transition.

That said, it is still the case that a temporary rise in inflation is needed to maintain the economy at full employment. To contain the inflationary pressures coming from tighter regulations on dirty energy sources, in fact, the central bank has to induce a large drop in demand and cause substantial slack on the labor market. Moreover, a hawkish monetary stance now reduces investment in green technologies, slowing down productivity growth in the clean sector and the reallocation of production toward clean intermediates goods. In addition, the shortfall in investment induced by tight monetary policy causes a drop in output over the medium run. This effect explains why the energy transition is associated with more persistent output losses under the hawkish monetary stance, compared to the full employment baseline.

Summing up, the transition toward a greener economy generates temporary inflationary pressures. These arise from the increase in the relative price of dirty goods needed to reallocate production toward clean goods. If the central bank takes a hawkish stance, fully focused on containing the rise in inflation, the result may be weak output growth and substantial slack on the labor market. Moreover, a tight monetary stance constitutes a drag on investment in new clean technologies. This effect not only slows down the energy transition, but it also leads to persistent output losses.

5 Empirical analysis: financial conditions and green innovation

In our model, tighter monetary policy, by increasing the cost of credit, slows down the development and adoption of green technologies. Is there something about it in the data? The empirical evidence that we present in this section suggests that the answer is yes.

Green innovation is particularly sensitive to the availability of risk capital and financial conditions in general as it requires large investment upfront with uncertain returns in the distant future (Martin et al., 2024). Indeed, financing transitions in emissions-intensive industry requires investments in new technologies and attracting capital at scale in key sectors such as cement, chemicals and steel. Many energy sectors are highly capital intensive and require large investment upfront but, while the oil and gas industry is not reliant on external debt, the renewable sector is. Moreover, evidence points to the fact that investment in renewables is more reliant on external finance and debt accounts for a higher share of the capital structure than equity. The reason is that green technology is characterized by long cycle time, slow return, difficult evaluation and high risk. The implication is that green innovators are likely to be more sensitive to financing conditions and interest rates than innovators in other sectors (Gormsen et al., 2023).

We now explore more systematically how changes in financial conditions affect spending on R&D activities, in particular those directed toward green technologies, by US firms.

As a measure of tightness of financial conditions, we use the Chicago's Fed index of financial conditions (NFCI). The index summarizes broad aspects of financial tightness that might be relevant for financing R&D. Through the lens of our model, a tightening of financial conditions can be captured by a rise in η_t, which has similar effects as an increase in the monetary policy rate r_t.

The NFCI is composed of 105 indicators of financial conditions in money, debt and equity markets and the shadow banking system.[14] The aggregate index summarized information in three categories: risk - which captures volatility and funding risk in the financial sector -, credit - which is composed of measures of credit conditions -, and leverage - which consists of debt and equity measures. A positive value of the index indicates tighter financial conditions as measured by increasing risk, tighter credit conditions and declining leverage while negative values indicate the opposite.

As for the dependent variable, we focus on research and development intensity. We define R&D intensity as research and development expenditure at time t divided by total assets at the beginning of the period.

We present results from two exercises. In the first, which is used as a benchmark, we exploit information from Compustat data on US listed companies and we estimate the dynamic effect of an unexpected change in tightness of financial conditions on R&D intensity on average across firms. In the second exercise, we classify all companies included in the Compustat data on the basis of the extent to which they are green innovators, using patent data and estimate the differential effects of financial conditions on R&D for green and non green innovators.

5.1 Average effect

We denote the dependent variable by Y_t. For each firm i we estimate a local projection constraining the response of the dependent variable to a tightness of financial condition to be the same across firms. The model is

$$\Delta^h Y_{i,t+h} = \gamma_i + \beta^h X_t + \Gamma^h \mathbf{Z}_t + \epsilon_{i,t+h}, \qquad \forall h \in 0, \cdots, H$$

where $\Delta^h Y_{i,t+h} = Y_{i,t+h} - Y_{i,t-1}$, X_t is the Chicago Fed's index of financial conditions (NCFI) and in $\mathbf{Z}_t$ we include a number of controls. As we do not have an instrument for financial conditions, we include as controls four lags and contemporaneous values of GDP growth

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[14] See http://www.chicagofed.org/webpages/research/data/nfci/background.cfm for a detailed description.

