Monetary Policy for the Green Transition*

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April 2025

Chapter 1: Introduction

Climate change is one of the most pressing challenges facing our planet today, leading to severe environmental and social repercussions. Rising global temperatures are causing glaciers to melt, sea levels to rise, and extreme weather events to become more frequent and intense. This results in floods, droughts, and hurricanes that threaten ecosystems and human livelihoods alike. The urgent need for action is clear, as the longer we delay addressing these issues, the more irreversible the damage to our planet and future generations will become. This recognition has prompted countries worldwide to embrace proposals aimed at promoting a green transition, that is a structural transformation of our economies away from polluting technologies, and towards clean ones.

A range of different policies have been implemented to promote the green transition all over the world. In particular, Europe has shown a strong commitment to sustainability and climate action. The European Green Deal is a comprehensive framework aimed at making the EU climate-neutral by 2050, encompassing initiatives like reducing greenhouse gas emissions, promoting renewable energy, and enhancing energy efficiency. Other countries have started or plan to phase out carbon emissions, through a combination of carbon taxes and regulatory constraints on the use of dirty energy sources.

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Although the long-term benefits of the green transition are extreme and evident, there is more discussion about what are the costs of the transition in the short term, how to mitigate them without slowing the transition down, and how the green transition affects different policy decisions. In this report, we explore how the green transition affects the traditional monetary policy objectives of maintaining price stability while sustaining economic activity, and how different monetary policy decisions impact the green transition. Our analysis thus remains neutral regarding whether central banks should actively pursue "green policies." Instead, we focus on unveiling mechanisms that are relevant to policymakers regardless of the central bank stance on the green transition.

After reviewing some of the facts on the green transition reported in the existing literature, we present some new empirical results. First, we want to understand the macroeconomic impact of restrictions on the use of fossil fuels. To this end, we perform a VAR analysis using European data to document the macroeconomic effect of increases in the price of natural gas. We find that a rise in the price of gas increases inflation, while depressing economic activity and employment. A higher cost of using fossil fuels thus worsens the inflation/employment trade off faced by the central bank. Our results are in line with Känzig (2023), who shows that tighter limits on carbon emissions allowed by the EU Emission Trading System lead to higher inflation and lower economic activity. These findings suggest that the green transition, and in particular the associated restrictions on the use of fossil fuels, will most likely push central banks in front of a more inflationary environment.

We then turn to an empirical analysis of the effects of monetary interventions. Again using a VAR approach and European data, we confirm the conventional view that monetary contractions are able to pull down inflation, but at the cost of lower economic activity and higher unemployment. Moreover, we show that monetary contractions have a particularly depressive impact on gas prices. This result hints at the fact that tight monetary policy may slow down the green transition, by making fossil fuels less expensive, and reducing the incentives for private agents to phase them out in favor of renewable energy sources.

While green regulations that constrain the use of polluting technologies foster the green transition, the associated structural reallocation of the economy will cause productivity losses, at least in the short term. Advances in renewable power technologies and green capital investments will be crucial to reconcile a healthy green transition with long-run growth. Interestingly, green investments seem to be particularly reliant on external financing, and highly sensitive to changes in financing conditions (Martin et al., 2024). To understand how monetary policy will shape the energy transition, it is then important to take its impact on green investments into account.

Using patent data for US Compustat firms, we derive a novel classification of green innovators, that is companies that are particularly prone to develop new green technologies. We then show that tight financial conditions are particularly detrimental to investments - both in capital and R&D - by green innovators, compared to non-green ones. This result, which is in line with the findings of Aghion et al. (2024) for the German automotive sector, implies that higher interest rates and tighter credit conditions could slow down the development and adoption of new green technologies, as well as the progress toward climate sustainability goals.

Building on these empirical facts, we then provide a framework to study monetary policy during the green transition. Our model is a variant of the New-Keynesian framework, in which production is carried out using two types of intermediate goods: clean and dirty. Clean goods are produced using non-polluting technologies, while production of dirty goods degrades the quality of the environment. The green transition corresponds to a phasing out of dirty goods, in favor of clean ones.

We model the green transition as the result of a gradual tightening of a production cap, or supply constraint, on dirty goods.[1] This constraint captures limits on carbon emissions imposed by green regulations, as in the EU Emission Trading System, or even carbon taxes designed to hit some emissions reduction target. The underlying assumption is that the regulator internalizes the long-term costs of climate change, although for simplicity we do not model those long-term risks explicitly.[2]

As the supply constraint on dirty goods becomes tighter, their relative price increases, inducing a reallocation of production out of dirty goods and towards clean ones. But the rise in the relative price of polluting goods is also a source of inflationary pressures. Even though the central bank - by implementing a sufficiently tight monetary policy - can prevent inflation from rising above target, this comes at the cost of a larger drop in

[1] The existing literature has mostly modeled the green transition as the introduction of a tax/subsidy scheme on clean/dirty technologies. To the best of our knowledge, we are the first to model it as a quantity constraint on the production of dirty goods. This bridges the literature on green transition with the literature on supply constraints, implying that central banks may face sharp non-linearities in the Phillips curve during the transition toward clean energy.

[2] There may also be non-regulatory reasons why the green transition may come together with supply constraints on dirty goods. For instance, a decrease in investment in the production of dirty goods can lead to reduced supply, limiting overall production capacity. Moreover, geo-political tensions may also translate into higher fossil fuels prices, and hence tighter supply constraints on polluting production technologies.

economic activity, and a slower re-balancing of production toward clean goods. So a temporary rise in inflation above target may be the natural symptom of the structural transformation needed to achieve the green transition.

The presence of a supply constraint on the dirty goods gives rise to a non-linear aggregate Phillips curve, becoming steeper when demand is high enough to make supply constraints on dirty goods bind, putting upward pressure on their price. The green transition makes a larger portion of the Phillips curve steeper, because supply constraints on dirty goods now bind at lower levels of demand, imposing a worse inflation/employment menu available to central bankers. Such a shift also implies that inflation volatility will be particularly high during the green transition.

We then introduce investment and endogenous productivity growth, both in green and polluting technologies. While the tightening of the supply constraint on dirty goods naturally depresses productivity, it also incentivizes more investment in green technologies, with potential positive productivity effects in the long run.[3]

Consistent with empirical evidence, in our model green investments are more sensitive to monetary interventions than dirty ones. This is due to two effects. First, monetary policy affects investment through its impact on interest rates and the cost of capital. But, due to the presence of green regulation, firms producing dirty goods have a short time horizon ahead. So their investment decisions are not that sensitive to changes in interest rates.

Second, monetary policy affects investment by determining aggregate demand and firms' profits. For instance, a monetary expansion stimulates investment because the associated increase in aggregate demand makes it more profitable for firms to build up their productive capacity. Green regulations, however, limit the ability of firms producing dirty goods to expand their output when aggregate demand is strong. As a result, an environment of strong aggregate demand mainly favors firms producing clean goods, and so green investments.

The implication is that implementing a tight monetary policy during the green transition has a particularly depressive impact on the development and adoption of green technologies. This effect not only increases the economic cost of totally suppressing inflation during the green transition, but it also creates an intertemporal inflation trade-off for central banks. That is, a monetary tightening contains inflation in the present, but it also slows down green productivity growth and the energy transition, thus creating inflationary

[3]For simplicity, in our quantitative exercise, we calibrate the model to a benchmark case where green regulations do not affect productivity growth in steady state, but this is an important area for future research.

pressures in the future.

Our model thus highlights a green dilemma for monetary policy. On the one hand, central banks may look through the temporary inflationary pressures caused by the phasing out of polluting technologies. But this comes at the risk of a potential disanchoring of inflation expectations. On the other hand, a narrow focus on controlling inflation during the green transition comes at the cost of a sharp economic contraction, as well as lower investment in green technologies and so a slower green transition.

How to reconcile a smooth green transition with low inflation? Our model suggests that subsidies to green investments may help. Subsidizing green investments, in fact, fosters productivity growth in clean sectors. Aside from its positive impact on output, faster productivity growth acts as a disinflationary force. Hence, subsidies to the development and adoption of new green technologies help the central bank to reconcile low inflation, high economic activity, and the transition toward a green economy. Aside from fiscal subsidies, our subsidies could also capture credit policies targeting green investments implemented by central banks. These unconventional monetary interventions may help central banks to achieve their traditional targets during the green transition.

Summing up, we show that the green transition may push our economies in a regime of high inflation volatility, in which central banks will face a potentially more inflationary environment. In this regime, some temporary rise in inflation is the natural symptom of the adjustment in relative prices needed to reallocate production and investment from dirty to clean goods. Coordination between monetary, fiscal and energy policies is going to be particularly important to keep inflation under control. In particular, fiscal and credit policies that subsidize green investments may be key to reconcile low inflation, high economic activity and an effective green transition.

Before moving on, let us spend a few words on how this report complements the rapidly-expanding literature on monetary policy and the green transition (Campiglio, 2016; Airaudo et al., 2022; Nakov and Thomas, 2023; Del Negro et al., 2023; Olovsson and Vestin, 2023; Mehrotra, 2024; Aghion et al., 2024; Rosas, 2024). Besides providing novel empirical evidence, our theoretical framework embeds at least two original aspects. First, we model the green transition as the imposition of supply constraints on the production of dirty goods, and show that this may generate a non-linear Phillips curve and high inflation volatility during the phasing out of fossil fuels.[4] Second, we consider the interplays

[4]In doing this, we build on a recent literature connecting supply constraints and relative price changes to inflation (Guerrieri et al., 2021; Boehm and Pandalai-Nayar, 2022; Fornaro and Romei, 2022; Guerrieri et al.,

between monetary policy and investment in clean and dirty technologies.[5] In this respect, our report is thus a step forward toward understanding the macroeconomics of the medium run, an under-explored area of research (Blanchard, 2025).

It is also useful to highlight two aspects that we don't cover in this report. First, we don't discuss how governments should design optimally green regulations.[6] Rather, we focus on the implications for monetary policy of a given path of carbon emissions reductions chosen by the legislator. Second, we don't derive the optimal monetary policy during the green transition. This is an interesting exercise, but we leave it for future research.

The rest of the report is composed of four chapters. Chapter 2 establishes the background of our analysis, by providing some motivating facts. Chapter 3 is devoted to our novel empirical evidence. Chapter 4 analyses the role of monetary policy during the green transition using our theoretical framework. Chapter 5 concludes by reviewing the existing literature on monetary policy and the green transition, and points towards some promising avenues for future research.

Chapter 2: Motivating facts

Climate change driven by carbon emissions is likely to lead to massive social and economic losses (Stern, 2015). Recent estimates by Bilal and Känzig (2024) indicate that a 1°C warming reduces world GDP by 12%. Worst-case scenarios are associated with even bigger economic losses. It is then clear that we need to act to fight climate change.

In their report to the French Prime Minister, Pisani-Ferry and Mahfouz (2023) make two important points. First, climate neutrality is achievable, but it will require a structural transformation on a scale comparable to an industrial revolution. Second, although development in green technologies may help reconcile growth and environmental sustainability in the long-run, in the medium term the macroeconomic costs of the green transition are likely to be large.

With this background in mind, in this chapter we discuss some motivating evidence that will guide our empirical and theoretical analyses. First, we review the notion that achieving

2023; Comin et al., 2023; Lorenzoni and Werning, 2023; Fornaro, 2024).

[5] We thus borrow elements from the literature on climate change and endogenous technological progress (Popp, 2002; Acemoglu et al., 2012; Hassler et al., 2021; Acemoglu et al., 2023; Fried, 2018), and from the literature on endogenous growth and monetary policy (Anzoategui et al., 2019; Benigno and Fornaro, 2018; Garga and Singh, 2021; Schmöller and Spitzer, 2021; Fornaro and Wolf, 2023).

[6] See Acemoglu et al. (2012), Golosov et al. (2014) and Campiglio et al. (2022) for examples of studies aiming at deriving the optimal green regulation.

carbon neutrality will require a global structural transformation of our economies, induced by policy interventions. Second, we will consider the role played by the development and adoption of new green technologies. In Chapters 3 and 4, we will then build on these facts to derive lessons for monetary policy for the green transition.

2.1 The green transition as a policy-induced structural transformation

Fossil fuels - including coal, oil, and natural gas - currently supply about 80 percent of the world's energy (Ritchie and Rosado, 2024). Even in the European Union, where more progress toward reducing dependency on fossil fuels has been made, fossil fuels still account for around 70% of energy production. As the 2024 BP Energy Outlook points out, investment in low carbon energy is estimated to have grown very rapidly in recent years, up around 50% since 2019 at approximately $ 1.9 trillion in 2023. However, the energy additions from low carbon sources have not been sufficient to meet the growth in total global energy demand, with the consequence that the use of fossil fuels has continued to increase. Indeed, fossil fuel consumption reached a new high in 2023 (Ritchie and Rosado, 2024).

The road to carbon neutrality is thus still long, and potentially costly. As Pisani-Ferry (2021) has suggested, "decarbonisation amounts to putting a price on a resource – a stable climate – that was previously available for free. Whether this pricing is explicit (in the case of carbon pricing) or implicit (if policy proceeds through regulation instead), it impacts adversely the potential for production from a given capital stock". The essence of this argument is that climate sustainability requires a policy-induced structural change away from high-emissions technologies and toward clean ones. As most processes of structural change, this is likely to involve economic disruptions and productivity losses while the economy transits towards its new long-run equilibrium.

These transitional costs are highly uncertain, at least for two reasons. First, historically the policy measures taken to achieve carbon neutrality have been limited. For instance, as shown in Figure 1, to accomplish its planned reduction in greenhouse gas emissions the EU has to accelerate substantially the pace at which fossil fuels are phased out. Second, as we will argue later on in the report, the economic impact of the green transition will be shaped by the policy framework.

Take the existing evidence on the macroeconomic impact of carbon taxes. Metcalf (2021),

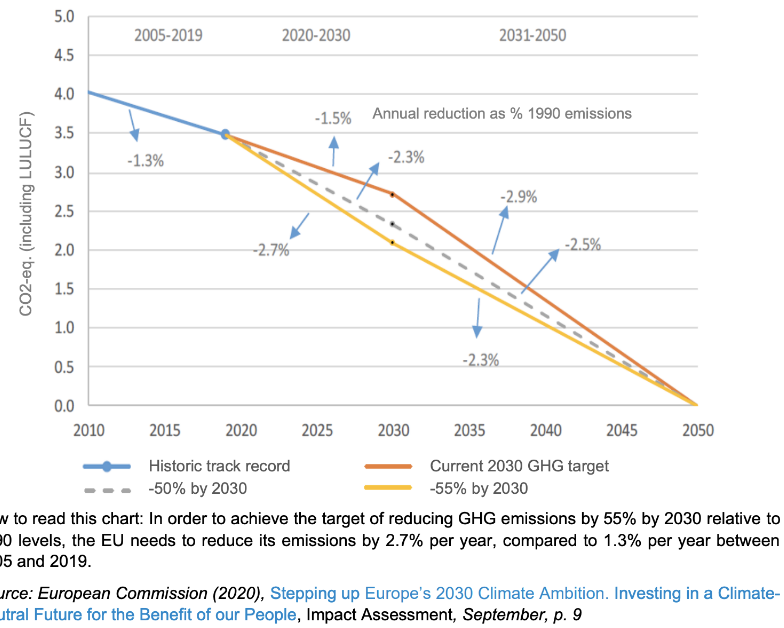

Figure 1: EU GHG emissions-reduction pathways under the "Fit for 55" package. Source: Pisani-Ferry and Mahfouz (2023).

