Monetary Policy for the Energy Transition*

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April 2024

Abstract

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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. The green 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 a new sustainable economic growth paradigm, the transition will naturally be associated with some 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 in monetary policy.

By definition, the green transition aims to reduce production by emission-intensive firms while increasing production by firms utilizing green technologies. This has led various national governments and supernational institutions to impose 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 European Union Trading System in the EU, but also imposing energy efficiency targets such as the ones imposed by the Energy Efficiency Directive of the European Union. These and other types of regulatory interventions have constrained the production of "dirty firms," that is, of firms with high usage of fossil fuel, either by imposing direct limit on emissions per employee or by increasing the costs of production.

At the same time, recent geopolitical events, such as the Russian invasion of Ukraine and the tensions in the Middle East, have have driven up the cost of commodities, like oil and natural gas. This has imposed higher production costs especially for firms that heavily rely on fossil fuels. This can also be interpreted as a tighter limit to production for "dirty firms." Additionally, the anticipation of the green transition has also had the effect of reducing investment in emission-intensive technologies. This under-investment can also be thought of as a tightening in the production limit of "dirty firms."

Overall, for all these different channels, we think that during this first decade of the green transition, emission-intensive firms, or "dirty firms," have been facing tighter supply constraints. To account for that, we build a new-keynesian model where the final good production requires, together with labor, a fraction of intermediate goods produced by "green firms", which do not face any constraint, and a fraction of intermediate goods produced by "dirty firms," which face a supply constraint that limit their production capacity. This generates a non-concavity in the production function that makes the Phillips curve non-linear: when employment is so large that the supply constraint for the dirty firms binds, the price of dirty intermediate goods start increasing and firms have to employ more labor to compensate for that, hence reducing labor productivity and increasing inflation further.

We think of the green transition as a tightening in the supply constraint for the "dirty firms." As the constraint becomes tighter, the Phillips' curve shifts to the left, similarly to a "cost-push shock," and there is a larger interval of employment values for which the slope of the curve is steeper. That is, during the green transition, we should expect higher inflation volatility in response to demand shocks. This means that the Central Bank will face a more difficult trade-off between inflation and employment and may need to accept a bit higher transitory level of inflation in order to avoid larger output losses. Moreover, some degree of inflation is also necessary to obtain an increase in the relative price of dirty goods and reallocating demand towards the green sector. A Central Bank that tries to fight inflation, not only will generate larger output losses but also a slower transition to an economy with a larger green sector. Although we believe that fiscal policy is also going to be key to help the economy to a smooth green transition and that ultimately a combination of monetary and fiscal policies should be desirable, in this paper we focus on the effects of monetary policy, abstracting from fiscal interventions.

It would be misleading to think about the green transition only in terms of tighter supply constraints for emission-intensive firms. In fact, an essential ingredient of the green transition is also to enhance production in green sectors. Many regulatory interventions aim to incentivize firms to invest in green technology to improve overall efficiency in an energy-saving fashion. In this context, we are also interested in exploring the effects of monetary policy on the investment in green technology. To this end, we enrich the model by allowing for investment in clean technology and highlight that monetary policy choices may also affect the speed of the green transition with more persistent effects. In particular, a Central Bank that tries to keep inflation at target does not only generate output losses because of the decline in demand but also because it slows down investment in the clean sector. This implies that output losses become more persistent and might have ever more adverse effect on the speed of the transition. As in the baseline model, accepting a temporarily higher level of inflation allows for an increase in the relative price of dirty goods that reallocate demand towards the green sector, but in this model also incentivize innovation in green technology. This also creates an intertemporal trade-off for the monetary authority: fighting inflation in the short run may come at the additional cost of higher inflation in the medium run because of less innovation.

Our paper belongs to a recent growing literature studying monetary policy in the context of the green transition. Among the others, two papers that are closer to ours are Del Negro et al. (2023) and Aghion et al. (2024).[1] 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 and green sector are relative to the rest of the economy. Aghion et al. (2024) propose a model where contractionary monetary policy dampens innovation in green technology, in the same spirit of our model. They also show empirically that a contractionary monetary policy have a larger effect on green than non-green patenting.

This paper builds on a recent literature on the role of supply constraints on 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 a New-Keynesian model and explore their role in affecting inflation dynamics. In particular, our model builds on Fornaro and Wolf (2023) who enrich the model with endogenous productivity growth. The authors show that contractionary monetary policy might be able to fight inflation in the short run but at the cost of permanent output losses and possibly higher inflation 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 a growing 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.

2 Motivating facts

TO BE COMPLETED

3 Model

We now propose a simple model with occasionally binding supply constraints on the production of a subset of intermediate goods. In particular, we think of the green transition as a situation where the supply constraints on intermediate goods produced with dirty technologies become tighter. We then show how this model generates a non-linear Phillips curve and explore the effects of different types of monetary policy. We then enrich the

[1] See also Airaudo et al. (2022), Nakov and Thomas (2023), Bartocci et al. (2024), Olovsson and Vestin (2023).

model with endogenous investment in green technology to think about the interaction between monetary policy and green innovation.

3.1 Baseline model

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

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 at time t, B_t one-period nominal bonds held by the households at time t, W_t and L_t the nominal wage and employment respectively at time t, D_t the firms' dividends that are distributed to the households at time t, and it_t the nominal interest rate at time t. 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.

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

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

where $0 < \alpha < 1$, and $A_{j,t}$ is the productivity (or quality) of input j.

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

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

and

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

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

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

Intuitively, the price of the final good is equal to its marginal production cost. This explains why P_t is increasing in wages and in the prices of the intermediate inputs, adjusted for their quality. Due to perfect competition, firms in the final good sector do not make any profit in equilibrium.

Intermediate goods. Each intermediate good j is produced by a single monopolist and all the profits are redistributed to the households as dividends. Intermediate goods are produced one-to-one with final goods, but there is a constraint on how much of each intermediate good j can be produced

$$x_{j,t} \leq \bar{x}_{j,t}, \tag{9}$$

where $\bar{x}_j$ denotes the upper bound for intermediate good j. Such constraints capture restrictions on access to some intermediate goods that can generate bottlenecks in the production process. As we will explain below, they capture some salient aspects of the energy transition.

To solve the monopolist problem, start by assuming that the upper bound (3.3) does not bind for good j. In this case, firm j maximizes profits by charging a markup $1/\alpha$ over its marginal cost

$$P_{j,t} = \frac{P_t}{\alpha}. \tag{10}$$

Equations (7) and (10) then imply that

$$x_{j,t} = \alpha^{\frac{2}{1-\alpha}} A_{j,t} L_t \equiv x^*_{j,t}, \tag{11}$$

where x^*_j denotes the desired production of intermediate good j. If $x^*_j > \bar{x}_j$ the production constraint binds, and firm j cannot attain its desired level of output. It follows that the quantity of intermediate j produced is

$$x_{j,t} = \min\left(\bar{x}_{j,t}, x^*_{j,t}\right). \tag{12}$$

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

$$P_{j,t} = P_t \alpha L_t^{1-\alpha} \left(A_{j,t}\right)^{1-\alpha} \bar{x}_{j,t}^{\alpha-1} > P_t/\alpha. \tag{13}$$

This implies that a binding supply constraint on a given intermediate good generates a rise in its price. This is because if the supply constraint is binding, the price has to increase so that the demand for the intermediate good stay equal to the fixed supply. This generates higher prices for the constrained goods.