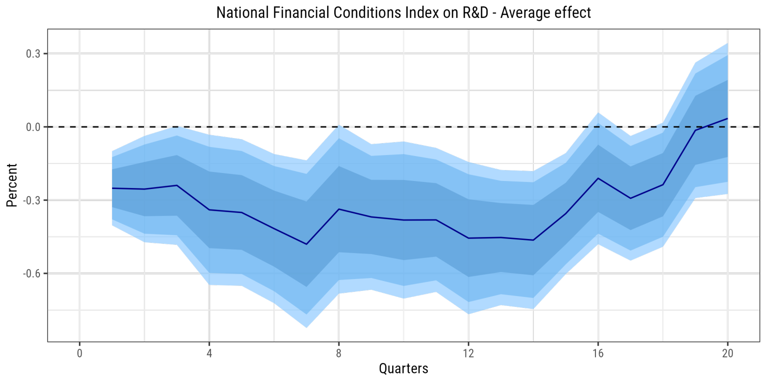

Figure 8: Effect of financial conditions on research and development intensity: average across firms

and of the one-year interest rate on treasury securities. Including the contemporaneous values as controls implies assuming a Choleski order where financial conditions are ordered last. Intuitively, this means assuming that the unexpected components of GDP growth and interest rate affect contemporaneously financial conditions, while the unexpected components of financial conditions affect GDP and interest rate with a lag. As controls, we also include three lags values of the level of the dependent variable $Y_{i,t}$, which implies incorporating one year of past information. In addition we include a firm-fixed effect to exploit firms' heterogeneity.

Under our identification assumption, we can estimate the dynamic causal impact of a tightness of financial conditions to $Y_{i,t}$ at different horizons. This delivers cumulative impulse response functions up to five years after the shock (for $h = 0, \cdots, 19$) and the corresponding 68%, 90% and 95% confidence intervals calculated using Driscoll and Kraay (1998) standard errors clustered by firm.

The cumulative impulse response function of R&D intensity to 1% tightness of the NFCI is reported in Figure 8. The chart shows a negative and significant cumulative effect of an increase in tightness which dies out after five years. This result is consistent with available evidence on the impact of tightening in financing conditions driven by monetary policy on R&D activities. In particular, both Moran and Queralto (2018b) and Ma and Zimmermann (2023) find that monetary policy tightenings lead to a decline in R&D spending by US firms.

5.2 "Green" and "non-green" firms

In this exercise we want to understand whether green and non-green investors and innovators respond differently to changes in financial conditions. To this end, we consider a stratified local projection model. We follow Hotten (2024) by classifying firms as green or non-green using patent data. We proceed in three steps.

First, we extract the entire universe of patents applications to the US patent and Trademark Office (USPTO) from 1976 to 2023 with information on patent's grant date and cooperative patent classification (CPC) code.

In the second step, we classify "green" and "non-green" patents based on the Y02 classification which uses the entire CPC class defined as "Technologies or applications for mitigation or adaptation against climate change".[15] The patent data are then matched to firms using the patent to firm matching of Arora et al. (2021). With this method, the green status of a firm is updated each time new patents information is received.

Having obtained these data, in the third step, we define a stratified local projection model to estimate the dynamic response of R&D to financial conditions and differentiating between green and non green innovators. For each firm, the patent mix at time t is the number of green patents granted at t divided by the total patents granted. The estimation period is 1986q1 to 2023q4 since for the earlier years Compustat data are not very reliable.