Metcalf and Stock (2023) and Konradt and Weder di Mauro (2023) find little evidence of a negative economic effect from the adoption of carbon taxes. However, as argued by Känzig and Konradt (2023), this result is likely due to the fact that so far carbon taxes have been implemented by a small number of countries, and their coverage has been limited. For instance, carbon taxes typically exclude the power sector, which is an extremely important player when it comes to carbon emissions. It is then not clear whether this evidence can be used to evaluate the impact of the policy measures that will be implemented in the coming years to fight climate change.

A more promising approach is to look at the EU Emission Trading System (ETS), currently the largest carbon market in the world, which covers about 40% of the EU's carbon emissions. Känzig (2023) studies the economic impact of exogenous variations in the quantity of carbon emissions allowed by the ETS on the EU economy. His empirical results are thus informative about the macroeconomic impact of the regulatory constraints that dirty technologies are going to face during the green transition.

Känzig (2023) finds that a tightening in the carbon emissions allowed by the ETS causes a drop in economic activity and employment, and an increase in inflation. More precisely, he finds that a regulation-driven reduction in emissions by 1% causes a decline in industrial production by around 2%, while unemployment increases by about 0.4 percentage points.

Moreover, consumer prices increase by about 0.4%.[7] Taken together, these empirical results suggest that tighter constraints on the use of fossil fuels act as negative supply shocks, worsening the trade-off between economic activity and inflation faced by the central bank. As we will see in Chapter 4, this is exactly what one would expect once the green transition is understood as a structural transformation of the economy.

Another useful guidance on transition costs comes from reports that combine macroeconomic scenarios with bottom-up industry knowledge. A recent McKinsey report quantifies transition costs associated with the NGFS Net Zero 2050 scenario, which assumes that coal production for energy use would nearly end by 2050, while oil and gas production volumes would be about 55 percent and 70 percent lower, respectively, than today (McKinsey, 2022). Their analysis, which weights both costs and opportunities, suggests that sectors with high-emissions products or operations (which generate about 20 percent of global GDP) would face substantial negative effects on demand, production costs, and employment. It also concludes that process changes would increase production costs in other sectors, with steel and cement facing increases by 2050 of about 30 and 45 percent, respectively. These observations indicate that, although substitution from dirty to clean technology will occur with time, the green transition will entail substantial productivity losses along the way.

2.2 Green investments are key for an effective energy transition

Green investments have a key role to play in a successful energy transition. Development and adoption of clean technologies, in fact, is necessary to ensure that the phasing out of fossil fuels does not translate into lower economic growth in the long run (Acemoglu et al., 2012).[8] As Gourinchas et al. (2024) point out, the success of the green transition depends on the outcome of a race between negative political backlashes against green regulations, and the positive effects of rapid technological progress.

The effect of technological progress is already visible in the fast decline in the price of electricity generated from renewables (Roser, 2020). As shown in Figure 2, the levelized cost of electricity for solar photovoltaics dropped by 85 percent between 2010 and 2020. Similar good news comes from the declining cost of onshore wind and battery storage.

However, substantial investments are needed for the large-scale adoption of new green technologies. For instance, Pisani-Ferry and Mahfouz (2023) argue that to hit its climate

[7] Berthold et al. (2023) report similar findings.

[8] Some commentators, such as Stern and Stiglitz (2023), have even argued that the deployment of new green technologies may spur a growth acceleration.

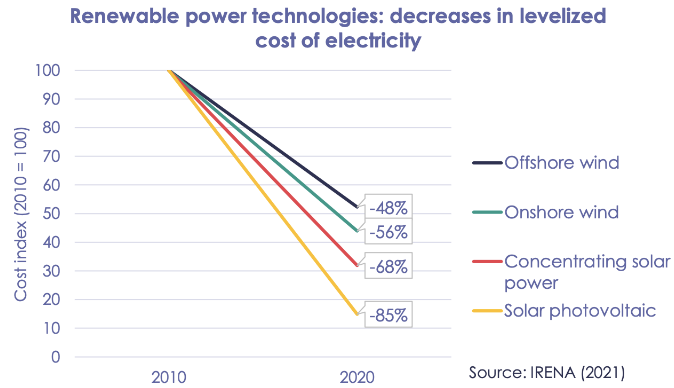

Figure 2: Reduction in the cost of electricity from renewable power technologies. Source: IRENA (2021).

goals the EU will have to increase its investments in green technologies by 2% of GDP. Inducing the private sector to scale up these investments will require a macroeconomic environment characterized by low cost of capital, as well as robust aggregate demand for green goods.

Could monetary policy affect green investments and the speed of diffusion of clean technologies? There are several reasons to believe that the answer is yes. To start, macroeconomic models imply that a tight monetary stance depresses investments, including in innovation (Benigno and Fornaro, 2018), and slows down the adoption of new technologies (Anzoategui et al., 2019).[9] This happens through two channels. First, monetary contractions increase the cost of capital, hence making it harder for businesses to finance their investments. Second, monetary tightenings depress aggregate demand, reducing the profits that firms gain from investing to scale up their productive capacity and developing new products.

The recent works of Moran and Queralto (2018), Jordà et al. (2020) and Ma and Zimmermann (2023) provide empirical evidence in favor of these effects. All these works consider the response of business investments, including in innovation activities, and productivity to exogenous monetary policy shocks. They find that monetary contractions cause a decline in firms' investments, both in physical and intangible capital, and a slowdown in future productivity growth. These findings suggest that a tight monetary stance may depress aggregate investments and delay the transition to a greener economy.

Moreover, as our theoretical model will imply, monetary policy is likely to influence

[9]See also Garga and Singh (2021), Schmöller and Spitzer (2021) and Fornaro and Wolf (2023).

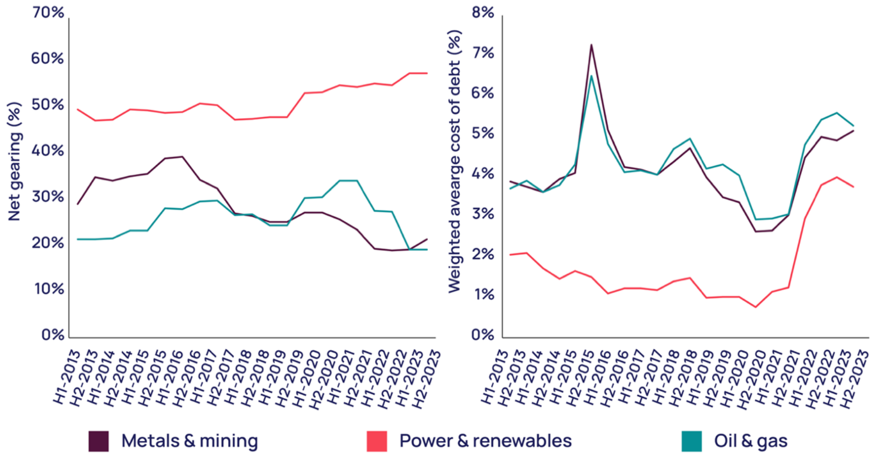

Figure 3: Gearing in the energy sector. Source: Martin et al. (2024).

the composition of investments between dirty and clean technologies during the green transition. The reason is that regulatory restrictions on carbon emissions shorten the horizon of firms investing in dirty technologies, as well as their ability to expand production when demand is robust, making dirty investments relatively insensitive to changes in interest rates and aggregate demand. For this reason, a macroeconomic environment characterized by low cost of capital and high aggregate demand fosters the reallocation of investment out of dirty and toward clean technologies.

Among practitioners, the view that green investments are particularly sensitive to financial conditions is widespread (Martin et al., 2024).[10] First, green investments are characterized by large investments upfront with uncertain returns in the distant future (Martin et al., 2024). Second, they are more reliant on external finance, and debt accounts for a higher share of their capital structure than equity (Figure 3, left panel). Moreover, as noted by Martin et al. (2024), during the latest monetary tightening the cost of capital increased by more for renewable power technologies, compared to traditional ones based on fossil fuels (Figure 3, right panel). This fact hints at an important role for monetary policy in shaping the incentives to invest in green technologies.[11]

[10]This view has motivated a large literature on the importance of financial factors for green investment and green R&D. Several papers have showed that lack of access to finance impedes the adoption of green innovations and limits green patenting activities. Selected citations are Accetturo et al. (2022), Aghion et al. (2022), Aghion et al. (2024), Costa et al. (2024), Ghisetti et al. (2015), De Haas et al. (2024), De Haas and Popov (2023), Lanteri and Rampini (2023), Yuan et al. (2021) and Zhang and Jin (2021).

[11]In a recent survey on 49 energy companies in the Netherlands (the Nederlandse Vereniging Duurzame Energie questionnaire) completed in March/April 2023, to the question "have the increases in interest rates had an effect on your financing options? ", 33% of the companies answered yes while 38% said that they

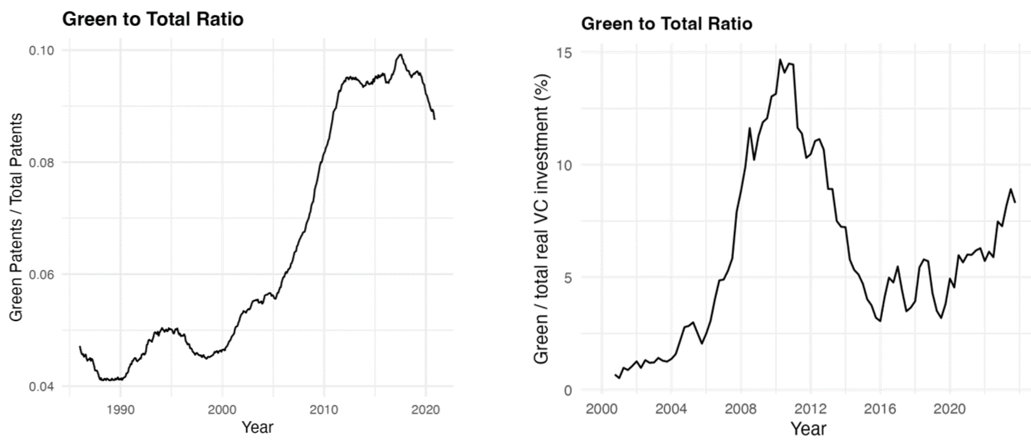

Figure 4: Patents and Venture Capital Investment : % green to total.

A way to assess heuristically the importance of aggregate demand and financial factors for green innovation is to look at the aftermath of the 2008 global financial crisis. Figure 4 shows the share of green patents over total (left panel), and the share of green venture capital investments over total (right panel) in the United States. It indicates a collapse of green venture capital just after the global financial crisis, and a plateau in the share of green patenting followed by a decline. A possible interpretation is that the aftermath of the global financial crisis, which featured a combination of high cost of capital and low aggregate demand, was especially detrimental to investments in green technologies.[12]

More detailed evidence on the impact of the 2008 financial crisis on green innovation comes from Aghion et al. (2024). Using German data for the auto mobile sector, they show that, following the financial crisis of 2008, green patenting activities declined more than non-green ones. They also provide evidence that a monetary policy contraction affects particularly strongly green patenting activities.

The available evidence thus suggests that investments in clean technologies are especially sensitive to monetary and financial factors. Taking into account the impact of monetary interventions on green investments is therefore crucial to understand the relationship between monetary policy and the green transition.

expected it soon. While just suggestive, this evidence is again consistent with the notion that a tight monetary stance discourages investments in green technologies.

[12]Of course, other factors may contribute to explain these trends. For instance, Acemoglu et al. (2023) argue that the development of green technologies has been negatively affected by the shale gas boom.

Chapter 3. Econometric evidence

Against the background painted in Chapter 2, we now provide some novel econometric evidence. First, we document that restrictions in the use of dirty energy sources generate negative supply shocks, and that monetary contractions are likely to slow down the increase in the relative price of fossil fuels needed to achieve the green transition. We then show that financial shocks have a particularly large impact on green investments, including in R&D.

3.1. Supply constraints on dirty goods

The energy transition is going to be characterized by a progressive tightening of supply constraints on the use of dirty technologies. What will be the impact on the inflation/economic activity trade-off faced by central banks? Here we report some evidence which complements the study by Känzig (2023) on the macroeconomic effects of the EU Emission Trading System.

The euro area is a substantial consumer of natural gas and relies heavily on gas imports. As a consequence, it is exposed to risks of gas shortages. In a comprehensive analysis of the gas market, Colombo and Toni (2024) report data from the European Council showing that the European Union's dependence on Russian natural gas has increased over time: in 2021, over 80% of the natural gas energy used in the EU was imported, with approximately half of this supply coming from Russia. For this reason, increases in gas prices in the euro area are akin to tightening on the use of dirty production technologies. Gas price shocks are thus informative of what may happen during the energy transition.

In a first exercise, we specify a 9-variable Vector Autoregressive (VAR) model including inflation, industrial production, real activity, headline and core inflation and some key variables on the energy market: oil and gas prices as well as gas production, gas imports and the stock of gas. We identify a supply shock to the gas price in Europe using the methodology proposed by Colombo and Toni (2024), who exploit market-relevant news and high-frequency data on natural gas futures prices to construct a valid instrument.