Clean and dirty goods. We now introduce a distinction between clean and dirty goods. Assume that there are two types of intermediate goods: a measure χ of clean goods and a measure $1-\chi$ of dirty goods. Clean goods have quality A^c_t and do not face any restriction in production ($\bar{x}_j = +\infty$). Dirty goods have constant quality A^d, and they all face the same production constraint $\bar{x}_t$. We define the share of clean goods in intermediates as

$$\frac{\chi \left(A^c_t\right)^{1-\alpha} \left(x^c_t\right)^{\alpha}}{\chi \left(A^c_t\right)^{1-\alpha} \left(x^c_t\right)^{\alpha} + (1-\chi)\left(A^d\right)^{1-\alpha}\left(x^d_t\right)^{\alpha}}. \tag{14}$$

We will use this variable as a measure of the speed of the clean energy transition.

The supply constraint on dirty goods captures a variety of factors that limit firms' use of polluting sources of energy. For instance, a tightening of the supply constraint, that is, a reduction of $\bar{x}_t$, can represent tighter regulation restricting the use of polluting technologies, a reduction in the access to foreign sources of dirty energy, such as oil and natural gas, due to geopolitical factors, or it may even be the result of past under-investment in production capacity by firms operating in the dirty energy sector.

All these factors create bottlenecks in the production process, negatively affecting labor productivity. To see how our model captures this effect, notice that the production constraint on dirty goods binds when employment is high enough, that is, when

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

This comes from the complementarity of labor and intermediate goods and the fact that we need to produce more dirty goods if there is more labor. Using this result, and combining equations (5) and (11), total production of the final good is given by

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

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. We will discuss below how this non-concavity is crucial to understand the impact of the energy transition on inflation.

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 π^* to zero and we assume that the employment target L^* is the households' desired labor supply $\bar{L}$.

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, $GDP_t \equiv Y_t -$

$\int_0^1 x_{j,t} dj$, while the right-hand side captures the fact that in the baseline model all value added is consumed. Using equations (11) and (16) we can write GDP as

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

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.

3.2 Dirty energy constraints and the Phillips Curve

To study the macroeconomic impact of the energy transition, we start by deriving the Phillips curve implied by our model, that is the relationship between price inflation and aggregate employment.

Let us denote by p_t^d the relative price of dirty intermediate goods in terms of the final good. Using expression (8), inflation can then be written as

$$1 + \pi_t = \frac{W_t}{W_{t-1}} \frac{\chi A_{t-1}^c + (1-\chi)A^d \left(\alpha p_{t-1}^d\right)^{-\frac{\alpha}{1-\alpha}}}{\chi A_t^c + (1-\chi)A^d \left(\alpha p_t^d\right)^{-\frac{\alpha}{1-\alpha}}}, \tag{19}$$

with the relative price of dirty intermediates defined by

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

When the cap on production of dirty goods binds their price increases to make sure demand does not increase above the fixed supply, creating upward pressure on the inflation rate. Equivalently, when the cap on dirty goods production binds, to increase production, labor has to increase more than in the case when supply constraints do not bind because it has to compensate for the fact that dirty intermediate goods cannot increase, leading to a decrease in labor productivity and hence higher production costs and a rise in inflation.[2]

[2]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

We are now ready to trace the Phillips curve. Imagine that the economy starts from a steady state in which production constraints do not bind. Then inflation in period 0 is

$$1+\pi_0 = \left(\frac{L_0}{\bar{L}}\right)^{\xi} \frac{\chi A^c_{-1} + (1-\chi) A^d}{\chi A^c_0 + (1-\chi) A^d \left(\alpha p^d_0\right)^{-\frac{\alpha}{1-\alpha}}}, \tag{22}$$

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 the cap on dirty goods production. As shown in Figure 1, the presence of this second term generates a non-linearity in the Phillips curve. The kink in the Phillips curve corresponds to the employment cut-off $\hat{L}_t$ above which the supply constraint on dirty goods becomes binding. As employment increases above that level, the price of dirty goods starts rising, increasing the implied level of inflation. This explains why the relationship between employment and inflation becomes steeper.

The non-linearity in the Phillips curve implies that fluctuations in employment, perhaps driven by demand shocks, translate into higher inflation volatility when employment is high enough. The left panel of Figure 1 shows the non-linear Phillips curve that has a kink at $\hat{L}_t$. If a shock increases the level of employment above the kink, the economy enters in a region where the Phillips curve is steeper and inflation volatility becomes higher. This is because when the constraint on dirty goods is binding, an increase in employment cause a rise in the price of dirty goods and hence an increase in inflation.

The right panel of Figure 1 shows how the Phillips curve responds to a tightening of the supply constraint on dirty goods, that is, an increase in $\bar{x}$, capturing a shock to the access to dirty sources of energy. Then, the kink shifts to the left, that is, the constraint starts to bind for a lower level of employment. This implies that when the energy constraint is tighter the Phillip's curve is steeper for a larger interval of employment levels, which immediately implies that for the same employment shocks distribution, there is going to be more inflation volatility. Suppose that the economy starts from an equilibrium with full employment and inflation on target (point $(\bar{L}, 0)$). Now imagine that $\bar{x}$ increases, so that the kink shifts to the left. As a result, the central bank faces a worse inflation/employment trade off. For instance, to maintain inflation on target monetary policy has to generate substantial slack on the labor market (point $(L^l_0, 0)$). Labor market slack is needed to contain

productivity growth reduces marginal costs and lowers price inflation.

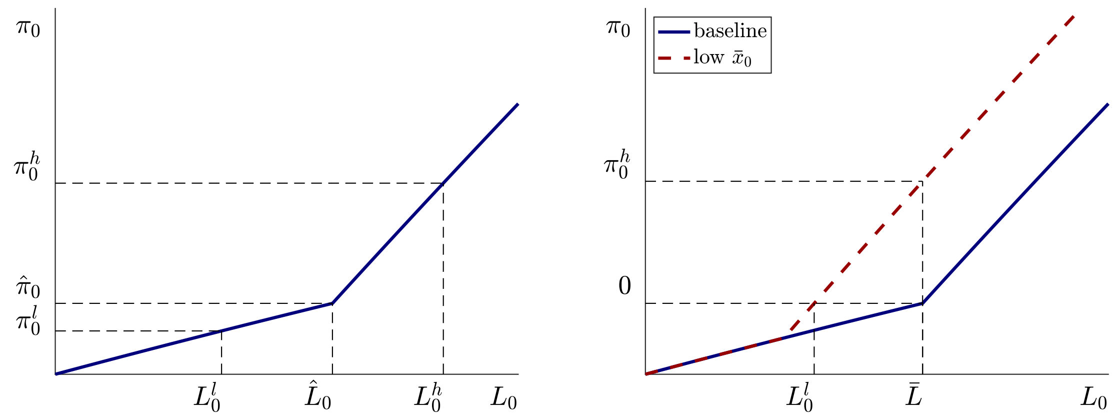

Figure 1: Phillips curve.