The model is

$$\Delta^h Y_{i,t+h} = \gamma_i + \sum_{g=1}^{G} \beta_g^h \times \mathbb{1}[\text{Green}_i \in g] \times X_t + \Gamma^h \mathbf{Z}_t + \epsilon_{i,t+h}, \qquad \forall h \in 0, \cdots, H$$

where variables are denoted as in the average specification and the Green dummy, which selects types of innovators, is defined as follows

$$\text{Green}_{i,t} = \begin{cases} \text{Green} & \text{if patent mix}_{i,t} > 25 \\ \text{Non} - \text{green} & \text{if patent mix}_{i,t} = 0\% \end{cases}$$

Results for R&D intensity for the green and non green sector are presented in Figure 9.[16] The charts show that tightenings in financial conditions have a negative effect on R&D investment for both groups of firms, although the size of the effect is much larger in absolute value and more persistent for the green innovators. Notice that the size of the average negative effect reported in Figure 8 is similar to that estimated for the non-green innovators which is explained by the fact that there are many more firms in that category.

Taking stock, these results suggest that tighter financial conditions have a particularly

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[15] This method selects 104 companies as green.

[16] The results for a third classification, of firms with a patent mix between 0 and 25% are the same as for the non-green group.

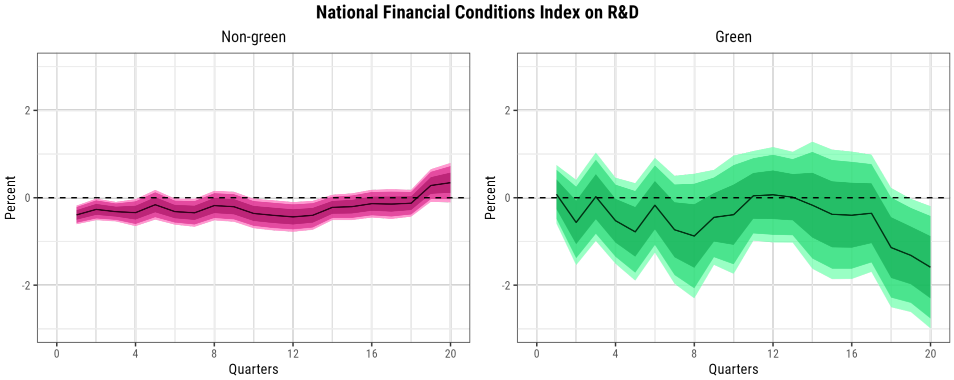

Figure 9: Effect of financial conditions on research and development intensity: green vs. non-green.

strong impact on investment in green technologies. Our empirical results are thus consistent with the practitioners view, illustrated for instance by Martin et al. (2024), that high interest rates, induced by hawkish monetary stances, are likely to affect heavily green investments.

6 Conclusions and thoughts for further research

The model we developed in this paper illustrates the difficult trade-offs faced by a central bank during the energy transition. There are two types of trade-offs. First, the tightening of supply constraints due to policies limiting the use of dirty technologies increases the cost of containing inflation, as some inflation is needed to obtain efficient relative price adjustments. Second, once we consider the endogenous choice of innovation in the green sector, and how it is negatively affected by an increase in interest rate, a strict inflation target penalizes productivity in the medium-run generating a tradeoff between lower inflation in the short run and higher inflation in the medium run.

In the empirical part of our analysis, we find that tightenings of financial conditions penalize research and development, and more so for green innovators. Although our model does not feature a specific credit channel for green innovation, this result is inspiring for further extensions of our analysis. Indeed the result is consistent with the observation that green technologies need large investments upfront and have uncertain returns, and with the fact that the green industry is highly leveraged and therefore particularly sensitive to financing conditions.

The core of our analysis suggests that a central bank with just one instrument - the short term interest rate - should consider calibrating the horizon at which to reach the inflation target in relation to the costs of inflation stabilization (the higher the costs, the longer the horizon). On the other hand, to the extent that central banks dispose of different instruments such as credit policies, asset purchases and collateral rules, it is desirable to calibrate those policies to make anti-inflation interest rate adjustment coherent with the energy transition. This is true for those central banks which have an explicit climate objective, but also for the ones that do not, given that a policy penalizing the green sector also depresses productivity in the medium run, thus putting upward pressure on inflation.

At this stage these are just conjectures, since the paper does not analyze normative questions and considers only the interest rate dimension of monetary policy. We leave normative analyses to further research.

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