We then compare those responses to the impulse response functions to a monetary policy contraction where we use the instrument constructed by Ricco et al. (2024). The sample is 2004-2023 and data are monthly. Details about the model specification of the VAR, construction of the instruments and variables definitions and transformations are

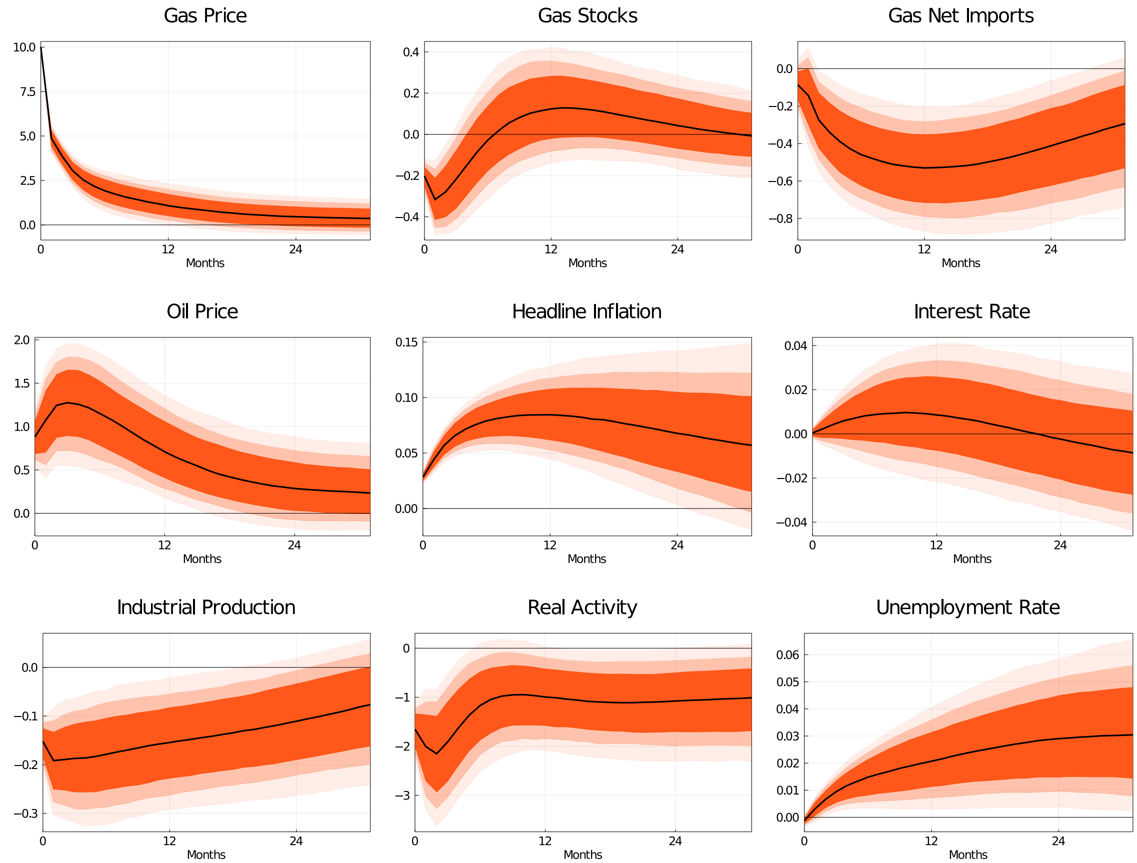

Figure 5: The effect of an unexpected increase in gas price.

provided in the Box at the end of the Section.

Figure 5 and 6 report the results. Gas supply responses are rescaled to represent the impacts after a 10% increase in gas prices, while monetary policy responses are rescaled to represent a 1% increase in interest rates.

Let us first focus on the response to the gas shock. Higher gas prices boost overall inflation, and lead to lower economic activity and employment. Moreover, the gas stock and net imports of gas decline, which we take as being an indication of the euro area economy being constrained in the use of gas. The results are consistent with those found by Känzig (2023) in relation to ETS shocks. In both cases the response is typical of a supply shock, featuring a decline in real activity and an increase in inflation.

The responses to an unexpected monetary policy contraction, instead, are informative of the macroeconomic impact of monetary interventions aimed at containing the rise in inflation due to supply constraints on dirty energy. As expected, a monetary contraction

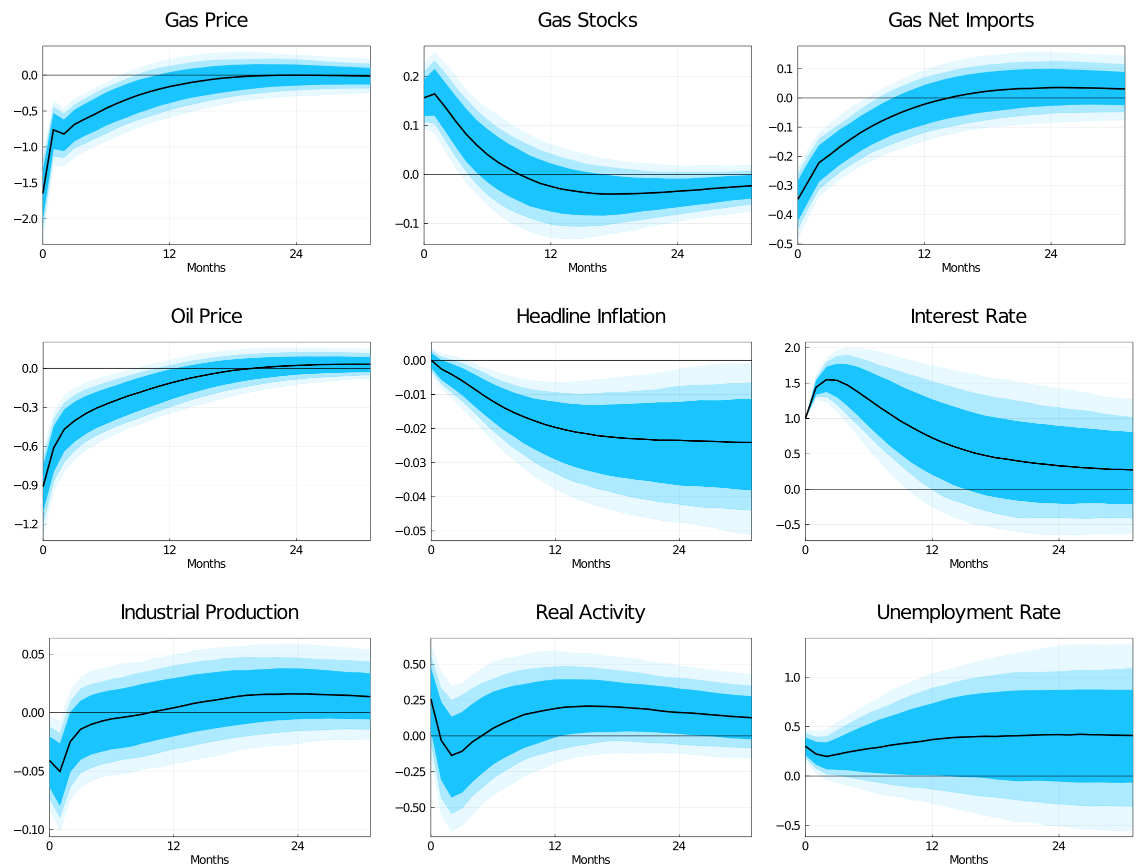

Figure 6: The effect of a monetary contraction.

manages to reduce inflation, but at the cost of lower economic activity and higher unemployment. Moreover, now the gas stock increases and net imports of gas decline, both effects signaling a demand-induced slack in the economy. In fact, the monetary tightening has a particularly large negative impact on gas prices. This result hints at the fact that monetary policy contractions may slow down the rise in the relative price of dirty goods needed to foster the green transition. We will get back to this point, when we study the green transition with the help of our theoretical framework.

BOX 1: VAR estimation and specification

The VAR model is defined as

$$Y_t = A_0 + A_1 Y_{t-1} + \cdots + A_p Y_{t-p} + u_t. \tag{1}$$

In all specifications, the VAR models have been estimated by Bayesian methods using a Normal Inverse Wishart prior and sum of coefficients prior. The tightness parameter is optimized using Bańbura et al. (2010). The structural shocks ϵ_t are related to the reduced form shocks as follows

$$\epsilon_t = A_0^{-1} u_t. \tag{2}$$

We are interested in identifying a gas price shock and a monetary policy shock. Let's label them ϵ_t^o and ϵ_t^m respectively. For identification we follow the "external instruments" approach developed by Mertens and Ravn (2014) and Stock and Watson (2018). This implies selecting an external instrument, z_t, to identify the shock ε_t^i where $i = m, o$. The instruments must satisfy two conditions:

- *Instrument relevance:*

$$\mathbf{E}(\epsilon_t^i . z_t') \neq 0. \tag{3}$$

- *Instrument validity (exogeneity):*

$$\mathbf{E}(\epsilon_t^i . z_t') = 0. \tag{4}$$

Using a valid instrument gives consistent estimation of shocks. Assuming that the shock of interest is ordered first, estimation of the shock is done in three steps

1. Estimate the VAR model and obtain the residuals ($\hat{u}_t$).
2. In order to obtain elements of the column of the matrix (A_0^{-1}), say a_1, regress $\hat{u}_t$ on z_t.
3. Take the ratio of regression coefficients obtained from step 2 with the coefficient a_{11}.

4. Normalize as $a_{11} = 1$.

Under these assumptions, the shock can be identified up to a scale by regressing the instrument on each innovation series. The key assumption is that the news revealed within the window that leads to the surprise in the futures price can be treated as exogenous with respect to the other variables in the VAR.

Gas shock
The external instrument for the gas shock is the high frequency gas shock, identified as in Colombo and Toni (2024). Due to the lack of a single authority capable to influence price movements as OPEC is for oil, the authors collect news from multiple sources related to gas supply for the euro area using Reuters.
To construct a time series of gas surprises, the authors take changes in gas futures prices following the news. Gas futures prices serve as a market-based indicator of gas price expectations. Gas surprises at day d and at month horizon h are defined as:

$$F_d^h - F_{d-1}^h,$$

where F_d^h is the log price of the h-months ahead gas future contracts in date d. Dutch TTF are the gas futures.

Monetary policy shock
For monetary policy surprises we use the shocks to conventional monetary policy using as instruments surprises as computed by Altavilla et al. (2019). We then follow Ricco et al. (2024) and correct for non-linear information effects. The general idea is to consider that part of the monetary policy surprise that is orthogonal to both the central bank's economic projections and to past market surprises.

Variables definition and transformation are described in the Appendix.

3.3. Monetary policy, financial conditions and green investments

We now provide some evidence on the sensitivity of investment, including in research and development (R&D), in the green sector to financial conditions. This is a challenging task, given that there are no data sources on green investment covering a time span long enough to perform an econometric analysis. We thus construct an indirect measure of green investments, based on firms' patenting activities.

In a comprehensive review of the quality and coverage of different indicators of green innovation, the OECD (Dussaux and Es-Sadki, 2023) suggests that the more accurate information comes from patent data and information on venture capital (VC) deal. The document makes the point that patents measure incremental technological change while VC captures technological disruption. Both aspects of innovation are interesting for the argument of this report. Unfortunately, however, data on green VC is available only for the last 20 years, and so they are not suitable for a formal econometric analysis.

In what follows we therefore focus on patenting activity of US public companies. The scope of the analysis does not include disruptive innovations and private companies, but has the advantage of benefiting from rich company level information on a variety of characteristics available for a long time series from Compustat. By matching these data with patent data available from the US patent and Trademark Office (USPTO), we can identify the green-innovators and study the specific characteristics of their investment behavior.

Our analysis proceeds in two steps. First, we classify all companies included in the Compustat data as generic or green innovators using patent data. More precisely, 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 filing date and cooperative patent classification (CPC) code, and we match this information to the firms included in the data set. Second, we run local projections to estimate the dynamic effect of financial shocks on investment and R&D expenditure for the different groups emerging from our classification.

Let us first describe the classification criterion and report few stylized facts on the characteristics of the groups. We classify 'green' patents using the methodology introduced by Jee and Srivastav (2024). This classification scheme exploits existing methodologies in the literature to provide a comprehensive identification of patents pertaining to emission reducing technologies (so-called 'clean' or 'green' patents) as well as those technologies that exacerbate the emissions problem (so-called 'dirty' patents). The patent data are then matched to the firms using the patent-to-firm matching of Arora et al. (2021).

At each point in time, we divide firms in three groups based on the patents that they have filed up to that period:

1. Non innovators: zero cumulative patents filed.

2. Non-green innovators: share of green patents in total patents smaller than 25%.

3. Green innovators: share of green patents in total patents greater than 25%.

This classification scheme selects a group of green innovators of about 50 companies on average. These are companies operating in the clean technology, renewable energy, and advanced materials firms, with a strong focus on solar energy, alternative fuels, and energy storage. Hotten and Reichlin (2025) provide a complete description of their characteristics.

Notably, many green patents are filed by what we classify as non-green innovators, which tend to be larger and older companies. But what we define as green-innovators almost exclusively apply for green patents. Therefore, it is reasonable to assume that this group mostly invest in green projects. Interestingly, this group includes also some high emission companies. This seems natural, since many green investments are performed by highly polluting firms, developing green technologies to comply with environmental regulations.[13]

The table below reports, for the three groups, average leverage, perceived cost of capital estimated using the measure of Gormsen and Huber (2024) and average exposure to risk as measured by asset-beta for the three groups[14]. A high asset beta indicates that the company's underlying business (before considering leverage) is highly sensitive to macroeconomic or market conditions. Since asset beta strips out the effect of the capital structure, it reflects the true business risk of these companies. Since R&D is a risky form of investment, it is natural that innovators are characterized by high asset betas.

Table 1: Average asset-beta, leverage, and cost of capital by group

	Non innovators	**Non-green innovators**	**Green innovators**
Asset-beta	1.36	3.90	3.86
Leverage	0.33	0.23	0.29
Cost of capital (%)*	8.81	9.41	9.58

* The measure is the perceived Weighted Average Cost of Capital (WACC).

As expected, non-innovators distinguish themselves from innovators - both green and non - by having a lower asset-beta, higher leverage and lower perceived cost of capital.

[13]Hence, our classification does not correspond to the one based on carbon emissions, which is for instance used by Bauer et al. (2024).

[14]The asset beta measures how sensitive the returns of a particular asset are to movements in the overall market. It reflects the business risk only, with no effect from leverage.

Green-innovators, when compared with non-green innovators, have higher perceived cost of capital and higher leverage. This confirms the evidence summarized in Chapter 2, and suggests that green innovators are likely to be more sensitive to financial conditions. This is particularly interesting if we consider that our analysis, which focuses on public firms, excludes disruptive innovators as captured by venture capital deals and by private start-ups, whose exposure to financial conditions must be even more significant.

Having established our classification, we now estimate the differential effect of a shock on tightness of financial conditions on investment and R&D expenditure across groups. To this end, we define a stratified local projection of the form

$$\Delta^h Y_{i,t+h} = \gamma_j^h + \sum_{g=1}^{3} \beta_g^h \times \mathbb{1}[\text{Green}_i \in g] \times X_t + \psi \mathbf{N}_t + \Gamma^h \mathbf{Z}_t + \epsilon_{i,t+h}, \quad \forall\, h \in 0, \cdots, H,$$

where h denotes the horizon, $Y_{i,t}$ ($i =$ investment, R&D) is the dependent variable with $\Delta^h Y_{i,t+h} = Y_{i,t+h} - Y_{i,t-1}$, γ_j^h is the firm's j fixed effect at horizon h, X_t is an index of financial conditions, $\mathbf{N}_t$ is a vector including the year-on-year growth rate of GDP and the one-year interest rate on treasury securities while in $\mathbf{Z}_t$ we have included lagged dependent variable and lagged right-hand-side variables. The green dummy selects the relevant group defined above as non innovators, green innovators, and non green innovators.

The measure of financial tightness X_t is 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 and investment. It is composed of 105 indicators of financial conditions in money, debt and equity markets and the shadow banking system. The NFCI summarizes 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.

The rationale for using this indicator is that our sample covers many years in which the monetary policy rate was stuck at the zero lower bound, and the Fed employed other instruments such as asset purchases and forward guidance. More generally, as suggested by Caballero and Simsek (2024), there is evidence that monetary policy works through financial conditions and that companies, in particular if financing is market based, react to changes in financial conditions rather than to the policy rate.

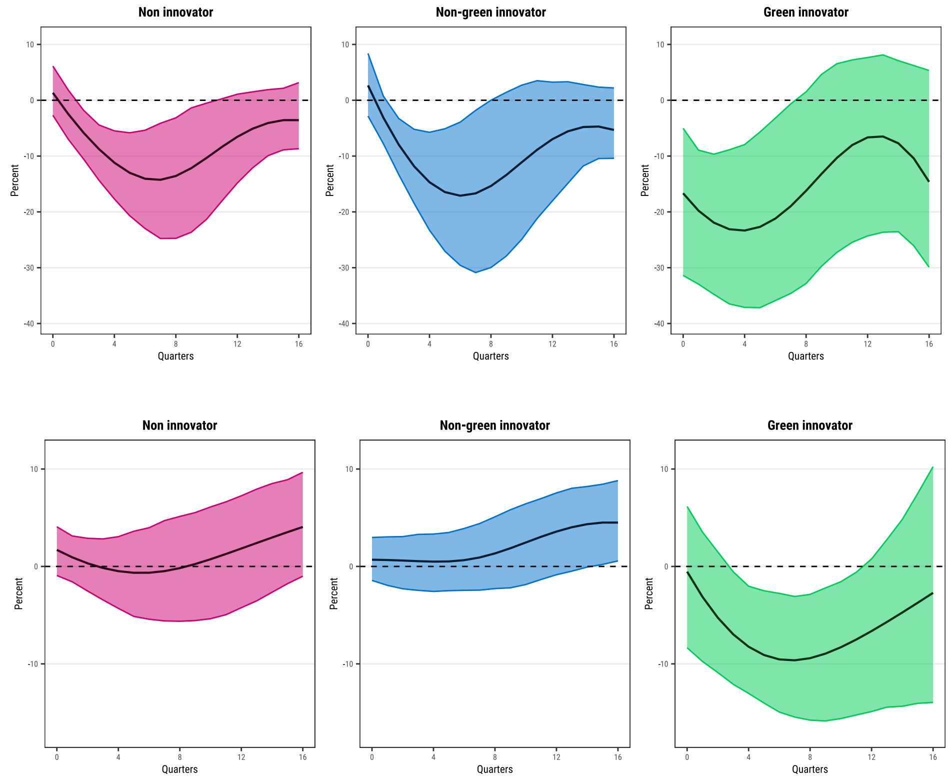

Figure 7: Effect of a one standard deviation tightening of financial conditions on investment (top panel) and R&D expenditure (bottom panel).

We identify the financial condition shock through Cholesky ordering. For the results reported below GDP growth is ordered first, the NFCI second and the interest rate last. In this case the assumption is that the unexpected component of GDP growth and the NFCI affect contemporaneously the interest rate, while the unexpected component of the interest rate affects GDP and the NFCI with a lag. Real investment is defined as nominal capital expenditure divided by the gross value added deflator, while R&D expenditure is nominal expenditure on R&D divided by the gross value added deflator.[15]

Figure 7 shows how a one standard deviation increase in the NFCI affects investment and R&D expenditure. Impulse responses are smoothed following Hartley and Mejia (2025). This method penalizes the impulse responses toward a polynomial (we use a polynomial of order 2). The shaded areas correspond to the 95% confidence intervals constructed using the wild cluster bootstrap method as in Hartley and Mejia (2025).

[15]Precisely, we use the business non-farm chain-type price index available from FRED, while capital and R&D expenditure data are available from Compustat.

As expected, a tightening in financial conditions is associated with a drop in investment for all groups, a result in line with the existing literature (Ma and Zimmermann, 2023). Moreover, consistent with our conjecture, the response of the green innovators is stronger. We also find that a tighter access to finance has a particularly strong depressive impact on R&D spending by green innovators. Our empirical results thus accord well with those found by Aghion et al. (2024) using data from the German automotive sector. These results point toward the importance of financial factors in shaping green investments and the energy transition.

Chapter 4. A model of the green transition

We now propose a model to explore the macroeconomic effects of the green transition. In particular, we will study the interaction between regulatory caps on carbon emissions, monetary policy, and investment in green and polluting technologies.

There are two key pieces of evidence from the previous chapters that motivate our modeling choices. First, the VAR analysis in Chapter 3.2 shows that a rise in the price of fossil fuels increases inflation, and depresses employment and economic activity. Second, in Chapter 3.3, we have shown that green investments, including in innovation, are particularly sensitive to financial markets conditions.

To capture these facts, we propose a model where final output is produced using "dirty" and "clean" intermediate goods. Producing dirty goods generates carbon emissions, which deteriorate the quality of the environment, while clean goods employ green technologies, that do not generate carbon emissions. This is why the production of dirty goods may be constrained by regulatory restrictions to facilitate the green transition. We model the green transition as a progressive tightening of a regulatory cap on the production of dirty goods, which constrains their supply.

The supply constraint on dirty goods gives rise to an aggregate non-linear Phillips curve, because the price of dirty goods rises steeply when the regulatory cap on their production binds. A tighter green regulation worsens the inflation/employment policy menu available to the central bank, which is consistent with the first empirical fact. To capture the second empirical fact, we introduce endogenous technological change in both sectors. We show that monetary policy has a particularly large impact on investments in clean technologies. Due to green regulations, the reason is, firms employing clean technologies have a longer horizon and are better able to scale up production when aggregate demand increases.

4.1. The inflationary consequences of supply constraints on dirty goods

We consider a New-Keynesian model where final goods are produced using labor together with a mix of clean and dirty intermediate goods. Because of the environmental costs of high emissions, we assume that the regulator wants to keep production of dirty goods below a certain cap, and enforces this constraint by levying an environmental tax on the production of dirty goods. Therefore, similar to what happens in the EU Emission Trading System, the price of dirty goods adjusts endogenously to ensure that the cap on emissions set by the regulator is not violated. The model is summarized in Box 3, and described in detail in the appendix.

BOX 3: Model Set-up

The economy features two sectors: a dirty sector with output Y_{Dt} that generates carbon emissions, and a clean sector with output Y_{Ct} that uses non-polluting technologies. There is a continuum of infinitely-lived households with preferences

$$\sum \beta^t (logC_t + v(S_t)),$$

where S_t represents the quality of the environment which deteriorates with the production of dirty goods, that is $S_t = S_{t-1} - \xi Y_{Dt}$, and $v(S_t)$ is an increasing function capturing households' preference for a clean environment.

The households face a standard budget constraint $P_t C_t + B_{t+1} = W_t L_t + D_t + (1 + i_t) B_t$, where P_t denotes the nominal price of the final good, C_t consumption, B_t one-period nominal bonds paying the nominal interest rate i_t, L_t employment, W_t nominal wages and D_t firms' dividends.

The final good Y_t is produced using labor and intermediate goods according to

$$Y_t = L_t^{1-\alpha} [Y_{Ct} + Y_{Dt}].$$

Nominal wages are rigid. Following Galí (2011), we assume that $W_t / W_{t-1} = (L_t / \bar{L})^{\zeta} \pi_{t-1}^{\lambda}$, with $\zeta > 0$ and $\lambda \in [0, 1)$, and where $\bar{L}$ denotes the natural level of employment, which we assume to be constant. When $L_t = \bar{L}$ we say that the economy is operating at full employment.

Within each sector $s = \{C, D\}$ there is a unit mass of firms $i \in [0, 1]$ that produce differentiated varieties x_{sit} that are combined in the sector output according to the following technology

$$Y_{st} = \int_0^1 A_{sit}^{1-\alpha} x_{sit}^{\alpha} di,$$

where A_{sit} denotes the productivity of variety si at time t, and for now grows at a constant exogenous rate. This production function implies that intermediate goods are imperfect substitutes.

The differentiated varieties x_{sit} are produced one-to-one with final goods by monopolistic competitive firms. The price of clean goods is equal to $P_{Cit} = P_t/\alpha$, and their production is $Y_{Ct} = \alpha^{\frac{2\alpha}{1-\alpha}} L_t^{\alpha} A_{Ct}$, where $A_{Ct} = \int_0^1 A_{Cit} di$. Firms producing dirty goods face a tax τ_{Dt} per unit produced, that is chosen by the government so that $Y_{Dt} \leq \bar{Y}_{Dt}$, where $\{\bar{Y}_{Dt}\}_t$ denotes production cap on dirty goods. The price for the dirty varieties is $P_{Dit} = P_t(1 + \tau_{Dt})/\alpha$ and production of dirty goods is equal to

$$Y_{Dt} = \alpha^{\frac{2\alpha}{1-\alpha}} (1 + \tau_{Dt})^{\frac{\alpha}{\alpha-1}} L_t^{\alpha} A_{Dt},$$

where $A_{Dt} = \int_0^1 A_{Dit} di$. The tax can be written as

$$\tau_{Dt} = \begin{cases} 0 & \text{if } \alpha^{\frac{2\alpha}{1-\alpha}} L_t^{\alpha} A_{Dt} \leq \bar{Y}_{Dt} \\ \left(\alpha^{\frac{2\alpha}{1-\alpha}} L_t^{\alpha} A_{Dt}/\bar{Y}_{Dt}\right)^{\frac{1-\alpha}{\alpha}} - 1 & \text{if } \alpha^{\frac{2\alpha}{1-\alpha}} L_t^{\alpha} A_{Dt} > \bar{Y}_{Dt}. \end{cases}$$

Naturally, a tighter production cap on dirty goods is associated with a higher environmental tax. Moreover, a stronger aggregate demand - captured by higher employment - is associated with higher demand pressures on dirty goods, which have to be counteracted with a rise in the tax to maintain their production constant. This explains why the tax is increasing in employment.

Output of final goods can be rewritten as

$$Y_t = L_t \left[\alpha^{\frac{2\alpha}{1-\alpha}} A_{Ct} + \min\left\{\alpha^{\frac{2\alpha}{1-\alpha}} A_{Dt}, \bar{Y}_{Dt}/L_t^{\alpha}\right\}\right].$$

This expression shows that binding supply constraints on dirty goods lead to drops in labor productivity, because dirty and clean intermediates are imperfect substitutes.

Moreover, in the Appendix we show that inflation is given by

$$1 + \pi_t = \frac{W_t}{W_{t-1}} \frac{A_{C,t-1} + A_{D,t-1} \left(\alpha p_{D,t-1}\right)^{-\frac{\alpha}{1-\alpha}}}{A_{C,t} + A_{D,t} \left(\alpha p_{D,t}\right)^{-\frac{\alpha}{1-\alpha}}},$$

with the relative price of dirty intermediates defined by

$$p_{D,t} = \frac{1}{\alpha} \max \left(1, \alpha^2 \left(\frac{L_t^\alpha A_{D,t}}{\bar{Y}_{D,t}}\right)^{\frac{1-\alpha}{\alpha}}\right).$$

Hence, when the supply constraint on dirty goods binds their price increases, creating upward pressure on the inflation rate. This effect generates a non-linear Phillips curve.

In our model, inflation is shaped by two effects. The first one is the classical wage effect, typical of New Keynesian models. When aggregate demand rises, firms hire more workers to ramp up production. As employment rises, workers require higher nominal wages. Finally, higher nominal wages push up production costs and prices.

The second effect is the result of green regulations. When supply constraints on dirty goods are not binding, a higher demand for dirty inputs is accommodated with a rise in their output, without affecting prices. When supply constraints on dirty goods bind, instead, firms producing polluting goods cannot expand production in response to a rise in demand. They thus adjust to increases in demand by charging higher prices. As illustrated by Figure 8, green regulations thus create non-linearities in price setting by firms operating in dirty sectors.

The implications of this effect for the aggregate Phillips curve are easy to derive. At low levels of aggregate demand, intermediate goods producers scale up output when demand increases, without adjusting their price. As aggregate demand and employment increase, however, production of both clean and dirty goods rises until a point where the supply constraint on dirty goods becomes binding. From then on, further increases in demand for dirty goods causes their price to rise. Higher employment thus boosts inflation not only because of the upward pressure on wage growth, but also because of the rise in the price of dirty goods induced by the binding supply constraint. Due to this effect, our economy features a non-linear Phillips curve.

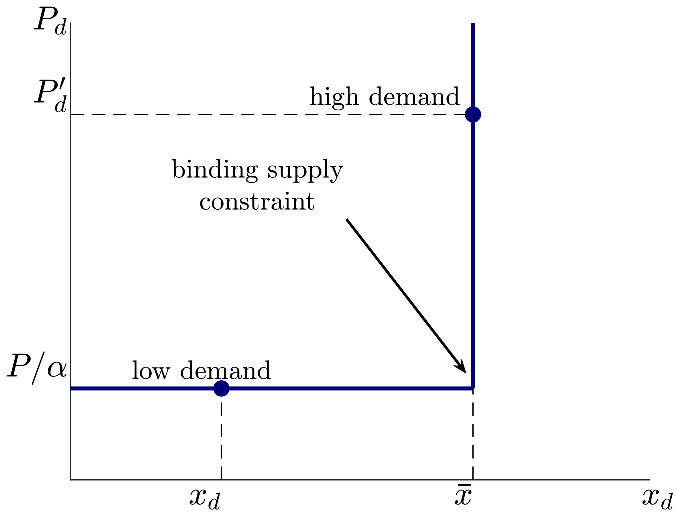

Figure 8: Non-linear pricing in the dirty sector.

Figure 9 shows the aggregate Phillips curve when there is no supply constraint on dirty goods (solid blue line), one with supply constraint (dashed red line), and one with an even tighter supply constraint (dotted green line). The introduction of green regulation makes a portion of the Phillips curve steeper, corresponding to values of employment for which the supply constraint on dirty goods binds. Moreover, as the green regulation becomes tighter, the Phillips curve shifts upward and the supply constraint on dirty goods starts binding at lower levels of employment, so that a larger portion of the Phillips curve becomes steeper.[16]

An important implication of this analysis is that demand shocks may give rise to high inflation volatility. Intuitively, periods of high aggregate demand are associated with binding supply constraints on dirty goods, causing sharp rises in their relative price and in overall inflation. When aggregate demand is low, instead, supply constraints on dirty goods are slack, inflation falls somehow, but not enough to compensate for the rise in inflation during demand-driven booms.

Moreover, shocks to the supply constraints on dirty goods, perhaps induced by changes

[16]Due to lack of data, it is hard to detect these non-linearities purely looking at macroeconomic variables. However, some recent sectoral-level evidence provided by Boehm and Pandalai-Nayar (2022) comes to help. Using data from US manufacturing, Boehm and Pandalai-Nayar (2022) show that the elasticity of prices with respect to demand shocks increases sharply with capacity utilization, which is evidence of convex sectoral supply curves. Insofar as supply restrictions on the production of dirty goods act as capacity constraints, we would thus expect tightening in green regulation to generate a non-linear trade-off between inflation and economic activity, i.e. a non-linear Phillips curve, during the energy transition. This is exactly what our theoretical model predicts.

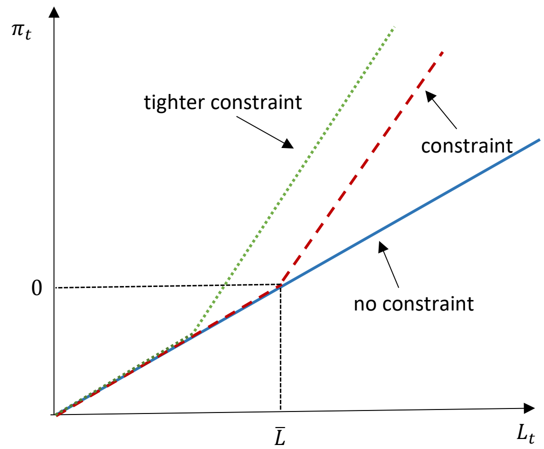

Figure 9: Supply constraints on dirty goods and the Phillips Curve.

in green regulation, act as another source of high inflation volatility. As shown in Figure 9, in fact, a tightening of the supply constraint on dirty goods worsens the inflation/employment menu for the central banker. To maintain inflation on target, monetary policy has to generate slack on the labor market 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. Once again, the reason is that a binding constraint on dirty goods triggers a rise in their price, as well as production bottlenecks that lower labor productivity, accommodated through higher price inflation.

How do these results relate to the macroeconomic impact of the green 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 face upward shifts in the Phillips curve and often end up on its steeper portion. If so, business cycles driven by demand shocks will likely lead to high inflation volatility and the employment cost of containing inflation will likely be high. These considerations suggest that because of the green transition, central bankers should be ready to act in a new economic environment where they have a worse inflation/employment menu available and where inflation is more volatile.

To better understand the mechanism of the model, Figure 10 shows the macroeconomic impact of a permanent tightening of the production cap on dirty goods.[17] Given that

[17] We report our calibration strategy in the Appendix. Although our model is stylized and not suited for

intermediate inputs are imperfect substitutes, constraining the supply of dirty goods lowers labor productivity. This explains why tightening the production cap on dirty goods leads to a drop in GDP. Moreover, since green regulation makes dirty goods scarcer, their relative price increases. As a result, the economy re-balances toward a larger use of clean intermediate inputs in the production process.

Monetary policy plays a key role in shaping the macroeconomic impact of this re-balancing process over the medium run. We consider two extreme scenarios: the blue solid lines represent what happens if monetary policy keeps the economy at full employment, while the red dashed lines refer to a central bank that maintains inflation always equal to its target (normalized to zero). Focusing on these two benchmarks is useful to illustrate the 'green dilemma' faced by monetary authorities.

Let us start by describing what happens if the central bank keeps the economy at full employment. The rise in the relative price of dirty goods is then associated with a temporary spike in the inflation rate. The reason is that the drop in productivity induced by green regulation depresses firms' labor demand. To prevent firms from firing workers, real wages have to fall. Since nominal wages are rigid, the drop in real wages needed to maintain full employment can only be attained through a temporary rise in price inflation. Looking through a temporary burst of inflation is thus required to reconcile the phasing out of dirty technologies with full employment.

Now consider what happens if the central bank follows a strict inflation targeting policy. By adopting a sufficiently tight monetary stance, the central bank is able to keep inflation at zero, but at the cost of a much larger drop in GDP. This happens because to contain the inflationary consequences of the rise in the price of dirty goods, nominal wages have to fall. But for nominal wages to drop, substantial slack on the labor market is needed. Moreover, by chocking off the increase in the relative price of dirty goods, this hawkish monetary policy stance has the additional cost of slowing down the reallocation of production towards clean goods.

Figure 10 is consistent with the empirical macroeconomic response to a tightening in the carbon emissions allowed by the EU Emission Trading System documented by Känzig (2023), as well as with our own empirical analysis in Chapter 3.2 on the response to an

a full-blown quantitative analysis, the order of magnitude of the response of inflation and GDP to a green regulation shock implied by our model are in the same ball park of the empirical estimates provided by Känzig (2023), and of our own estimates on the macroeconomic impact of gas price shocks provided in Chapter 3.2.

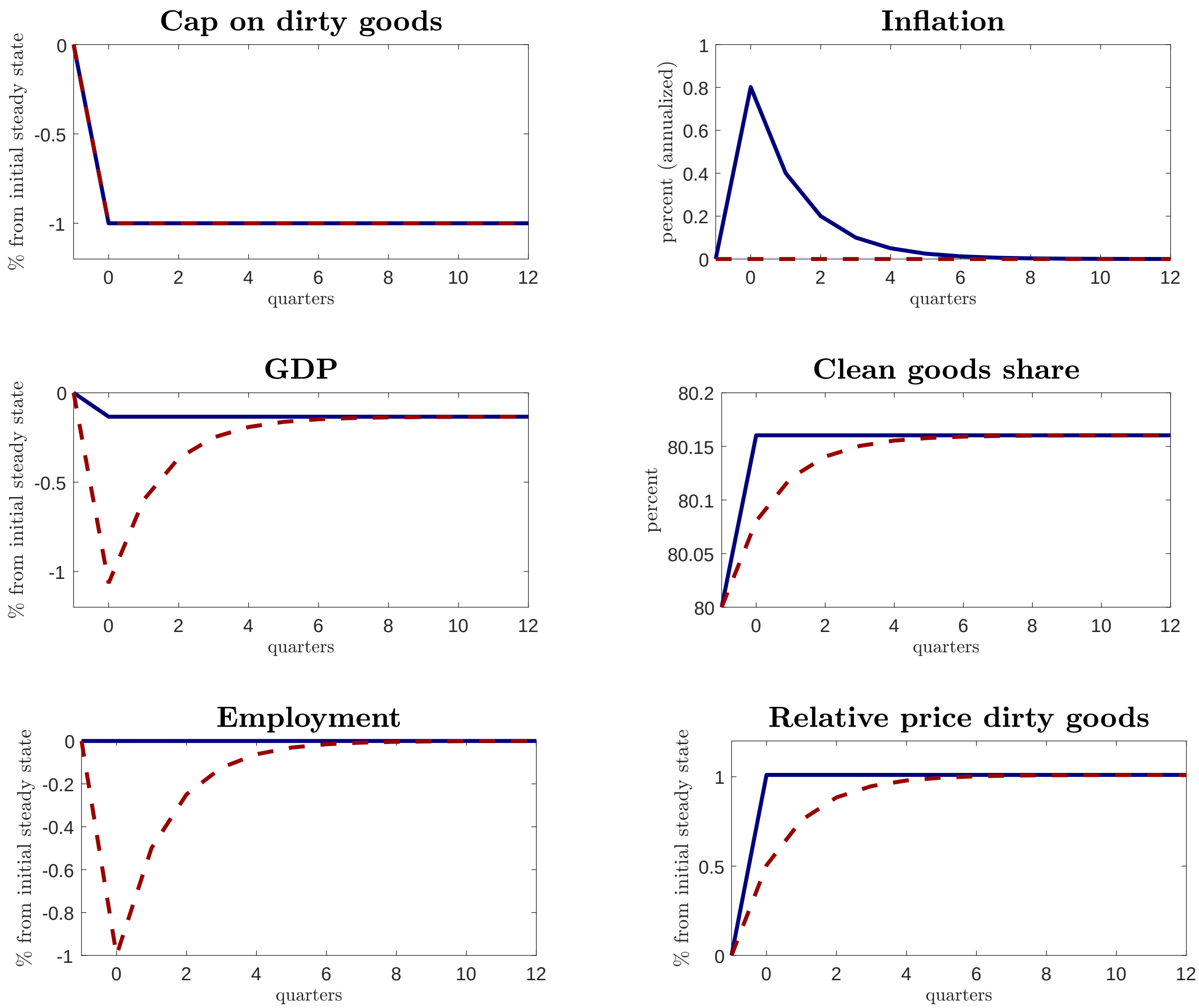

Figure 10: Permanent reduction of the cap on dirty goods. Solid lines: employment targeting. Dashed lines: inflation targeting.

increase in the price of natural gas in the Euro area. In both cases, a reduction in the use of fossil fuels leads to higher inflation and lower economic activity. This is exactly what happens in our model, in which tighter supply constraints on dirty goods generate an up-ward shift of the Phillips curve, worsening the inflation/employment menu available to the central bank. Through the lenses of our model, a temporary rise in inflation is the natural symptom of the re-balancing of production from dirty to clean goods, and fully counteracting it may substantially amplify the output losses caused by the phasing out of polluting production techniques.[18]

[18]Of course, letting inflation exceed its target for too long comes at the risk of a de-anchoring of inflation expectations, something that is not present in our model. In practice, during the energy transition central

What determines the strength of the inflationary pressures caused by the green transition? Our model indicates that the elasticity of substitution between dirty and clean intermediate goods plays a key role. Intuitively, the harder it is to substitute dirty inputs with clean ones, the bigger will be the rise in the price of dirty goods during the green transition. Estimating empirically the economy-wide elasticity of substitution between dirty and clean intermediate inputs is a difficult task, which is beyond the scope of this report. In our simulations, we have considered a relatively high elasticity equal to 2. This choice implies responses of inflation and GDP to a green regulation shock of the same order of magnitude as those estimated by Känzig (2023). Lower values of this elasticity would amplify the rise in inflation associated with the green transition.

4.2. Endogenous technological change

As we discussed in Chapter 3.3, green investments are going to be crucial for a successful energy transition, to counteract the productivity drop due to the tighter supply constraint on dirty goods. Moreover, we argued that empirically green investments are especially sensitive to monetary and financial shocks. We now show that our model can rationalize these notions, and develop some implications for the appropriate monetary/fiscal policy mix during the green transition.

We model endogenous technological change by allowing firms producing intermediate goods to invest to increase their future productivity. As it is natural, firms choose their investments in order to maximize their expected stream of profits. Importantly, the presence of a regulatory supply constraint on dirty goods implies that polluting production technologies tend to disappear in the long run. Investments in dirty technologies thus have a shorter horizon compared to clean ones.[19] As we will see, this effect implies that green investments are particularly sensitive to changes in interest rates and aggregate demand driven by monetary policy interventions.

banks will have to carefully balance the risk of de-anchoring inflation expectations, against the risk that phasing out dirty technologies will cause large drops in output and employment.

[19]On top of that, clean firms typically have a longer horizon in their investment decisions relative to dirty firms because the production of clean energy requires large upfront investments and small variable costs.

BOX 4: Endogenous productivity growth

A firm producing variety x_{sit} can invest to increase the productivity of its variety A_{sit}. In particular, investing I_{sit} units of the final good in period t leads to an increase in future productivity equal to

$$A_{sit+1} = (1-\delta_s)A_{sit} + \chi I_{sit}^{\phi_s} A_{st}^{1-\phi_s},$$

where δ_s and ϕ_s denote respectively the depreciation rate and the strength of diminishing returns from investment in sector s, while χ pins down the productivity of investment. We introduce intra-sectoral knowledge spillovers by assuming that the productivity of investment in sector s is increasing in the average level of productivity in the same sector A_{st}. The strength of these spillovers is set equal to $1-\phi_s$, to ensure balanced growth in steady state.

Each firm i in sector s chooses investment to maximize the discounted stream of future profits

$$\max_{I_{sit}, A_{sit+1}} \sum_{\tilde{t}=t}^{+\infty} \left(\prod_{k=t}^{\tilde{t}-1} \frac{1}{1+r_k} \right) \left((1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}} (1+\tau_{s\tilde{t}})^{\frac{\alpha}{\alpha-1}} L_{\tilde{t}} A_{si\tilde{t}} - I_{si\tilde{t}} \right),$$

where $\tau_{C\tilde{t}} = 0$ for all $\tilde{t}$ and $\tau_{D\tilde{t}}$ is such that $Y_{D\tilde{t}} \leq \bar{Y}_{D\tilde{t}}$. Notice that profits are increasing in future productivity $A_{si\tilde{t}}$ - this is the reason why firms want to invest in the first place - and in future aggregate demand, as encapsulated by the term $L_{\tilde{t}}$. Moreover, a higher tax lowers profits in the dirty sector. Finally, firms discount profits using the real interest rate r_t.

The optimality condition for investment is

$$\frac{1}{\chi\phi_s} \left(\frac{I_{sit}}{A_{st}} \right)^{1-\phi_s} = \sum_{\tilde{t}=t+1}^{+\infty} (1-\delta_s)^{\tilde{t}-(t+1)} \left(\prod_{k=t}^{\tilde{t}-1} \frac{1}{1+r_k} \right) \frac{\alpha^{\frac{1+\alpha}{1-\alpha}} (1-\alpha) L_{\tilde{t}}}{(1+\tau_{s\tilde{t}})^{\frac{\alpha}{1-\alpha}}}.$$

This expression shows that expectations of high interest rates and low aggregate demand in the future depress current investment. However, these effects are weaker for investment in the dirty sector. The reason is that during the energy transition the tax on dirty goods rises over time, which effectively reduces the horizon of dirty investments. As we will discuss in the main text, this the reason why clean investments are particularly sensitive to monetary policy in our model.

Figure 11 shows the response of the economy to the introduction of green regulation, when technological change in both sectors is endogenous. We are now considering a more realistic gradual tightening of the supply constraint on dirty goods, which is designed to cut the production of dirty goods by 50%, roughly over a twenty years horizon.

The model allows for different scenarios concerning the impact of green regulation on long-run productivity growth. For concreteness, we calibrate the model so that green regulations do not affect productivity growth in steady state, which is the baseline case considered by Pisani-Ferry and Mahfouz (2023). This means that green technologies are productive enough so that the phasing out of dirty technologies does not affect long-run growth, but they are not sufficiently productive to fully compensate for the productivity losses experienced by the economy during the transition.

We again compare two extreme scenarios: a central bank that targets full employment (solid blue lines), against a hawkish monetary policy of strict inflation targeting (dashed red lines). Focusing on these two benchmarks highlights the green dilemma that monetary authorities are going to face during the energy transition.

The new result here is that the imposition of supply constraints on dirty goods induces a reallocation of investment toward clean technologies. Intuitively, firms in the dirty sector anticipate that they will be severely constrained by green regulations in the future, which leads to a sharp drop in dirty investments. The opposite happens to firms producing clean goods, which ramp investments up. This sectoral reallocation of investment mitigates the productivity losses associated with the phasing out of polluting production techniques.

Moreover, our model suggests that the monetary policy stance adopted by the central bank may have important implications for the path of sectoral investments and innovation. In particular, a hawkish monetary stance reduces the incentives to invest in green technologies, slowing down productivity growth in the clean sector, while not affecting much investment in the dirty sector. This result rationalizes the empirical finding that green investments are more sensitive to financial conditions than dirty ones. The reason is that firms in clean sectors put more weight on the future additional profits coming from investing in innovation today, while green regulations shortens the horizon of firms in the dirty sectors. Moreover, a macroeconomic environment characterized by strong aggregate

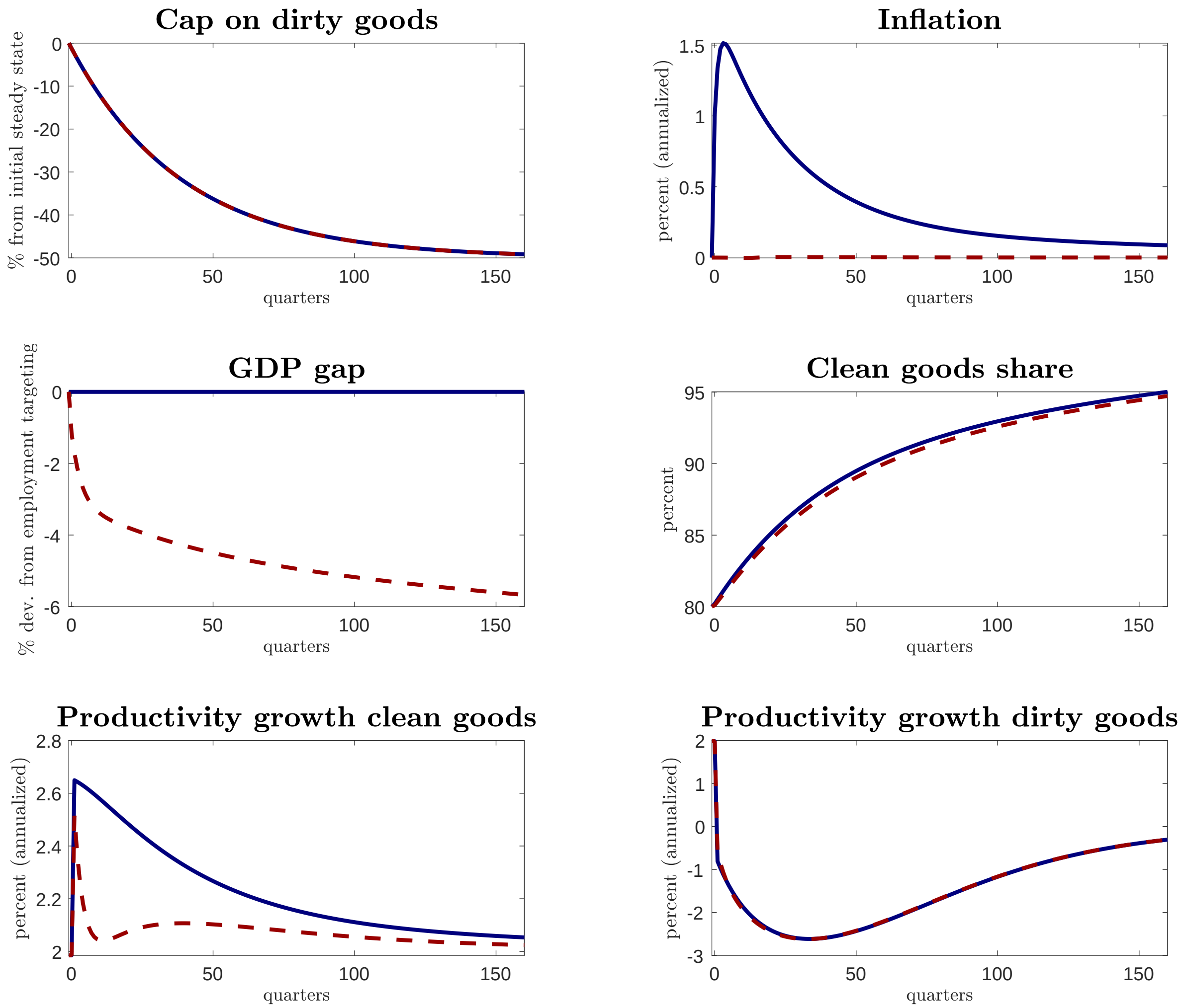

Figure 11: Transition toward a clean economy. Solid lines: employment targeting. Dashed lines: inflation targeting.

demand favors green investments, because green regulations prevent polluting firms from expanding production when demand gets stronger.

The implication is that allowing a temporary rise in inflation during the energy transition fosters the reallocation from dirty to clean investments. A narrow focus on containing inflation, instead, discourages green investments and amplifies the output and productivity losses associated with the phasing out of dirty goods. In fact, as Figure 11 suggests, a tight monetary policy that fully counteracts the inflationary pressures associated with the energy transition may result in very persistent output and productivity losses, due to its negative impact on the development and adoption of green technologies.[20]

[20] To be more precise, since in our model productivity growth is fully endogenous, our framework implies

Endogenous technological change thus adds a new dimension to the green dilemma faced by central banks. Letting inflation rise during the green transition, albeit temporarily, comes at the risk of a dis-anchoring of inflation expectations. But a narrow focus on containing inflation during the transition exacerbates the economic costs of transitioning away from polluting technologies, by discouraging green investments and slowing down the green transition.

Before moving on, let us spend a few words on the impact of the green transition on equilibrium interest rates predicted by our model. This is shaped by three effects. On the one hand, a rise in green investments is akin to a positive demand shock, pushing real interest rates up. Moreover, high inflation during the green transition calls for a higher nominal interest rate.

On the other hand, replacing dirty technologies with clean ones is likely to lead to productivity losses. As long as households internalize the negative impact of lower productivity on their long-run income, this effect should push demand and interest rates down. However, the strength of this effect depends on households' ability to forecast the, potentially far-distant, future and this might be more limited than what assumed in standard models. Moreover, this effect is muted if households are constrained in their access to credit. These observations imply that forecasting the impact of the green transition on equilibrium interest rates is subject to huge uncertainty.

4.3. An intertemporal inflation trade-off

To better understand the effects of monetary policy when technological change is endogenous, Figure 12 shows the impact of a contractionary monetary policy shock in our baseline economy with endogenous growth (blue solid lines), relative to a counterfactual economy in which investments in both sectors do not react to the monetary shock (red dashed lines).[21]

Let us first describe the counterfactual economy with fixed investments. The monetary contraction increases the real interest rate, depressing aggregate demand, GDP and em-

that a temporary drop in investment generates permanent GDP losses. Had we adopted a semi-endogenous growth approach, these losses would be temporary, but still extremely persistent.

[21]Figure 12 shows the impulse responses to a monetary policy shock around an economy undergoing the energy transition under full employment. The energy transition is triggered by a permanent tightening in the supply constraint on dirty goods, similar to the one shown in Figure 10, while the monetary shock that we consider is an unexpected temporary rise in the real interest rate above its path under full employment.

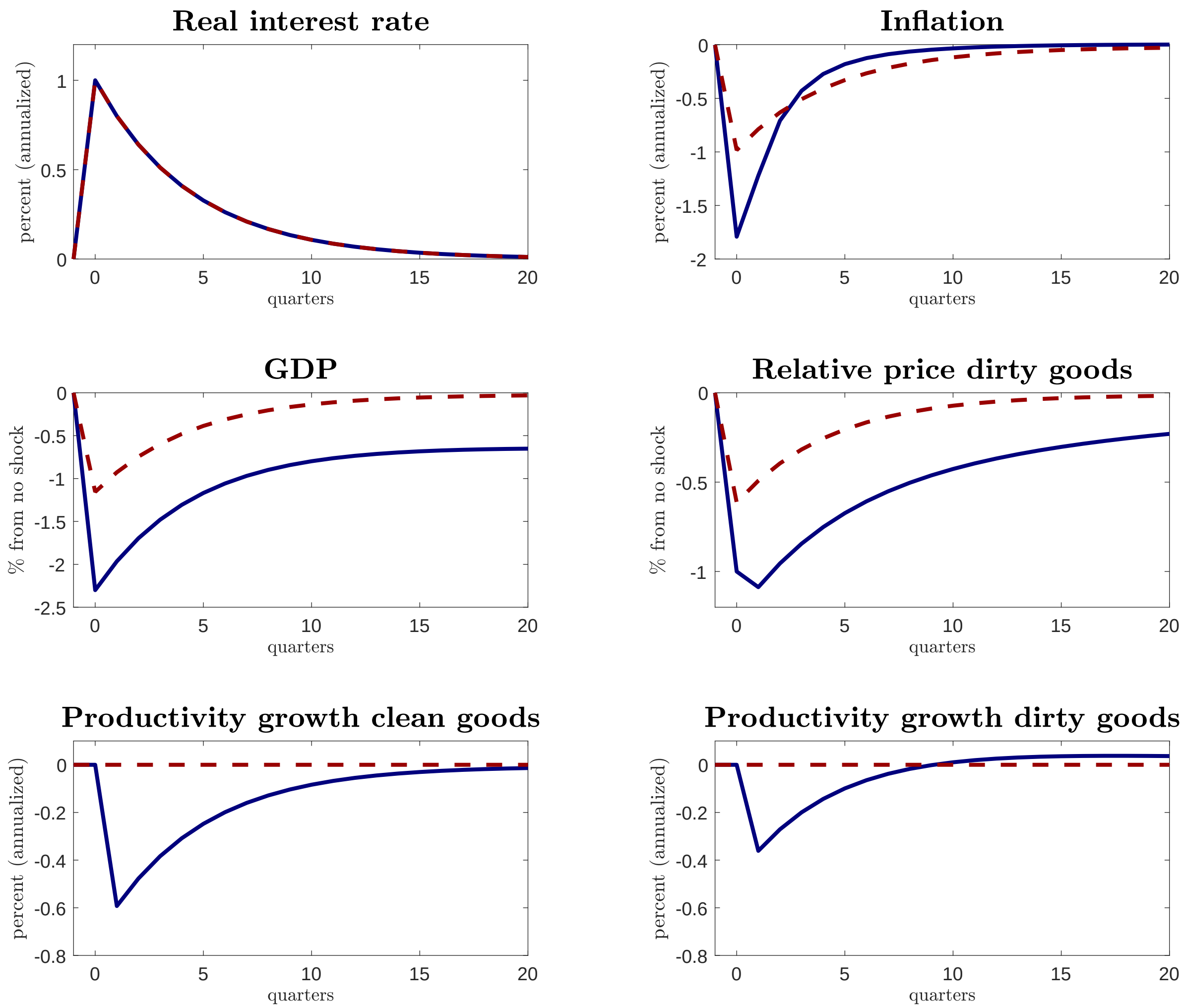

Figure 12: Impact of a monetary contraction. Solid lines: baseline economy. Dashed lines: counterfactual with no impact of monetary policy on investment.

ployment. Due to the standard Phillips curve logic, lower employment reduces nominal wage growth, and so price inflation. Moreover, given that the dirty sector is constrained by the supply cap, lower demand also translates into a decrease in the relative price of the dirty goods. This additional channel contributes to further reduce the overall inflation rate. Finally, notice that the negative effect of the monetary contraction is fully transitory, as GDP quickly bounces back to its pre-shock trend.

Now consider our baseline model, in which clean and dirty investments are allowed to react to the monetary shock. As it is intuitive, a monetary contraction - by increasing the cost of credit, as well as depressing aggregate demand and profits - leads to a drop in investment. However, the effect is much stronger for green investments, which explains why productivity growth falls by more in the clean sector, compared to the dirty one. The reason, as we argued above, is that green regulation reduces the horizon of firms producing dirty goods, making their investment plans relatively insensitive to monetary shocks. Moreover, lower investment and productivity growth imply that the monetary shock has a persistent - in fact, in our fully endogenous growth model permanent - impact on GDP. Hence, the investment channel propagates in time the depressive effect on output of tight monetary policy.

What about inflation? Initially, the monetary contraction has a bigger impact on inflation when investment is endogenous. This is to be expected, since lower demand for investment depresses output and employment, contributing on impact to the inflation drop, due to the standard Phillips curve logic. More interestingly, in the medium run inflation is higher when investment is endogenous. The cause is that lower investment depresses productivity growth and sustains firms' marginal costs over the medium run, creating persistent inflationary pressures. In a sense, the central bank is facing an intertemporal inflation trade. A monetary tightening lowers economic activity and inflation in the present, but it also leads to lower productivity and higher inflation in the future. This means that, due to its adverse effect on productivity growth, a tight monetary policy is less effective in disinflating the economy in the medium term.

4.4. Subsidies to green investments help macroeconomic stabilization

We have emphasized that some degree of inflation during the green transition helps reallocating resources from dirty to clean technologies. A strict focus on containing inflation, on the other hand, may lead to large losses in economic activity, and a slower transition to green technologies. We now argue that policy interventions aiming at sustaining green investments, such as fiscal or monetary subsidies, may help to reconcile a smooth energy transition with low and stable inflation.[22]

We make this point with the help of Figure 13, which shows the effects of a gradual tightening of the supply constraint on dirty goods under three possible scenarios: full employment targeting (solid blue lines), strict inflation targeting (red dashed lines), and a policy of strict inflation targeting coupled with a subsidy to clean investments , designed to replicate the pattern of technological growth in the clean sector that would arise under

[22]See Jourdan et al. (2024) and Monnet et al. (2023) for similar perspectives.

full employment (dash-dotted green lines).[23]

There are two results worth highlighting. First, subsidizing green investments reconciles low inflation with a fast energy transition. This happens because the subsidies are designed to insulate investments in clean technologies from the tight monetary policy needed to keep inflation always on target during the phasing out of dirty goods. Second, the output losses needed to maintain inflation on target are now much smaller and transitory. In part this can be explained by the fact that the subsidies prevent contractionary monetary interventions from negatively affecting productivity and output over the medium run. In addition, fast productivity growth in the green sector acts as a disinflationary force, reducing the need for the central bank to implement a tight monetary policy to maintain inflation on target. In sum, policy interventions fostering green investments may be an important complement to traditional monetary policy to control inflation during the green transition.

Let us emphasize that these subsidies to clean investments may be interpreted literally as fiscal subsidies. But they can also capture policy interventions, perhaps implemented by central banks, that facilitate access to credit for firms investing in green technologies. Our analysis suggests that these interventions may play a key role in containing inflation during the transition toward a clean economy.

Summing up, we show that the green transition may push our economies in a regime of high inflation volatility, in which central banks will have to trade-off controlling inflation against sustaining economic activity. In this regime, some temporary rise in inflation is the natural symptom of the structural change process associated with the green transition, in particular with the required adjustment in relative prices. Coordination between monetary, fiscal and energy policies is going to be crucial to maintain inflation under control. In particular, fiscal and credit policies that subsidize green investments may be key to reconcile low inflation, high economic activity and an effective green transition.

Chapter 5. The state of the literature

We conclude this report with an overview of the literature on monetary policy and the green transition. Although still in its infancy, this literature is already so vast that it is not possible to survey it all, and we will thus need to be selective. Moreover, this

[23] We assume that these subsidies are financed with lump-sum taxes. Of course, matters become more complicated if subsidies have to be financed with distortionary taxes, especially when public debt is high (see Fornaro and Wolf (2025)).

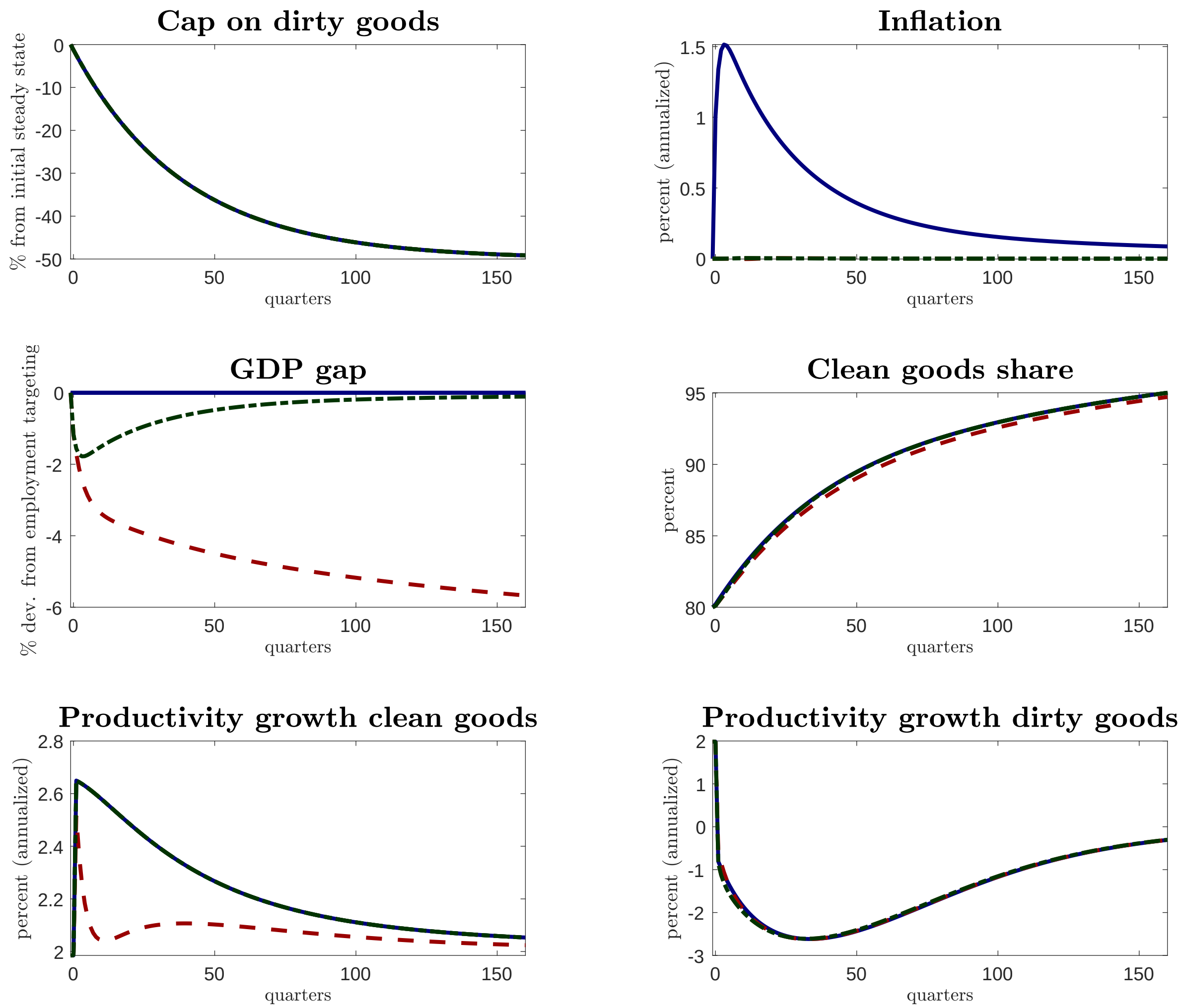

Figure 13: Transition toward a clean economy with subsidies to green investments. Solid lines: employment targeting. Dashed lines: inflation targeting. Dash-dotted lines: inflation targeting with subsidy to clean investment.

literature is characterized by lack of consensus on several fundamental issues. Therefore, we will highlight some areas in which we believe that future research could be particularly promising.

5.1 Inflation during the green transition

A quickly-expanding literature studies the inflationary consequences of the green transition, typically modeled as a gradual rise in carbon taxes. The key insight of this literature is that increases in carbon taxes, by pushing up the price of carbon-intensive goods, act as negative supply shocks causing inflationary pressures.[24] Where this literature diverges is on the quantitative importance of this effect, and on the trade-offs entailed for monetary authorities.

A good example of this literature is Del Negro et al. (2023). They consider a medium scale New Keynesian model featuring multiple sectors, carefully model network interactions and heterogeneity in price rigidities among sectors, and study the impact of a progressive increase in carbon taxes decreasing emissions by 40%. In their model, if the central bank chooses to look through this shock and to stabilize output, the green transition causes a sharp rise in inflation. This burst of inflation is, however, short-lived, lasting for about a year. This result may be driven by the particular path of the carbon tax chosen, which is quite front-loaded.

Sahuc et al. (2025), instead, argue that the green transition is going to generate sizable and persistent inflationary pressures, lasting for several decades. They reach this conclusion using a very rich New-Keynesian model, combining productivity losses from climate change with carbon taxes implemented to foster the green transition, estimated using Bayesian techniques. Dietrich et al. (2025), who consider a New Keynesian model with brown and green durable goods, find that the green transition is going to be associated with a persistent, but quantitatively small, rise in inflation.

These three examples illustrate how different modeling assumptions can lead to disparate conclusions on how big the impact of the green transition on inflation is going to be. Tackling two issues may help to make progress on this front. First, most of the literature ignores possible non-linearities in firms' price setting. But recent evidence suggests that supply constraints cause firms to adopt non-linear pricing strategies (Boehm and Pandalai-Nayar, 2022). As we discussed in Chapter 4, this effect is going to be particularly salient during the green transition, because green regulations effectively tighten supply constraints in high-emission sectors. Hence, to evaluate quantitatively the impact of the green transition on average inflation and its volatility, future research should take this effect into account.

Second, a careful modeling of the wage setting process is crucial. At least in the first stages of the green transition, regulatory caps on carbon emissions are going to have effects similar to a negative supply shock, putting downward pressure on real wages. Empirically,

[24] To clarify, doing nothing to fight climate change may lead to even higher inflationary pressures, insofar as high temperatures disrupt economic activity. Baleyte et al. (2024) provide empirical evidence in favor of this view.

downward nominal wage rigidities are widespread (Hazell and Taska, 2020), implying that higher inflation is needed to achieve a drop in real wages. Missing this effect would bias downward estimates of the impact of the green transition of inflation. Moreover, a protracted period of high inflation may lead to the introduction of indexation clauses in wage contracts, similar to what happened during the 1970s (Galí and Gambetti, 2019). This effect would amplify and prolong the inflationary pressures triggered by the green transition.

The importance of carefully modeling the wage setting process becomes apparent also when thinking about the optimal monetary policy response to the green transition. Nakov and Thomas (2023), for example, propose a framework in which carbon taxes pose no challenges for monetary authorities, which can both attain stable inflation and the optimal level of output during the green transition. However, this result is due to the fact that their model abstracts from nominal wage rigidities, so that the inflationary pressures coming from the green transition are compensated by a deep fall in nominal wages. This is shown formally by Olovsson and Vestin (2023), who argue that the optimal monetary policy during the green transition will have to strike a balance between stabilizing inflation and economic activity, precisely because nominal wages are rigid.

5.2 Monetary policy and green investments

The green transition is going to require a large scaling up of investments in clean technologies (Pisani-Ferry and Mahfouz, 2023; Draghi, 2024). This observation has sparked a lot of research studying the macroeconomic impact of green investment booms (Campiglio et al., 2022; Mehrotra, 2024). From a monetary policy perspective, there are two key issues at stake.

The first one is about the impact on the equilibrium, or natural, interest rates. On the one hand, a rise in green investments is akin to a positive demand shock, pushing interest rates up. On the other hand, replacing dirty technologies with clean ones is likely to lead to productivity losses Pisani-Ferry and Mahfouz (2023). As long as households internalize the negative impact of lower productivity on their long-run income, this effect should push demand and interest rates down (see Mehrotra (2024), as well as our own analysis in Chapter 4). However, the strength of this effect depends on households' ability to forecast the, potentially far-distant, future (Ferrari and Nispi Landi, 2024). Moreover, this effect is muted if households are constrained in their access to credit. These observations imply that forecasting the impact of the green transition on equilibrium interest rates is subject to huge uncertainty.

The second is about the effect of monetary policy on green investments. As we argued throughout this report, both theoretical reasoning and preliminary empirical evidence suggest that monetary contractions depress green investments. Estimating the magnitude of this effect, however, requires overcoming several empirical challenges.

The main challenge comes from data limitation. Existing data on green investments are scarce. Moreover, due to the recent diffusion of clean technologies, they are limited in terms of time span. For this reason, most econometric analyses use stock prices or patents as proxies for green investments.

For instance, Bauer et al. (2024) show that monetary contractions have a particularly negative effect on the market value of polluting firms. This observation lead them to conclude that green investments are not strongly affected by monetary policy. But this argument is problematic, since polluting firms are also big investors in green technologies (see Chapter 3).[25] Döttling and Lam (2024), which also document a negative impact of monetary contractions on the stock prices of high-emission firms, find that monetary tightenings hinder polluting firms' investments to abate emissions. This result is consistent with the notion that a tight monetary stance discourages green investments. This debate points toward the difficulties in separating green and brown investments using stock prices.

A similar debate surrounds the relationship between credit frictions and green investments. Aghion et al. (2024) argue that green innovations are mainly performed by young firms, who are more likely to be credit constrained. Lanteri and Rampini (2023), on the other hand, observe that the majority of investments in green physical capital in the maritime transport sector is performed by large firms, who are unlikely to be severely affected by credit frictions. Insofar as monetary policy can mitigate credit market frictions, clarifying the impact of financial market imperfections on green investments is needed to understand the impact of monetary policy on the diffusion of clean technologies.[26]

5.3 International considerations

Most of the literature on monetary policy and the green transition takes a closed economy perspective. But there are a few important issues that call for an open-economy approach.

[25] In fact, De Haas and Popov (2023) find that deeper stock markets facilitate green innovations in carbon-intensive sectors.

[26] See also Kaldorf and Giovanardi (2023) and Kaldorf and Shi (2024).

First, open-economy considerations are important to understand the macroeconomics of the green transition in developing countries. Foreign capital inflows, in fact, may play a key role in financing the green transition in emerging economies. But high foreign indebtedness may come at the expense of a rise in risk premia, making it harder to firms to finance the investments needed to adopt green technologies. Airaudo et al. (2022) provide a first analysis of these issues, but more research in this area would be welcome.

But an open economy approach may be useful for advanced economies too. For instance, Berthold et al. (2023) find that tightenings in the carbon emissions allowed by the EU ETS have stronger negative macroeconomic effects in high-emission countries. Since most of these countries are part of the euro area, this finding suggests that during the green transition the ECB will have to deal with an asymmetric macroeconomic shock. Therefore, studying the impact of environmental regulations in monetary unions seem to be a natural next step for the literature on monetary policy and the green transition. In doing so, it will be important to take into account the fact that capital flows may amplify the structural asymmetries characterizing the euro area (Fornaro, 2022; Fornaro and Grosse-Steffen, 2024).

Another important issue concerns the usefulness of international monetary cooperation during the green transition. Replacing dirty with clean technologies is likely to lead to a temporary scarcity of tradable manufactured goods. Fornaro and Romei (2022) argue that, during episodes of global scarcity of tradable goods, lack of international cooperation may lead central banks to adopt an excessively contractionary monetary stance. If so, international monetary cooperation may be useful to smooth the macroeconomic costs of the green transition.

Appendix

A Full description of the model

In this appendix, we provide a full description of our theoretical framework, as well as of the calibration strategy used to construct the figures described in Chapter 4.

A.1 Model with exogenous growth

Consider an infinite horizon closed economy in discrete time, indexed by $t = 0, 1, 2, ...$ For simplicity, we focus on a perfect foresight economy.

A.1.1 Households

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

$$\sum_{t=0}^{\infty} \beta^t \left(\log C_t + \nu\left(S_t\right)\right), \tag{A.1}$$

where $0 < \beta < 1$ is the subjective discount factor and C_t denotes consumption of a homogenous final good. The function $\nu(\cdot)$ captures the impact on utility of the quality of the environment S_t. The households' budget constraint is

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

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. T_t captures lump-sum transfers received from the government.

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

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

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

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

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.

A.1.2 Final good production

The final good is produced by competitive firms using labor and a continuum of measure two of intermediate inputs $x_{j,t}$, indexed by $j \in [0,2]$. Denoting by Y_t the output of the final good, the production function is

$$Y_t = L_t^{1-\alpha} \int_0^2 A_j^{1-\alpha} x_{j,t}^{\alpha} dj, \tag{A.5}$$

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

$$P_t(1-\alpha)L_t^{-\alpha} \int_0^2 A_j^{1-\alpha} x_{j,t}^{\alpha} dj = W_t, \tag{A.6}$$

and

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

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

$$P_t = \left(\frac{W_t}{\int_0^2 \frac{A_j}{P_{j,t}^{\frac{\alpha}{1-\alpha}}} dj}\right)^{1-\alpha} \frac{1}{(1-\alpha)^{1-\alpha}\alpha^{\alpha}}. \tag{A.8}$$

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.

A.1.3 Intermediate goods production and profits

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 1 of clean goods with productivity $A_{C,t}$ and a measure 1 of dirty goods with productivity $A_{D,t}$. For now, we will assume that the path of productivities is exogenously given.

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

$$\frac{Y_{C,t}}{Y_{C,t} + Y_{D,t}}, \tag{A.9}$$

where we defined $Y_s = \int_0^1 A_s^{1-\alpha} x_s^{\alpha} ds$ for $s = C, D$. We 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. However, firms producing dirty goods have to pay a tax τ_t for each unit manufactured. As we will explain below, the tax τ_t captures environmental regulations.

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

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

Equations $(A.7)$ and $(A.10)$ then imply that

$$x_{C,t} = \alpha^{\frac{2}{1-\alpha}} A_{C,t} L_t, \tag{A.11}$$

so that firms producing clean goods earn (real) profits

$$\left(\frac{P_{C,t}}{P_t} - 1\right) x_{C,t} = \frac{1-\alpha}{\alpha} \alpha^{\frac{2}{1-\alpha}} A_{C,t} L_t \equiv \varpi A_{C,t} L_t. \tag{A.12}$$

Similarly, dirty intermediate goods are sold at price

$$P_{D,t} = \frac{P_t(1+\tau_t)}{\alpha}. \tag{A.13}$$

Hence, a higher tax increases the relative price of dirty goods. Equations ($A.7$) and ($A.13$) then imply that

$$x_{D,t} = \left(\frac{\alpha^2}{1+\tau_t}\right)^{\frac{1}{1-\alpha}} A_{D,t} L_t. \tag{A.14}$$

Naturally, a higher production tax reduces the supply of dirty goods. Moreover, the profits earned by firms producing dirty goods are equal to

$$\left(\frac{P_{D,t}}{P_t} - (1+\tau_t)\right) x_{D,t} = \frac{\varpi A_{D,t} L_t}{(1+\tau_t)^{\frac{\alpha}{1-\alpha}}}. \tag{A.15}$$

So a higher tax reduces profits in the dirty sector, because it lowers the demand for dirty inputs from firms producing the final good.

A.1.4 Environmental regulation

As in Acemoglu et al. (2012), the quality of the environment evolves according to

$$S_t = S_{t-1} - \xi Y_{D,t} \tag{A.16}$$

so that a higher production of dirty goods damages the environment. We frame environmental regulation as a target path for the production of dirty goods. In particular, we assume that the government imposes the constraint

$$Y_{D,t} \leq \bar{Y}_{D,t}, \tag{A.17}$$

where $\bar{Y}_{D,t}$ captures a cap on total emissions. This cap is implemented through the tax schedule

$$\tau_t = \begin{cases} 0 & \text{if } A_{D,t} L_t^{\alpha} \alpha^{\frac{2\alpha}{1-\alpha}} \leq \bar{Y}_{D,t} \\ \left(\frac{A_{D,t} L_t^{\alpha}}{\bar{Y}_{D,t}}\right)^{\frac{1-\alpha}{\alpha}} \alpha^2 - 1 & \text{if } A_{D,t} L_t^{\alpha} \alpha^{\frac{2\alpha}{1-\alpha}} > \bar{Y}_{D,t}. \end{cases} \tag{A.18}$$

In words, the tax is positive if under laissez faire production of dirty goods would exceed $\bar{Y}_{D,t}$. Moreover, the environmental tax is (weakly) increasing in labor L_t, which can be taken as a proxy of aggregate demand. The reason is that higher aggregate demand increases demand for dirty intermediates by the final sector. To maintain dirty goods production constant, higher aggregate demand has to be compensated by a higher tax. A similar logic explains why the tax is increasing in the productivity of dirty intermediates $A_{D,t}$. All the revenue from the tax is rebated to households through lump sum transfers.

This environmental regulation resembles the EU Emissions Trading System, in which the regulator sets a goal for total carbon emissions, and the price that firms have to pay to use dirty technologies adjusts to guarantee that this goal is reached. More broadly, it can be taken as a reduced form way of capturing a host of interventions that governments carry out to hit some emission reduction targets. Throughout, we take the path of target emissions $\bar{Y}_{D,t}$ as given, and focus on how this environmental regulation affects monetary policy.

An important feature of our model is that restricting the supply of dirty goods leads to productivity losses (of course, absent green regulation climate change is likely to trigger even larger productivity losses, see for instance Bilal and Känzig (2024)). To see this point, consider that

$$Y_t = L_t \alpha^{\frac{2\alpha}{1-\alpha}} \left(A_{C,t} + \frac{A_{D,t}}{(1+\tau_t)^{\frac{\alpha}{1-\alpha}}} \right). \tag{A.19}$$

So gross output is decreasing in the tax, because taxing dirty goods distorts the demand for intermediate goods by firms in the final sector. We can also express gross output as a function of the cap on emissions

$$Y_t = L_t \alpha^{\frac{2\alpha}{1-\alpha}} \left(A_{C,t} + \min\left(A_{D,t}, \frac{\bar{Y}_{D,t}}{\alpha^{\frac{2\alpha}{1-\alpha}} L_t^{\alpha}} \right) \right). \tag{A.20}$$

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.

A.1.5 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 (A.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 $\bar{L}$.

A.1.6 Aggregation and market clearing

Market clearing for the final good implies

$$Y_t - \int_0^2 x_{j,t} dj = C_t. \tag{A.21}$$

The left-hand side of this expression is the GDP of the economy, while the right-hand side captures the fact that in the baseline model all the GDP is consumed. Using equations $(A.14)$ and $(A.20)$ we can write GDP as

$$GDP_t = Y_t - \int_0^2 x_{j,t} dj = \begin{cases} \Psi(A_{C,t} + A_{D,t})L_t & \text{if } A_{D,t} L_t^{\alpha} \alpha^{\frac{2\alpha}{1-\alpha}} \leq \bar{Y}_{D,t} \\ \Psi A_{C,t} L_t + \left(\bar{Y}_{D,t} L_t^{1-\alpha} - \left(\frac{\bar{Y}_{D,t}}{A_{D,t}^{1-\alpha}} \right)^{\frac{1}{\alpha}} \right) & \text{if } A_{D,t} L_t^{\alpha} \alpha^{\frac{2\alpha}{1-\alpha}} > \bar{Y}_{D,t}. \end{cases} \tag{A.22}$$

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.

A.1.7 The Phillips Curve

We now derive 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. Inflation can then be written as

$$1 + \pi_t = \frac{W_t}{W_{t-1}} \frac{A_{C,t-1} + A_{D,t-1} \left(\alpha p_{D,t-1} \right)^{-\frac{\alpha}{1-\alpha}}}{A_{C,t} + A_{D,t} \left(\alpha p_{D,t} \right)^{-\frac{\alpha}{1-\alpha}}}, \tag{A.23}$$

with the relative price of dirty intermediates defined by

$$p_{D,t} = \frac{1}{\alpha} \max \left(1, \alpha^2 \left(\frac{L_t^{\alpha} A_{D,t}}{\bar{Y}_{D,t}} \right)^{\frac{1-\alpha}{\alpha}} \right). \tag{A.24}$$

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.[27] Combining these two expressions gives the non-linear Phillips curve described in Chapter 4.1.

A.1.8 Equilibrium and calibration

An equilibrium for the exogenous productivity growth version of our model is defined as a set of sequences $\{GDP_t, L_t, C_t, W_t/W_{t-1}, \pi_t, \tau_t, p_{D,t}\}_{t=0}^{+\infty}$ satisfying (A.3), (A.4), (A.18), (A.21), (A.22), (A.23) and (A.24) for all $t \geq 0$, given paths for environmental regulation $\{\bar{Y}_{D,t}\}_{t=0}^{+\infty}$, monetary policy $\{r_t\}_{t=0}^{+\infty}$, and productivities $\{A_{C,t}, A_{D,t}\}_{t=0}^{+\infty}$, and the initial condition π_{-1}.

While performing a full-blown quantitative analysis is not our objective, to construct the figures in the main text we try to pick reasonable values for the parameters. We calibrate the model at quarterly frequency. We set $\alpha = .5$, which corresponds to an elasticity among intermediate inputs of 2. We set $A_{c,0}/A_{d,0}$ so that in the initial steady state the share of dirty goods in total intermediates is 20%, roughly in line with the share of GDP accounted by the high carbon emissions sectors covered by the EU Emission Trading System. 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 assume that productivity in both sectors grows at an annual rate of 2%, and set β so that the annualized real interest rate in steady state is 4.5%. Finally, we assume that in the initial steady state inflation is on target ($\pi_{-1} = 0$), the economy operates at full employment ($L_{-1} = \bar{L}$), and the cap on

[27] More formally, using $(A.5)$ and $(A.6)$ gives the expression for price inflation

$$1 + \pi_t = \frac{W_t}{W_{t-1}} \frac{L_t}{Y_t} \frac{Y_{t-1}}{L_{t-1}}, \tag{A.25}$$

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.

production of dirty goods is marginally binding ($\bar{Y}_{D,-1} = A_{D,-1}\bar{L}^{\alpha}\alpha^{\frac{2\alpha}{1-\alpha}}$).

A.2 Endogenous technological change

To endogenize productivity growth, we assume that firm producing intermediate goods can invest to increase their productivity. In particular, if firm i invests $I_{s,i,t}$ units of the final good in period t, its future productivity is equal to

$$A_{s,i,t+1} = (1-\delta_s)A_{s,i,t} + \chi I_{s,i,t}^{\phi_s} A_{s,t}^{1-\phi_s}, \tag{A.26}$$

where δ_s and ϕ_s denote respectively the depreciation rate and the strength of diminishing returns from investment in sector s, while χ pins down the productivity of investment. We introduce intra-sectoral knowledge spillovers by assuming that the productivity of investment in sector s is increasing in the average level of productivity in the same sector $A_{s,t}$. The strength of these spillovers is set equal to $1-\phi_s$, to ensure balanced growth in steady state.

Each firm i in sector s chooses investment to maximize the discounted stream of future profits

$$\max_{I_{s,i,t}, A_{s,i,t+1}} \sum_{\tilde{t}=t}^{+\infty} \left(\prod_{k=t}^{\tilde{t}-1} \frac{1}{1+r_k} \right) \eta^{\tilde{t}-t} \left(\frac{\varpi L_{\tilde{t}} A_{s,i,\tilde{t}}}{(1+\tau_{s\tilde{t}})^{\frac{\alpha}{1-\alpha}}} - \eta I_{s,i,\tilde{t}} \right), \tag{A.27}$$

where $\tau_{C,\tilde{t}} = 0$ for all $\tilde{t}$ and $\tau_{D,\tilde{t}}$ is given by (A.18). Firms discount profits using the real interest rate r_t, and, following Benigno and Fornaro (2018), we assume that each period a firm has a probability $1-\eta$ of dying before the investment decision is made. In this case, its product is inherited by a new-born firm.

The optimality condition for investment is

$$\frac{1}{\chi\phi_s}\left(\frac{I_{sit}}{A_{st}}\right)^{1-\phi_s} = \sum_{\tilde{t}=t+1}^{+\infty} \left(\eta(1-\delta_s)\right)^{\tilde{t}-(t+1)} \left(\prod_{k=t}^{\tilde{t}-1} \frac{1}{1+r_k} \right) \frac{\varpi L_{\tilde{t}}}{(1+\tau_{s\tilde{t}})^{\frac{\alpha}{1-\alpha}}}. \tag{A.28}$$

This expression can be used to understand the impact of green regulations and monetary policy on investment. As it is natural, a more stringent green regulation - captured by a higher tax on dirty goods - reduces the incentive to invest for firms' in the dirty sector. The reason being that a higher tax on dirty goods lowers the profits of firms operating polluting technologies.

What about monetary policy? First, monetary policy has a direct impact on investment, because it determines the stream of real interest rates used by firms to discount future profits. As it is intuitive, a higher interest rate induces firms to decrease their investment in new 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.

Interestingly, the model suggests that the interaction between green regulation and monetary policy implies that clean investments react more to monetary interventions compared to dirty ones. First, dirty firms have a shorter time horizon, because during the energy transition the production cap on dirty goods is expected to fall over time (equivalently, the tax on dirty goods is expected to rise over time). This means that investment decisions by dirty firms are less sensitive to interest rates movements.

Second, investments in dirty technologies are not much affected by variations in aggregate demand. The reason is that environmental regulation limits the ability of firms producing dirty goods to expand their production when aggregate demand increases. For this reason, green firms capture most of the increase in profits derived from an increase in aggregate demand. As a result, clean investments are more sensitive than dirty ones to variations in demand induced by monetary policy interventions. These two forces explain why a monetary tightening decreases the share of green investments in total investment spending.

Finally, with endogenous investment, the market clearing condition becomes

$$GDP_t = C_t + I_{D,t} + I_{C,t}. \tag{A.29}$$

A.2.1 Equilibrium and calibration

An equilibrium for the exogenous productivity growth version of our model is defined as a set of sequences $\{GDP_t, L_t, C_t, W_t/W_{t-1}, \pi_t, \tau_t, p_{D,t}, I_{D,t}, I_{C,t}, A_{D,t+1}, A_{C,t+1}\}_{t=0}^{+\infty}$ satisfying

(A.3), (A.4), (A.18), (A.29), (A.22), (A.23), (A.24), (A.26) and (A.28) for all $t \geq 0$, given paths for environmental regulation $\{\bar{Y}_{D,t}\}_{t=0}^{+\infty}$ and monetary policy $\{r_t\}_{t=0}^{+\infty}$, and the initial conditions $A_{C,0}$, $A_{D,0}$, π_{-1}.

For simplicity, we assume that the parameters determining the investment functions are identical across the two sectors, so that $\delta_D = \delta_C = \delta$ and $\phi_D = \phi_C = \phi$. We set χ so that productivity growth in steady state is equal to 2% per year. We set $\delta = 0.08/4$, to match a yearly depreciation rate of 8%. We then set η to ensure that in steady state investment is equal to 10% of GDP, roughly in line with the business investment-to-GDP ratio in the EU. Given the lack of consensus in the literature it is hard to calibrate ϕ, the parameter that governs the curvature of the innovation investment function. We set it equal to $\phi = 0.8$, to roughly match the fact that investment responds three times as much as output to monetary shocks (Christiano et al., 2005).

B Data description and data transformation for the VAR analysis

- *Gas price*:
  - Definition and source: TTF spot price (monthly close), Refinitiv (TRNLT-TFD1)
  - Transformation: log of the ratio between gas prices and HICP multiplied by 100
- *Oil price*:
  - Definition and source: Brent converted to euros using time series of exchange rates, FRED (DCOILBRENTEU and DEXUSEU)
  - Transformation: log of the ratio between oil prices and HICP times 100
- *Headline Inflation*:
  - Definition and source: Harmonized Inflation Consumption Prices, Eurostat (000000)
  - Treansformation: log
- *Interest rate*:

- Definition and sources: short term money market rate 12 months, Eurostat (IRT M12)
- Transformation: log divided by 100

- *Industrial production*:
  - Definition and source: Industry except construction, Eurostat
  - Transformation: log
- *Unemployment rate*:
  - Definition and source: Eurostat (PC-ACT)
  - Transformation: divided by 100
- *Real activity*:
  - Definition and source: from Kilian's website (IGREA)
  - Transformation: divided by 100
- *Gas production*:
  - Definition and source: IEA (not a free series)
  - Transformation: log
- *Gas Stocks*:
  - Definition and source: IEA (not a free series)
  - Transformation: log
- *Gas net imports*:
  - Definition and source: computed from bilateral imports and exports, IEA (not a free series)
  - Transformation: log

C Variable definitions - Local projection regressions

Firm level data

Definitions

- Investment rate is 4×100 times the ratio between capital expenditure during quarter t and net plant, property and equipment at beginning of quarter t.
- R&D intensity is 4×100 times the ratio between R&D expenditure during quarter t and Total assets at beginning of quarter t.

Transformations

Trimmed at top and bottom 1% by year; annualised units; missing observations within firm interpolated

Source

Compustat

Patent data

US Patent and Trademark Office

National Financial Conditions Index

Source : http://www.chicagofed.org/webpages/research/data/nfci/background.cfm. 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.

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