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.

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 Phillips curve will be steeper starting at a lower level of employment. This implies that busyness cycles driven by demand shocks are likely to lead to higher inflation volatility and containing inflation is going to lead to larger employment losses. This suggests that the energy transition may trigger an increase in both the volatility and the average level of inflation. We elaborate on this point below, with the help of some simple numerical simulations.

3.3 The macroeconomic impact of tighter dirty energy constraints

A natural question to address with our model is what are the effects of different types of monetary policies when the economy is subject to tighter supply constraints on the dirty goods. Although we believe that the optimal response to such a shock would involve a combination of fiscal and monetary policy, in this section we focus on the effects of monetary policy and assume that there is no fiscal policy in action. In particular, we want to highlight that if energy constraints on dirty goods become tighter, there is a natural upward pressure on prices of dirty goods that efficiently reallocate resources towards clean goods. This implies that some degree of transitory inflation is a natural symptom of an efficient reallocation of resources and a monetary authority that tries to fight that can generate larger output losses in the transition.

Temporary energy shortages. We start by considering temporary 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 example. 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.[3] In this section, we assume that productivity in the clean sector is constant. 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).

To capture energy shortages, we consider a temporary drop in $\bar{x}_t$. More precisely, in period 0 the cap on the production of dirty goods drops below its steady state value. From then on, $\bar{x}_t$ evolves according to

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

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_0^d 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.

Figure 2 shows the result. Let us start by considering the solid lines, which correspond to a central bank that targets full employment ($L_t = \bar{L}$). Under this policy, the energy shortage causes a recession and sharp rise in inflation. The recession is due to the fact that tighter access to dirty goods drives down productivity. Lower productivity, moreover, depresses real wages. But under full employment nominal wages are slow to adjust, so the cut in real wages is attained through a burst of inflation.

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

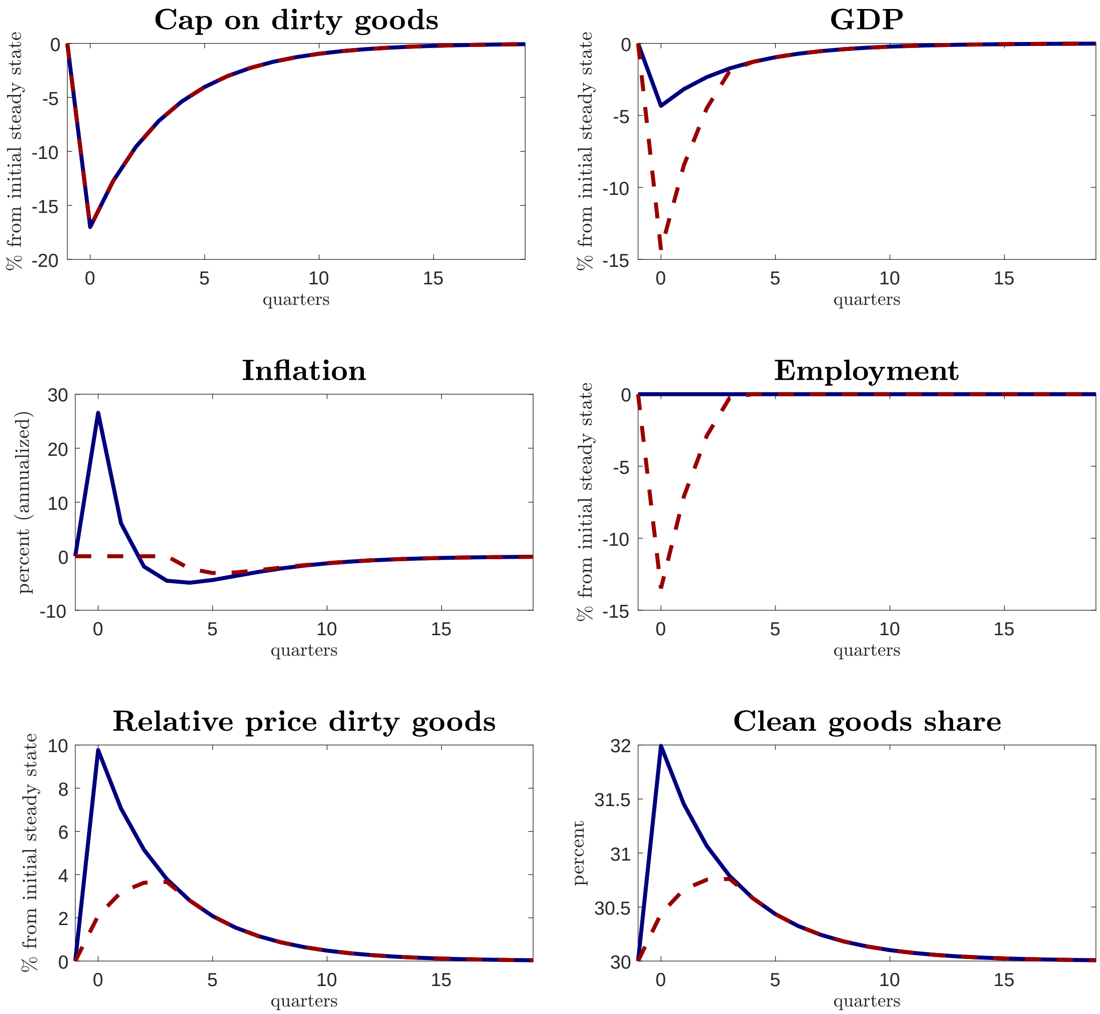

Figure 2: Temporary dirty-energy shortages. Notes: solid lines refer to a central bank that targets full employment ($L_t = \bar{L}$), dashed lines refer to a hawkish monetary stance, which does not allow inflation to rise above target ($\pi_t \leq 0$).

What if the central bank chooses to counteract the inflationary pressures? To address this question, we consider a hawkish monetary stance, which prevents inflation from rising above target.[4] To do so, the central bank engineers a monetary contraction, which amplifies substantially the recession associated with the energy shortage. Substantial slack on the labor market, in fact, is needed to contain the inflationary pressures caused by the dirty energy shock. Moreover, dampening the rise in the price of dirty goods reduces the

[4]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.

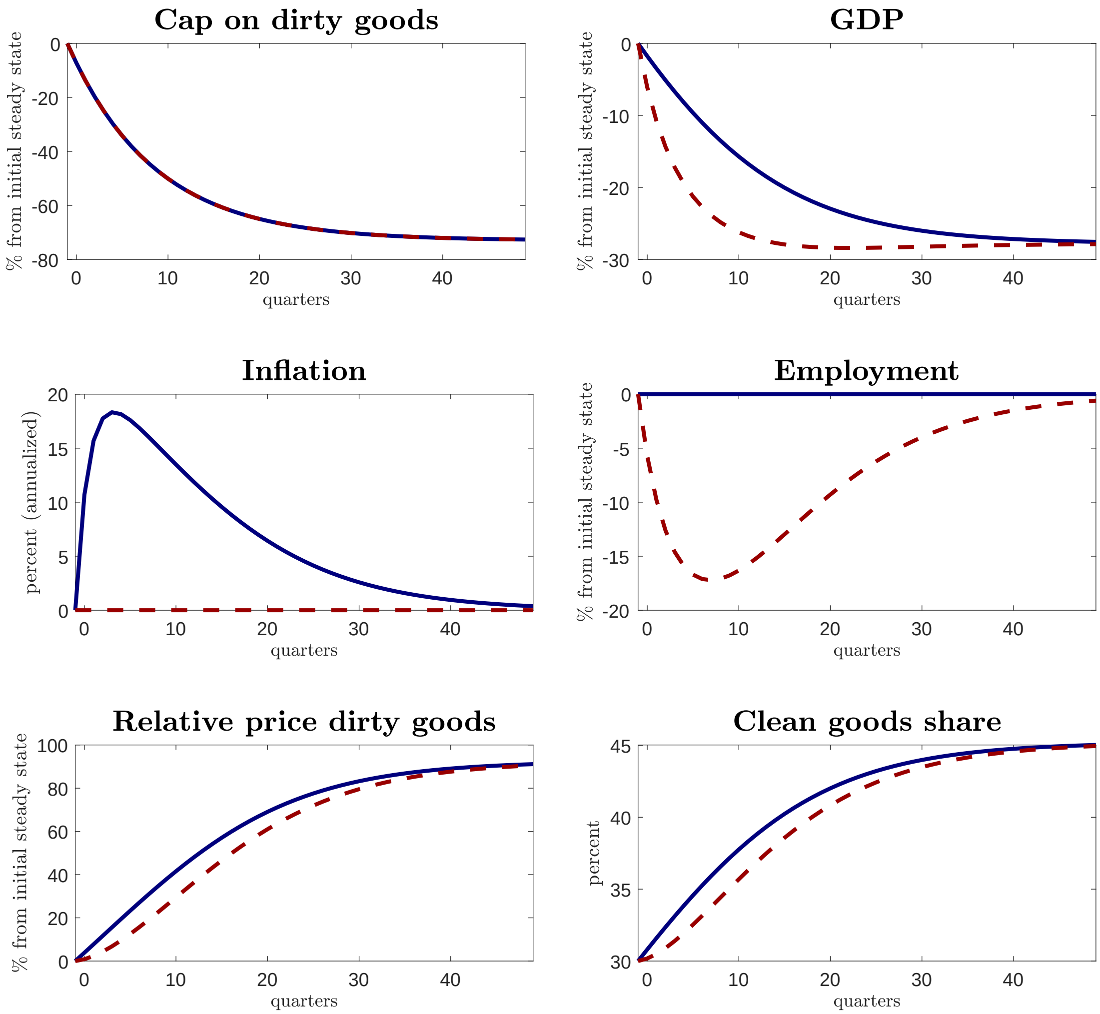

Figure 3: Phasing out of dirty energy sources. Notes: solid lines refer to a central bank that targets full employment ($L_t = \bar{L}$), dashed lines refer to a hawkish monetary stance, which does not allow inflation to rise above target ($\pi_t \leq 0$).

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

Phasing out of dirty energy sources. Our model can also be used to study the macroeconomic impact of a gradual phasing out of polluting energy sources, driven by a progressive tightening of regulations restricting the production of dirty goods. 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 3 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 constraint on dirty goods production becomes more binding, the price of dirty goods rises, putting upward pressures on firms' marginal costs. This is the reason why the transition toward lower use of dirty goods is accompanied by an outburst of inflation.

Of course, by running a sufficiently tight monetary policy, the central bank can prevent inflation from rising during the transition. This is the case shown by the dashed lines. However, a monetary contraction causes a drop in employment during the transition. Substantial slack on the labor market, in fact, is needed to dampen the inflationary pressures during the transition to a greener economy. Moreover, under this policy the central bank slows down the rise in the relative price of dirty goods. The result is a slower reallocation of production toward clean goods.

Taking stock, these two experiments show how some degree of transitory inflation is a natural symptom of an efficient reallocation of production out of dirty goods, and toward clean ones. 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.

3.4 Endogenous green innovation

So far, we have abstracted from technological change, but when we think about the transition to a green economy, it is key to consider the effects of different types of policies on innovation, especially in the clean technology. We introduce endogenous technical change in the clean sector, by allowing firms producing clean intermediate goods to increase their productivity through investment.

The productivity of a generic clean intermediate good j evolves according to

$$A^c_{j,t+1} = (1-\delta)A^c_{j,t} + \frac{\psi_t}{\phi}\left(I^c_{j,t}\right)^{\phi}, \tag{24}$$

where $I_{j,t}$ 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 $P_t \varpi A^c_{j,t} L_t$ 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[5]

$$\left(I^c_{j,t}\right)^{1-\phi} / \psi_t = \frac{\varpi L_{t+1} + (1-\delta)\left(I^c_{j,t+1}\right)^{1-\phi} / \psi_{t+1}}{1 + r_t + \eta}. \tag{25}$$

Intuitively, firms equalize the marginal investment cost $\left(I^c_{j,t}\right)^{1-\phi} / \psi_t$ 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 $\left(I^c_{j,t+1}\right)^{1-\phi} / \psi_{t+1}$. Following Fornaro and Wolf (2023), we introduce a spread η 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 $1 + r_t + \eta$.

We introduce this wedge for two reasons. First, for empirical realism. In fact, recent 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 captures in reduced form these effects, because it leads firms to underestimate the positive impact of their investments on social welfare.

To understand how monetary policy affects investment in clean technologies, it is useful to iterate equation (26) forward to obtain

$$\left(I^c_{j,t}\right)^{1-\phi} = \psi_t \sum_{\tau=t}^{\infty} \left(\prod_{\hat{\tau}=t}^{\tau} \frac{1}{1 + r_{\hat{\tau}} + \eta} \right) \left((1-\delta)^{\tau - t} \varpi L_{\tau+1} \right). \tag{26}$$

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

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

$$\sum_{t=0}^{\infty} \left(\prod_{\tau=1}^{t} \frac{1}{1 + r_{\tau-1} + \eta} \right) \left(\varpi A^c_{j,t} L_t - I_{j,t} \right),$$

subject to (24), given the initial condition $A_{j,0}$.

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

$$GDP_t = C_t + \chi I_t^c, \tag{27}$$

where we are focusing on a symmetric equilibrium in which all the firms are identical, and so $I_{j,t}^c = I_t^c$. Since only firms in the clean sector invest, aggregate investment is then equal to χI_t^c.

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

$$I^c = \left(\frac{\varpi\psi\bar{L}}{r+\eta+\delta}\right)^{\frac{1}{1-\phi}}, \tag{28}$$

while the productivity of clean inputs is

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

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.

3.4.1 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. We set η 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).[6] 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 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 4 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.

[6] 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%.

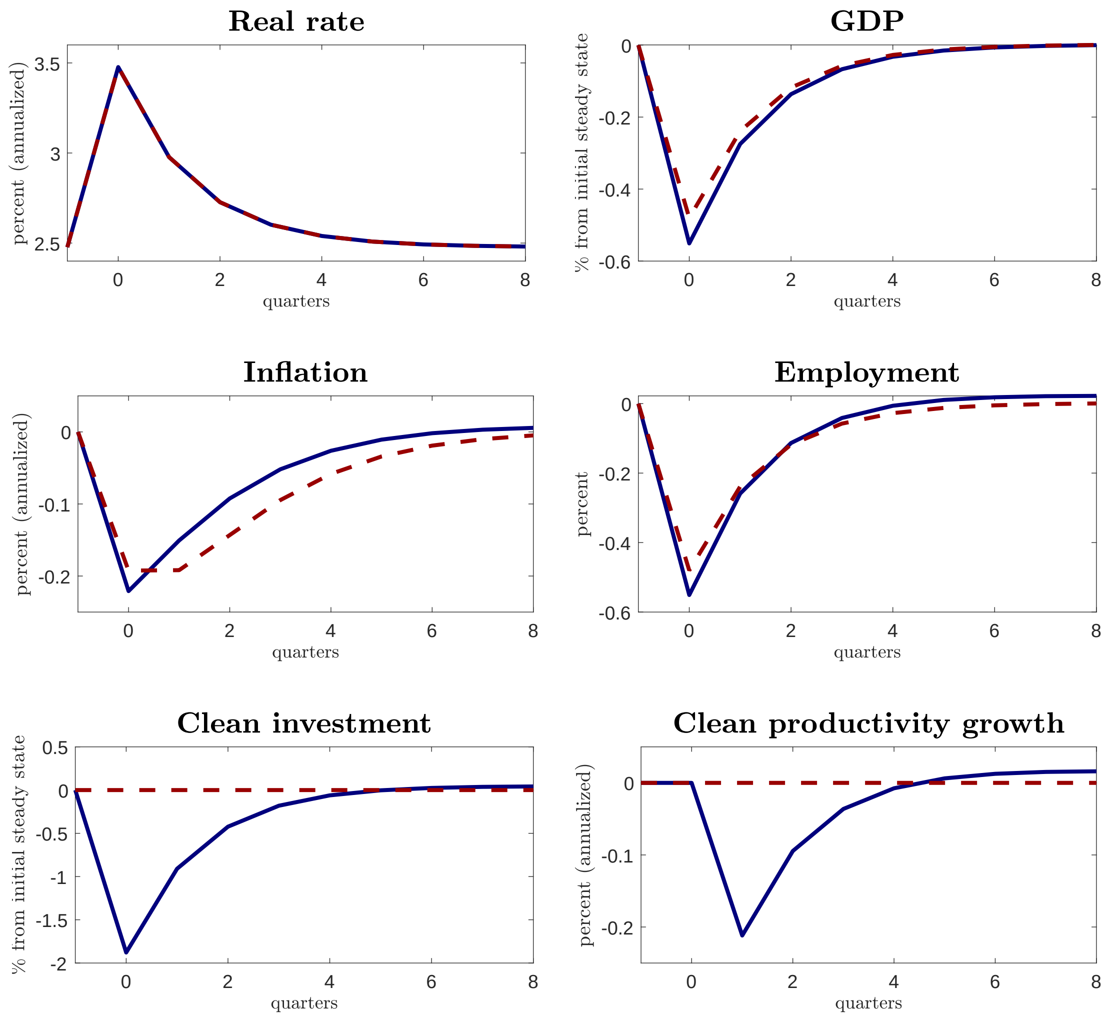

Figure 4: Impact of a monetary contraction. Notes: solid lines refer to the baseline model with endogenous investment, dashed lines refer to a counterfactual economy in which investment is fixed to its steady state value.

The 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).

3.4.2 The energy transition

We now study the transition toward clean energy sources. As in Section 3.3, we assume that during the transition $\bar{x}_t$ declines, 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 5 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).

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. 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 due to the increase in the relative price of dirty goods necessary to generate reallocation of production out of dirty production processes, and toward clean ones. If the central bank takes a hawkish stance, fully focused on containing the rise in inflation, the

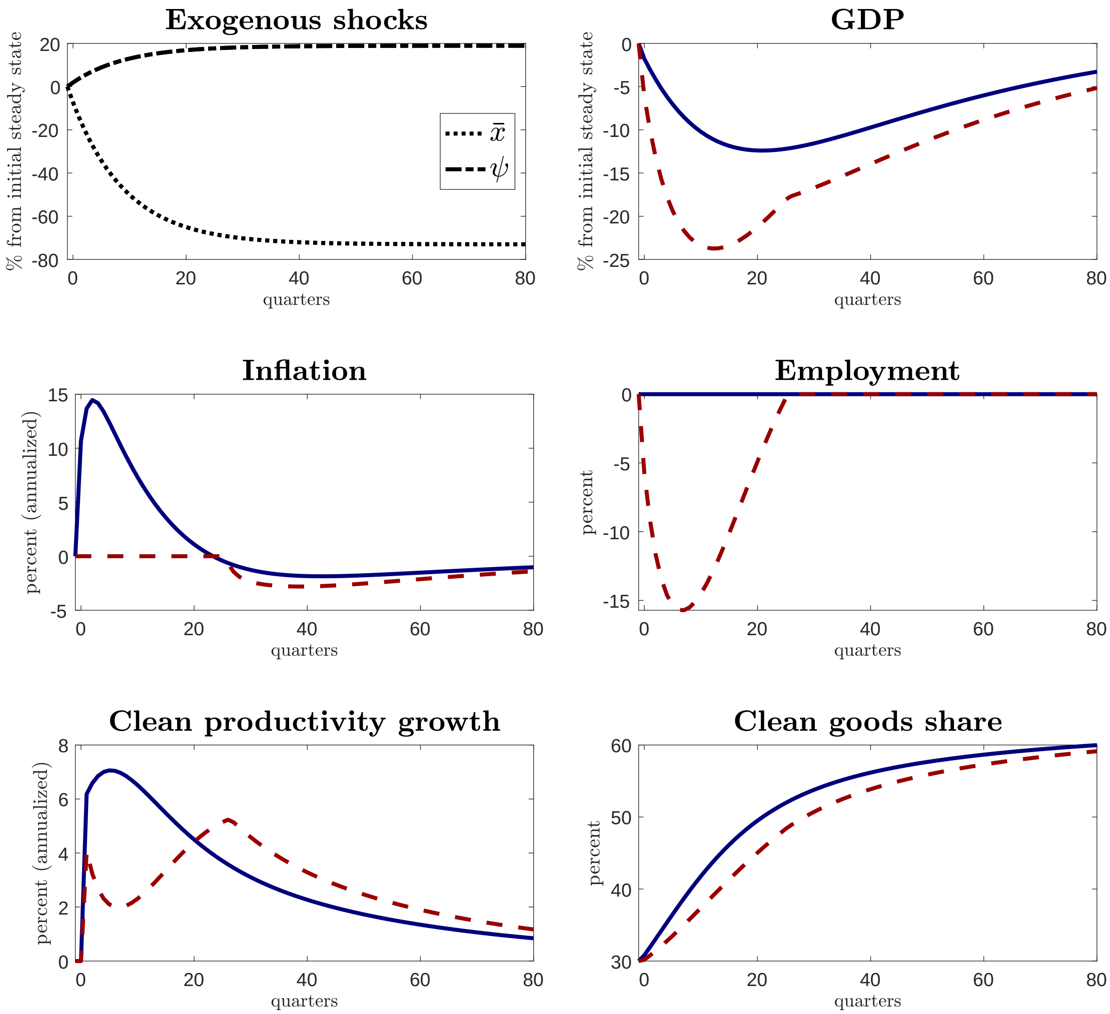

Figure 5: Transition toward a clean economy. Notes: solid lines refer to a central bank that targets full employment ($L_t = \bar{L}$), dashed lines refer to a hawkish monetary stance, which does not allow inflation to rise above target ($\pi_t \leq 0$).

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. Not only this slows down the energy transition, but it is also depresses output over the medium run.

4 Empirical analysis (preliminary)

The model suggests that an increase in the discount factor affects investment in innovation negatively in the green sectors. To capture wedges between the market interest rate and other factors influencing the cost of capital, we have added a wedge.

In this section, we design an empirical strategy to assess the extent to which factors influencing the cost of capital affect investment and R&D on average and for green innovators. We provide some preliminary results for the US economy.

The first problem is the choice of the relevant causal variable. A natural strategy would be to estimate a model in which the exogenous variable is a monetary policy shock identified via external instruments. The problem with this strategy is that the policy rate, although it influences the cost of capital, may miss important relevant factors which are relevant for innovation financing such as risk and leverage. As an alternative, we propose, in our baseline exercise, to use the Chicago's Fed index of financial conditions (NFCI) as a proxy for tightness of financial conditions. Although the index is related to the monetary policy cycle, it picks up broader aspects of financial tightness that might be relevant for financing investment, especially in R&D. 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. For these reasons, we consider the NCFI as the best proxy for the mechanism discussed in the model. At the end of the Section, we report results on the monetary policy shock for comparison.

The NFCI is composed of 105 indicators of financial conditions in money, debt and equity markets and the shadow banking system (see http://www.chicagofed.org/webpages/research/data for a detailed description). The aggregate index is divided in three categories: risk, credit and leverage. The risk subindex captures volatility and funding risk in the financial sector; the credit subindex is composed of measures of credit conditions; and the leverage subindex consists of debt and equity measures. Increasing risk, tighter credit conditions and declining leverage imply tightening financial conditions. Thus, a positive value for an individual subindex indicates that the corresponding aspect of financial conditions is tighter than on average, while negative values indicate the opposite. In the empirical analysis we will use the aggregate index and the sub-components.

As for the dependent variable, we would ideally need data on investment in research and development by type of innovation. Unfortunately, these data are not available. To address this problem, we collect data on US listed companies from Compustat on investment and R&D and classify the companies on the basis of the extent to which they are green innovators, using patent data.

The first exercise is to explore the average (across firms) dynamic effect of an unexpected change in tightness of financial conditions on R&D intensity and on investment. In a second exercise we explore the differential effect across "green" and "non-green" innovators.

Average effect

We define R&D intensity as research and development expenditure at time t divided by total assets at the beginning of the period. a

The investment rate is constructed as the ratio between capital expenditures and net total property, plants and equipments.

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 sub-components) and in $\mathbf{Z}_t$ we include a number of controls. As we do not have an instrument for financial conditions, we include, as control lagged (four lags) and contemporaneous values of GDP growth and 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 te 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 (for the total and the three components) to $Y_{i,t}$ at different horizons. This delivers impulse response functions for the three groups 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.

Results for R&D are illustrated in Figure 6. Each chart reports the response to a different definition of the index: the aggregate and the three sub-components.

The charts show a negative and significant effect of an increase in tightness for the aggregate index and its leverage and risk component. The credit component is less significant which we explain by the fact that the latter basically captures the cyclical conditions so that the shock has small extra explanatory power beyond the values of contemporaneous and lagged GDP growth included as controls. R%D investment is less pro-cyclical than total investment and this may also what explains the results.

Results for investment are reported in 7

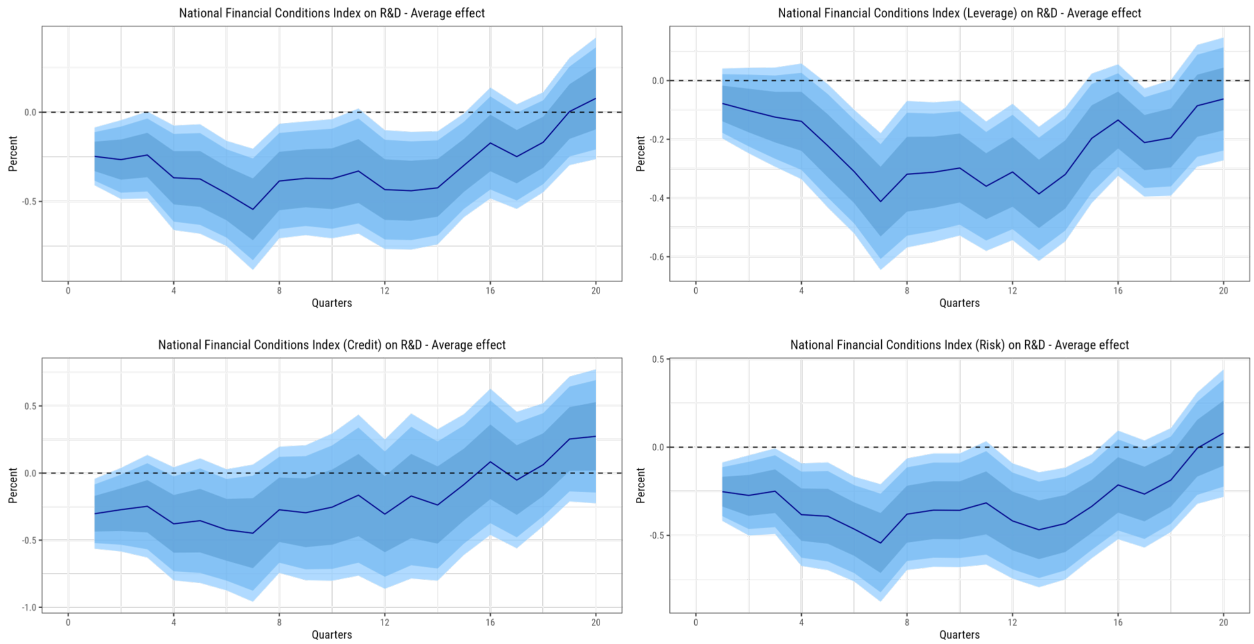

Figure 6: Effect of financial conditions on research and development intensity - average across firms

In this case we have a large and significant negative effect with both credit and risk.

"Green" and "non-green" firms

We now come to the core of our analysis. We want to understand whether green and non-green investors and innovators respond differently to tightness of financial conditions. To this end, we considered 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 granted by the US patent and Trademark Office (USPTO) from 1976 to 2023 with information on patent's filing date, grant date and cooperative patent classification (CPC) code.

In the second step, we classify "green" and "non-green" patents based on the CPC classification as in Acemoglu et al. (2019).[7]. 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. The numbers of observations for each group is 138023 for "non-green", 1975 for "some-green" and 1053 for "green", corresponding to just over 100 companies for the green group.

Having obtained these data, in the third step, we define a stratified local projection model to estimate the dynamic response of R&D and investment to financial conditions

[7]According to this specification, a patent is "green" if it contains one of the following CPC codes: Y02E10, Y0230 and Y02E50.

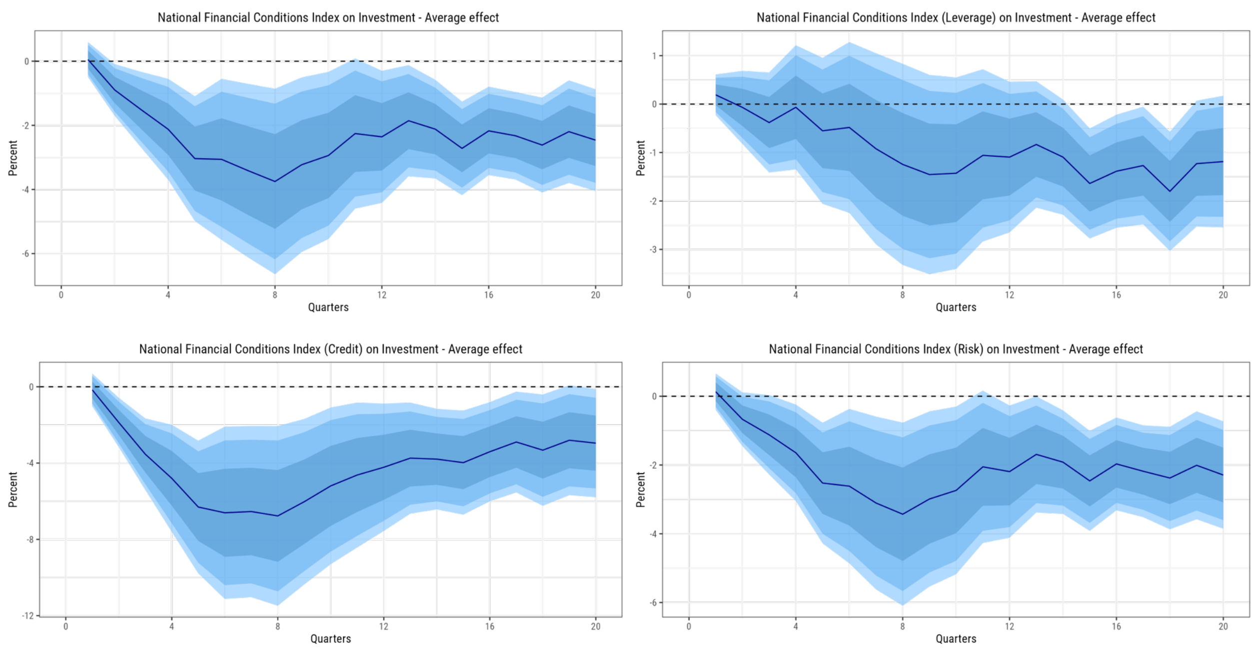

Figure 7: Effect of financial conditions on investment - average across firms

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:

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

Results for R&D intensity are presented in Figure 8.

The charts show that the average effect found in Figure 6 is explained by the green innovators group. In the appendix we report the name of the companies selected by our classifier. **[To be done: match companies with dimension. Conjecture: green companies are the large companies].**

The next chart reports results for the investment regressions.

The effect of tightness of financial conditions on investment by group is badly estimated and the impulse responses for the green companies are very volatile. The aggregate result seems to be mostly the reflection of the behaviour of the larger group of non-green companies for which tightness of credit affects negatively the investment rate.

As a final exercise, we report the local projections estimates based on a specification in which we consider the monetary policy shock rather than the financial condition indexes. We identify the shock as an external instrument using the methodology in Miranda-Agrippino and Ricco (2021). There are three limitations of this exercise. First, the instrument is monthly while here we have quarterly data so we need to average shocks over the quarter. Second, the instrument is only available until 2016 so a part of the sample where we have a lot of variations in the data has to be excluded. Third, since 2009 the US economy was at the zero lower bound so that the interest rate shock does not capture effective financing conditions as determined by quantitative easing. Indeed, the previous analysis based on the NFCI showed that the risk sub-index is very relevant for R&D and this reflects the dynamics of terms spreads heavily influenced by QE. With these caveats in mind, we include the results in the next chart. We report only average effects because the results by group are very imprecisely estimated. [**To be done: use QE instruments**]

The chart confirms the negative effect of monetary policy tightness on both investment and R&D conjectured in our model.

5 Conclusions

TO BE COMPLETED

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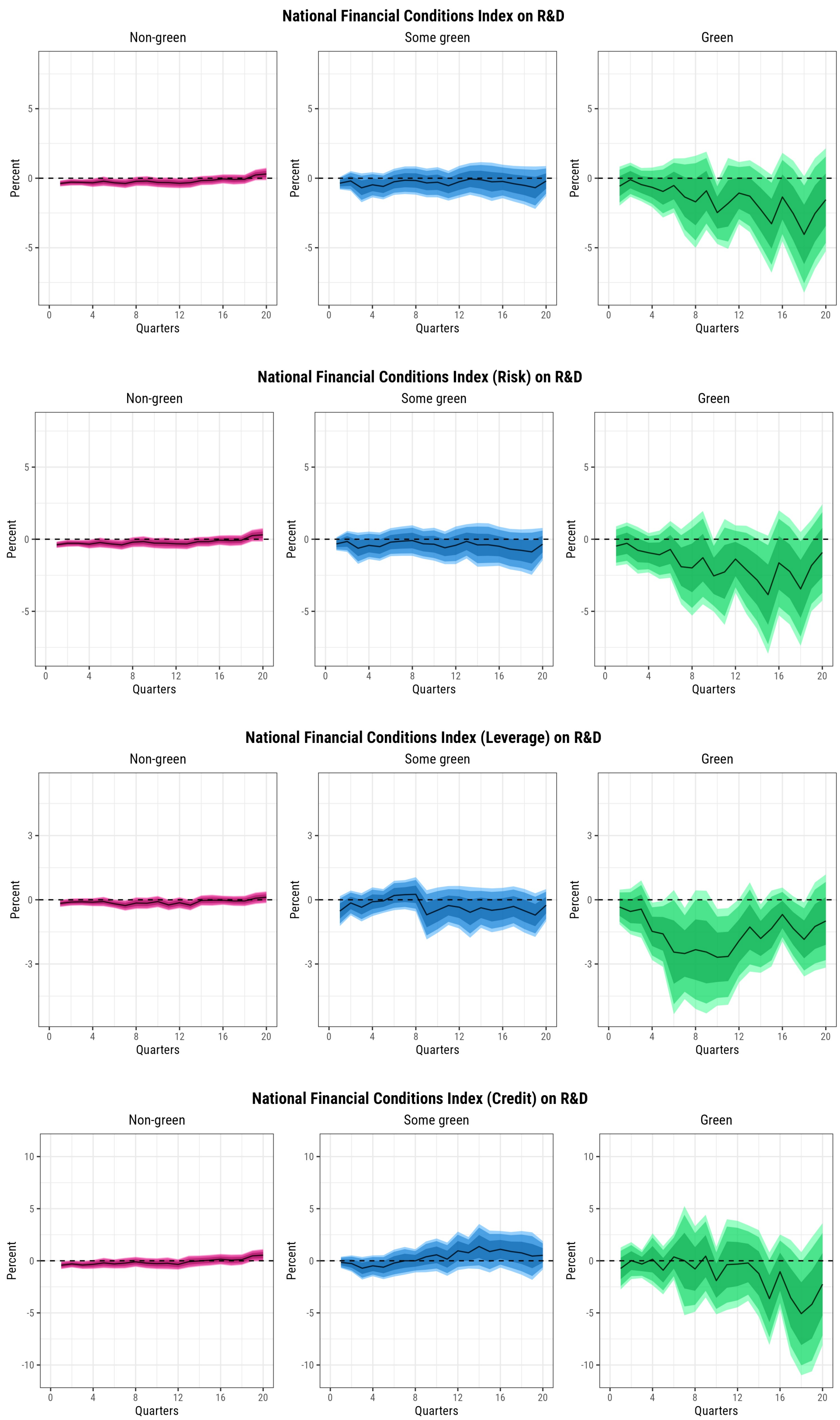

Figure 8: Effect of financial tightness on research and development intensity - by group
Notes:

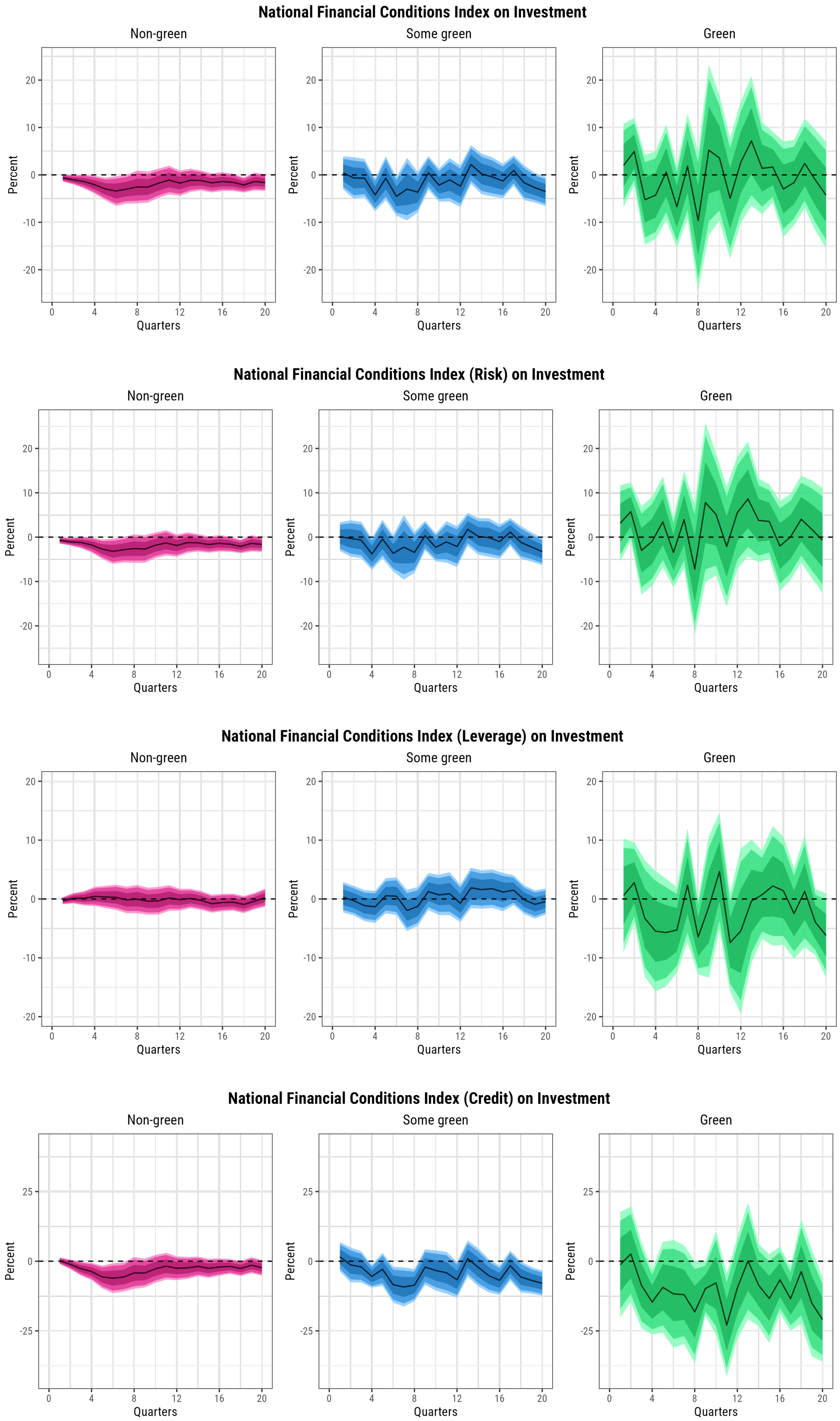

Figure 9: Effect of financial tightness on investment - by group

Notes:

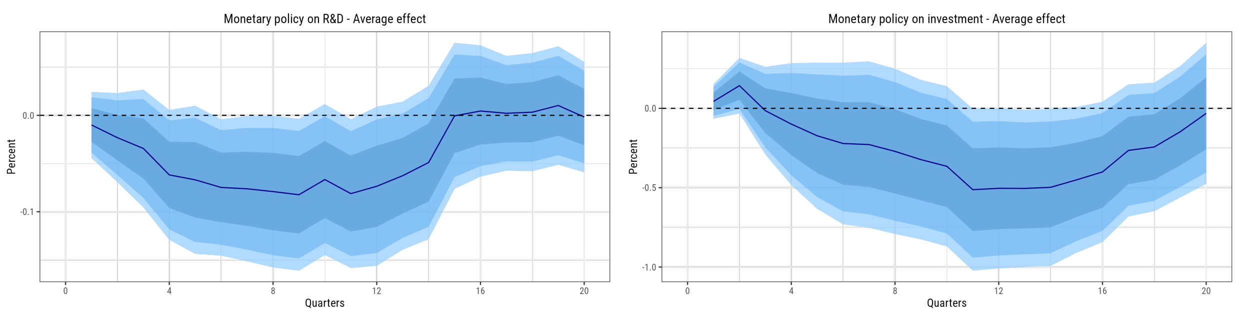

Figure 10: Effect of a monetary policy tightness on R&D and on investment - average effect
Notes: