BIS Working Papers
No 1237

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Monetary and Economic Department

December 2024

JEL classification: O44, E31, E52, E58.

Keywords: Energy transition, innovation, inflation dynamics, monetary policy.

ISSN 1020-0959 (print)
ISSN 1682-7678 (online)

The Macroeconomics of Green Transitions[*]

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This Draft: November 2024
First Draft: October 2024

Abstract

The paper investigates the macroeconomics of an energy transition – a shift from brown to green energy production through carbon taxation. Using a medium-scale DSGE model with energy production sectors and endogenous innovation in the green energy sector, we show that an energy transition – initiated through a brown energy tax – resembles a large supply side shock, causing a surge in inflation and energy prices and a decline in consumption. Innovation increases the efficiency of green energy production and drives energy prices down in the medium run. We document that monetary policy plays a critical role for the dynamics and pace of the transition, even if the transition is not explicitly part of the policy rule. A monetary policy with less emphasis on inflation stabilization allows for temporarily higher inflation and energy prices, which boosts R&D and innovation, enhancing welfare and accelerating the transition.

Keywords: Energy transition, innovation, inflation dynamics, monetary policy
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[*] We thank Fiorella De Fiore, Emanuel Gasteiger, Ivan Jaccard, Daniel Rees and seminar participants at the Bank for International Settlements, the European System of Central Banks, the International Monetary Fund and London School of Economics for helpful comments. Gregor Boehl gratefully acknowledges financial support from the Deutsche Forschungsgemeinschaft (DFG) under project number 441540692, and Flora Budianto from the Austrian National Bank (OeNB) grants no. 18611 and 18915. Part of this project was initialized at the Bank for International Settlements.

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1 Introduction

One of the key challenges today is the transition from fossil fuels to renewable energy sources. In recent years, a growing global consensus has recognized the necessity of this shift to reduce carbon emissions and mitigate the risks of climate change. However, there remains a significant gap in understanding the economic consequences of this transition. How will it affect energy prices, inflation, and the broader economy? What role will economic policy, particularly monetary policy, play in shaping this process? In this paper, we explore these questions to shed light on the macroeconomic implications of the energy transition.

To this end, we develop a model framework to study the transition dynamics of an economy in both the short and medium run. Our model extends a medium-scale New Keynesian DSGE model by three components. First, we introduce energy as an additional production factor alongside labor and capital. Energy is modeled as a mix of brown (fossil) and green (renewable) sources, each produced in distinct energy sectors. Second, we incorporate endogenous technological progress in the green energy sector, allowing for innovation-driven efficiency gains. Finally, we assume the energy transition is triggered by the implementation of a permanent tax on brown energy. This tax creates a relative price distortion between brown and green energy production, encouraging a gradual shift in demand and resources from the brown sector to the green sector. Over time, this price distortion drives the economy toward a new steady state with a larger share of green energy in the overall energy mix.

In our framework, green innovation dynamics – based on Anzoategui et al. (2019) and Comin and Gertler (2006) – are endogenous, driven by larger incentives for research and development (R&D) when expected profits in green energy production are high. Innovation plays a central role in expanding the range of technologies available for green energy production. Each firm produces green energy using a specific technology, so as the number of technologies increases, the number of firms in the market rises accordingly. This increased competition among firms enhances resource allocation and boosts productivity in green energy production.

Throughout our analysis, we assume that the central bank operates with ”traditional” objectives, specifically focusing on stabilizing inflation and output in line with a standard Taylor-type monetary policy rule. Under this framework, the energy transition is not explicitly part of the central bank's policy rule. However, we find that the conduct of monetary policy –particularly in how effectively it stabilizes inflation in response to the brown energy tax– plays a crucial role in shaping the dynamics and pace of the transition process.

The energy transition process unfolds as follows: In the short run, the brown energy tax raises energy prices, which subsequently increases production costs and aggregate inflation. Due to price rigidities, the tax hike is gradually passed on to goods prices, causing inflation to rise over time. In response, the central bank raises nominal interest rates to control inflation, which leads to an increase in the real interest rate. A higher real interest rate dampens both consumption and investment. As a result, the effects of the brown energy tax closely resemble those of a large supply-side shock.

Additionally, energy production shifts from the brown to the green energy sector. Brown energy production declines immediately, while the use of green energy increases. Combined with higher energy prices, this shift boosts profits for green energy producers, amplifying incentives to invest in new green technologies. These incentives lead to an increase in R&D spending, which eventually raise productivity in the green energy sector. As green productivity growth accelerates, it reinforces the shift toward renewable energy in the medium term, further supporting the overall transition.

At this point, the conduct of monetary policy becomes crucial. In an economy where the central bank has a relatively weak inflation stabilization motive, the brown energy tax will lead to a significant surge in energy prices and inflation. However, this price surge also boosts profits for green energy producers, further strengthening incentives for R&D investment. Consequently, monetary policy plays a key role in shaping the trajectory of green technology development. Accelerated innovation early in the transition process can help expedite the shift toward the new steady state, thereby speeding up the overall energy transition.

This finding highlights a key tradeoff for monetary policy. Weaker inflation stabilization leads to higher inflation and energy prices in the short run, but it also accelerates the transition to the new steady state in the medium run.[1] To assess these tradeoffs, we conduct a welfare analysis. Our results show that the optimal degree of inflation stabilization depends on the level of the tax rate. In most cases, lower inflation stabilization is preferable, except when the tax rate is extremely high.

We explore the sensitivity of our findings across several key dimensions. First, we examine the role of the innovation process. While technological advances have accelerated in recent years, the future path of green innovation remains uncertain. We consider a scenario where R&D investments lead to innovation at a much slower rate. In this case, a monetary policy with weaker inflation stabilization continues to be optimal across most tax rates, except at very high levels. Second, we assess the impact of nominal price rigidities on monetary policy's effectiveness. As price flexibility increases, the influence of monetary policy on the transition process diminishes. With fully flexible prices, monetary policy has no effect on real variables, and the transition is driven entirely by real dynamics. Finally, we explore output gap targeting as an alternative to inflation targeting. Across all tax rates, incorporating some degree of output gap stabilization proves optimal. This finding complements our earlier results: prioritizing output stabilization over inflation targeting helps accelerate the transition in the medium run.

Our paper contributes to the growing number of studies that analyze the effects of climate change policies on the macroeconomy. The insights in these studies are fairly mixed. For instance, using a small open-economy DSGE model, Airaudo et al. (2022) find that carbon taxes can lead to permanently higher brown energy prices, resulting in a short-term inflation surge and persistent output losses. Similarly, Bartocci et al. (2024) argue that the gradual introduction of a carbon tax has recessionary and disinflationary effects in a large-scale DSGE model of the Euro Area. However, these recessionary effects are mitigated when green energy is subsidized, and labor taxes are simultaneously reduced. Lastly, Ferrari and Nispi Landi (2024) emphasize the role of expecta-

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[1] Note that monetary policy does not affect the long-run equilibrium level, as it remains neutral in the long run.

tions in shaping the economic effects of carbon taxes. Under rational expectations, a carbon tax is deflationary as agents internalize future income losses, while it initially leads to inflation under bounded rationality.

Furthermore, this paper contributes to the broader discussion on the role of monetary policy during the green transition. The central question in this debate is whether central banks should "look through" energy price fluctuations or actively respond to them. The common argument is that monetary policy is likely ineffective in stabilizing highly volatile components like energy and food prices. Lags in the transmission channel limit the impact of monetary policy in the very short-run, meaning it only influences inflation over time in the medium run. As a result, central banks may choose to focus on stabilizing core inflation, ignoring fluctuations in volatile components.

However, price dynamics during a green transition likely differ from typical energy price shocks (Schnabel, 2022; Olovsson and Vestin, 2023). A transition driven by policies like a carbon tax could lead to persistent shifts in the relative price of energy, potentially affecting underlying inflation trends. Therefore, an appropriate monetary policy response is crucial for ensuring price stability in the medium run.

In this context, several studies highlight the challenges monetary policymakers might face during the green transition. For instance, when the transition resembles a large supply-side shock, as documented in this paper, central banks might confront a non-trivial tradeoff between stabilizing inflation and risking a recession (e.g. Dupraz et al., 2022; Del Negro et al., 2023). Moreover, Nakov and Thomas (2023) emphasize that policymakers may face tradeoffs between core inflation goals and climate objectives. If carbon taxes are set below the socially optimal level, given the damage from emissions, the economy might consume too much fossil energy. In this scenario, the central bank might have an incentive to depress output to reduce overall energy consumption, even at the cost of temporarily undershooting the inflation target and reducing output below its natural level.[2] Our paper adds a new dimension to the debate, revealing that the tradeoffs may be even more complex. The connection between short-term fluctuations and long-term growth, driven by incentives for investment in new technologies, demonstrates that monetary policy can indirectly shape the dynamics and pace of the green transition. Effectively navigating this process presents an additional challenge for policymakers.

Our paper is also related to the long-standing literature on endogenous growth in DSGE models, including Comin and Gertler (2006), Bilbiie et al. (2008), Comin and Mulani (2009), Bambi et al. (2014), Bianchi et al. (2019), Anzoategui et al. (2019), and Okada (2022). These studies share a common approach of modeling endogenous technological change as an increase in the variety of goods, following Romer (1990), combined with a "time-to-build" structure, as in Kydland and Prescott (1982), to capture the delayed effects of technology investment and adoption. This body of work highlights the role of R&D spillover effects in establishing an endogenous link between business cycle fluctuations and long-run growth. For instance, Bianchi et al. (2019) show that the equity financing shocks prominent in the 2001 recession led to a more persistent and severe

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[2] This tradeoff does not occur if carbon taxes are set to follow the socially optimal path.

growth slowdown than the 2008 financial crisis, as these shocks are more critical to driving R&D investment. In contrast, debt financing shocks, which were more relevant during the 2008 crisis, had a smaller impact on long-term growth through R&D channels.

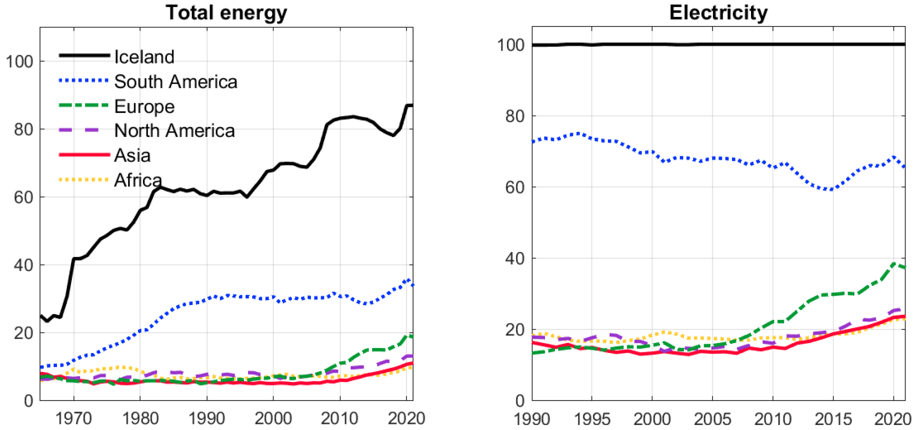
The remainder of the paper is organized as follows. Section 2 presents stylized empirical facts. Section 3 describes the model. Section 4 presents the main results. Section 5 presents the senstivity analysis. Finally, Section 6 concludes.

2 Recent developments and stylized facts

In this section, we discuss three stylized facts that guide our theoretical model. First, the share of energy from renewable sources varies widely across countries, influenced by geographical, geological, as well as economic and political factors. Second, innovation in green technology has accelerated significantly over the recent decades. Finally, the cost of generating renewable energy has substantially decreased, primarily due to technological advancements.

The left panel of Figure 1 illustrates the share of primary energy consumption derived from renewable technologies, which include hydropower, solar, wind, geothermal, wave energy, and modern biofuels.[3] The share of renewables varies considerably across countries and regions. For example, in 2020, Iceland generated nearly 90% of its primary energy from renewable sources, largely due to its abundant hydropower and geothermal resources (Ritchie et al., 2022). Brazil, which dominates the South America aggregate in the figure, produced about 50% of its primary energy from renewables in 2020. This development is primarily the result of significant investments in solar and wind energy in recent years.

Figure 1: Share of renewable energy



Notes: in per cent. Source: BP

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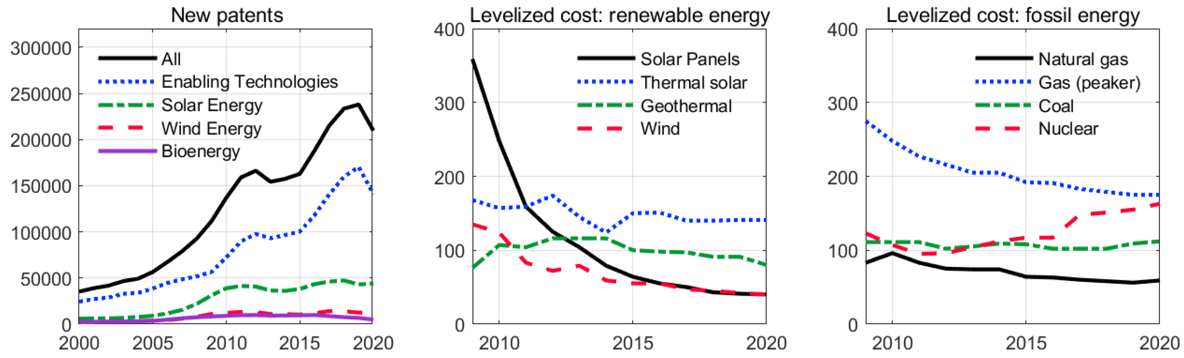
[3] Primary energy refers to energy in its raw form before being converted into electricity, heat, or transport fuels. The data is based on primary energy calculated using the 'substitution method,' which accounts for energy losses when converting fossil fuels into usable energy. This method converts non-fossil fuel sources to their 'input equivalents,' i.e., the amount of primary energy that would be required to produce the same amount of energy using fossil fuels. For more details, see `https://ourworldindata.org/energy-substitution-method`

Final energy consumption takes the form of electricity, heating, and transport fuels. The share of renewables is generally higher in electricity generation, as transport and heating remain more dependent on oil and gas. The right panel of Figure 1 shows the evolution of renewables in the electricity mix over time. For instance, since the 1990s, Iceland has produced all of its electricity from renewable sources. South American countries averaged around 70% renewable electricity in 2020, while other regions have been catching up since the early 2000s.

Overall, countries with large fossil fuel industries or less developed economies tend to have lower shares of renewable energy in their overall energy mix. These observations suggest that there is significant potential for economies to substitute fossil fuels with renewable energy in the future.

Innovation in low-carbon energy (LCE) technologies plays a crucial role in the transition toward green energy. Patenting activity in these technologies has been steadily increasing over the years. The left panel of Figure 2 illustrates the annual number of new patents for LCE technologies. Enabling technologies, such as batteries, hydrogen, and smart grids, represent the largest share of these patents.[4]

Figure 2: Innovation and production costs



Notes: New patents worldwide. Right panel in USD/MWh. Sources: International Renewable Energy Agency, Lazard

Simultaneously, the cost of producing renewable energy has significantly declined over recent decades. The middle and right panels of Figure 2 show the evolution of the Levelized Cost of Energy (LCoE) for both renewable and fossil energy sources. The LCoE measures the average cost of generating one Megawatt hour (MWh) of electricity over the lifetime of an energy-generating system, factoring in all costs, including installation, operation, maintenance, and fuel.[5] Figure 2 highlights significant cost declines, particularly for solar and wind energy supply technologies. These reductions have been driven by factors such as technological advancements, decreasing capital costs, and increased competition. By 2020, the Levelized Cost of Energy (LCoE) for renewable energy had reached levels comparable to conventional energy generation technologies, placing them in a

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[4] LCE technology patents are broadly categorized into three groups: energy supply technologies, technologies that improve energy efficiency or enable fuel-switching in end-use applications (e.g., transport, buildings, industrial production), and enabling technologies that enhance infrastructure to accommodate higher levels of clean energy (IRENA (2020)).

[5] Figure 2 shows unsubsidized cost (Lazard and Youngs (2021)).

similar cost range overall.

3 Model

Our model framework is a medium-scale New Keynesian DSGE model with three key extensions: (i) Energy is a production factor, alongside labor and capital. It consists of a mix of fossil (brown) and renewable (green) energy, which are perfectly substitutable. (ii) Brown and green energy are produced in separate sectors using intermediate goods. Brown energy producers are subject to a tax on their input prices, which distorts the relative costs between producing brown and green energy. (iii) Finally, there is endogenous technological progress in the green energy sector. This progress increases the number of green energy producers in the market. Since individual producers operate under positive but decreasing returns to scale, an increase in the number of producers improves the allocation of resources, making green energy production more efficient at the aggregate level. Time is assumed to be quarterly.

3.1 The energy sector

Final energy is a combination of brown and green energy, produced in several steps: First, producers in the brown and green energy sub-sectors combine their respective energy inputs to produce brown and green energy, respectively. Second, these energy types are sold at competitive prices to a final energy producer, who combines them to create the final energy product. Finally, this final energy product is sold to goods-producing firms. Prices in all energy sectors are assumed to be perfectly flexible.

The representative final energy producer combines brown and green energy:

$$E_t = BR_t + GR_t \tag{1}$$

where E_t is final energy, BR_t is brown energy and GR_t is green energy. Assume q_t^E is the price that energy producers receive for selling E_t to the goods producing sector, q_t^{BR} is the price of brown energy and q_t^{GR} is the price of green energy. Given perfect competition and perfect substitution between BR_t and GR_t, the price of final energy is equal to the price of both brown and green energy:

$$q_t^E = q_t^{BR} = q_t^{GR}. \tag{2}$$

Therefore, in the remainder of the model description, we will focus on q_t^E as the representative price.

The brown energy sub-sector. A representative brown energy producer aggregates a continuum of inputs to produce brown energy:

$$BR_t = \left(\int_0^1 BR_{jt}^{\frac{\varepsilon_{BR}-1}{\varepsilon_{BR}}} \, dj \right)^{\frac{\varepsilon_{BR}}{\varepsilon_{BR}-1}} \tag{3}$$

where $\varepsilon_{BR} > 1$ is the elasticity of substitution between the brown intermediate goods. Profit maximization yields the demand function for input BR_{jt}:

$$BR_{jt} = \left(\frac{q_{jt}^{BR}}{q_t^E}\right)^{-\varepsilon_{BR}} BR_t \tag{4}$$

where q_{jt}^{BR} is the price of brown input j. Using Eqs. (3) and (4) yields:

$$q_t^E = \left(\int_0^1 \left(q_{jt}^{BR}\right)^{1-\varepsilon_{BR}} dj\right)^{\frac{1}{1-\varepsilon_{BR}}} \tag{5}$$

Inputs are produced by brown intermediate goods firms. Each firm j produces one variety of the input, using a Cobb-Douglas technology with capital K_{jt}^{BR} as production factor:[6]

$$BR_{jt} = A^{BR}\left(K_{jt}^{BR}\right)^{\alpha_{BR}} \tag{6}$$

with $\alpha_{BR} < 1$ and where A^{BR} denotes the technological level of brown energy production. Each firm j rents capital at rate r_t^k and pays a tax τ_t on each unit of capital. Therefore, the profit maximization problem for firm j is

$$\Pi_{jt}^{BR} = q_{jt}^{BR} BR_{jt} - (1+\tau_t) r_t^k K_{jt}^{BR}, \tag{7}$$

subject to the demand condition in Eq. (4), and leading to the price-setting condition

$$q_{jt}^{BR} = \frac{\varepsilon_{BR}}{\varepsilon_{BR}-1} \frac{(1+\tau_t) r_t^k}{\alpha_{BR} A_t^{BR} \left(K_{jt}^{BR}\right)^{\alpha_{BR}-1}}. \tag{8}$$

Symmetry across brown energy producers ensures that $K_t^{BR} = \int_0^1 K_{jt}^{BR} dj$. The aggregate production function for brown energy is, hence,

$$BR_t = A_t^{BR}\left(K_t^{BR}\right)^{\alpha_{BR}}. \tag{9}$$

Substituting Eq. (8) into (5) yields the final price of brown energy,

$$q_t^E = \frac{\varepsilon_{BR}}{\varepsilon_{BR}-1} \frac{(1+\tau_t) r_t^k}{\alpha_{BR} A_t^{BR} \left(K_t^{BR}\right)^{\alpha_{BR}-1}}. \tag{10}$$

The green energy sub-sector. This sector operates similarly to the brown energy sector, with two key differences. First, green energy production utilizes a set of inputs of measure A_t^m, which can vary over time. Second, unlike brown energy production, no taxes are levied on the inputs or factors of production used in green energy.

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[6] For simplicity, we ignore labor as an input because the labor share is relatively low in the production of energy.

The representative green producer combines green inputs of measure A_t^m to produce green energy:

$$GR_t = \left(\int_0^{A_t^m} GR_{jt}^{\frac{\varepsilon_{GR}-1}{\varepsilon_{GR}}} dj \right)^{\frac{\varepsilon_{GR}}{\varepsilon_{GR}-1}} \tag{11}$$

where $\varepsilon_{GR} > 1$ is the elasticity of substitution between the green intermediate goods. A_t^m is endogenous and represents the stock of various types of green inputs. The demand function for GR_{jt} is:

$$GR_{jt} = \left(\frac{q_{jt}^{GR}}{q_t^E} \right)^{-\varepsilon_{GR}} GR_t \tag{12}$$

where q_{jt}^{GR} is the price of green input j. Again, aggregation requires:

$$q_t^E = \left(\int_0^{A_t^m} \left(q_{jt}^{GR} \right)^{1-\varepsilon_{GR}} dj \right)^{\frac{1}{1-\varepsilon_{GR}}} \tag{13}$$

The production technology for each green input is analog to that of brown energy producers:

$$GR_{jt} = A_t^{GR} \left(K_{jt}^{GR} \right)^{\alpha_{GR}} \tag{14}$$

with $\alpha_{GR} < 1$. The profit maximization problem of the green input producer yields

$$q_{jt}^{GR} = \frac{\varepsilon_{GR}}{\varepsilon_{GR}-1} \frac{r_t^k}{\alpha_{GR} A_t^{GR} \left(K_{jt}^{GR} \right)^{\alpha_{GR}-1}}. \tag{15}$$

Once again, symmetry across green input firms implies that $K_t^{GR} = \int_0^{A_t^m} K_{jt}^{GR} dj = A_t^m K_{jt}^{GR}$. Thus, using the production function from Eq. (11), the aggregate production function for green energy becomes:

$$GR_t = A_t^{GR} \left(A_t^m \right)^{\frac{\varepsilon_{GR}}{\varepsilon_{GR}-1} - \alpha_{GR}} \left(K_t^{GR} \right)^{\alpha_{GR}} \tag{16}$$

with $\frac{\varepsilon_{GR}}{\varepsilon_{GR}-1} - \alpha_{GR} > 0$. The variable A_t^m serves as a scaling factor for aggregate production. Since each firm operates under a production technology with decreasing marginal productivity, a market with more firms (i.e., a higher value of A_t^m) ensures that production resources are allocated more efficiently across firms. As a result, a larger market for green inputs enhances aggregate productivity within the green energy sector. This implies for the price of energy that

$$q_t^E = \frac{\varepsilon_{GR}}{\varepsilon_{GR}-1} \frac{r_t^k}{\alpha_{GR} A_t^{GR} \left(A_t^m \right)^{\frac{\varepsilon_{GR}}{\varepsilon_{GR}-1} - \alpha_{GR}} \left(K_t^{GR} \right)^{\alpha_{GR}-1}}. \tag{17}$$

3.2 The green R&D sector

Innovation expands the number of green intermediate firms in the green sector. The process works as follows: innovators allocate resources to research and development (R&D) to develop technologies for new green intermediates. In the following period, they sell the production rights for these products to new firms, reflecting that it takes time for innovation to be created and adopted.

Innovators conduct R&D by using a final good composite S_t as input for developing new products, with the linear production function $\xi_t S_t$. Provided the innovation survives with probability ϕ_m until the next period, the innovator receives a price J_{t+1} for selling it to the firm. Thus, the representative innovator's profits are given by

$$\Pi_t^I = -S_t + \beta \phi_m E_t \Lambda_{t,t+1} J_{t+1} \xi_t S_t, \tag{18}$$

where $\Lambda_{t,t+1}$ is the households' stochastic discount factor. Under perfect competition and free entry, the innovator's zero profit condition requires

$$\frac{1}{\xi_t} = \beta \phi^m E_t \Lambda_{t,t+1} J_{t+1}. \tag{19}$$

The price for the new product J_t is equal to the value of successfully bringing the new green intermediate into use, which represents the present value of the future profits to the green firm j,

$$J_t = \Pi_{jt}^{GR} + \beta \phi^m E_t \Lambda_{t,t+1} J_{t+1}, \tag{20}$$

where Π_{jt}^{GR} denotes the current profits of the green firm j, and the term $\beta \phi^m E_t \Lambda_{t,t+1} J_{t+1}$ captures the discounted expected value of future profits.

In the aggregate, the total stock of innovations is given by:

$$A_{t+1}^m = \xi_t S_t + \phi^m A_t^m \tag{21}$$

This equation reflects that the stock of innovations in the next period depends on new innovations generated from R&D investments, $\xi_t S_t$, and the surviving stock of existing technologies, $\phi^m A_t^m$.

We assume that the conversion probability ξ_t is endogenous, with the following functional form:

$$\xi_t = \chi^m \left(\frac{A_t^m}{S_t} \right)^{\varepsilon^m} \tag{22}$$

This formulation implies that there is a positive spillover effect from the existing stock of technologies, A_t^m, on the success rate of new innovations. However, these spillovers are dampened by congestion effects captured by S_t, reflecting potential inefficiencies in scaling up innovation efforts.

3.3 Production of consumption goods

The production of consumer goods occurs in two stages. First, a continuum of intermediate goods firms, indexed by j, produce differentiated output goods using capital, labor, and energy. Then, a final goods firm combines these products from intermediate firms into a final output good according to a standard CES technology,

$$Y_t = \left(\int_0^1 Y_{jt}^{\frac{\varepsilon_y}{\varepsilon_y - 1}} dj \right)^{\frac{\varepsilon_y - 1}{\varepsilon_y}}, \tag{23}$$

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

Intermediate good firms face a Cobb-Douglas production technology using labor, capital and the final energy product as inputs:

$$Y_{jt} = \left(K_{jt}^Y \right)^{\alpha_y} N_{jt}^{1 - \alpha_y - \alpha_E} E_{jt}^{\alpha_E} \tag{24}$$

Each firm rents capital at rental rate r_t^k, hires labor at real wage w_t and uses energy at price q_t^E to produce its variety $Y_{j,t}$. In addition, it faces price stickiness, modeled as in Calvo (1983), where in any given period, the firm has a probability $1 - \theta$ of re-optimizing its price. For firms that do not re-optimize, their prices are partially indexed to steady-state inflation, with ω representing the degree of indexation. Denoting the optimal reset price of firm j by $P_{j,t}^*$, the re-optimizing firm solves the following profit-maximization problem:

$$\max E_t \sum_{s=0}^{\infty} (\beta\theta)^s \Lambda_{t+s} \left(\frac{P_{j,t}^*}{P_{t+s}} \overline{\Pi}^{j\omega} - mc_{t+s} \right) Y_{j,t+s} \tag{25}$$

where mc_t are the firm's marginal costs.[7]

3.4 Households

Households supply differentiated labor input, N_{it}, to competitive labor contractors, who aggregate these inputs into homogeneous labor, N_t, using the technology

$$N_t = \left(\int_0^1 N_{it}^{\frac{\varepsilon_w - 1}{\varepsilon_w}} di \right)^{\frac{\varepsilon_w}{\varepsilon_w - 1}}, \tag{26}$$

where $\varepsilon_w > 1$ measures the elasticity of substitution among different types of labor.

There is a continuum of households $i \in [0, 1]$ in the economy. Each individual household maximizes its lifetime utility, given by

$$\max E_t \sum_{s=0}^{\infty} \beta^s \left\{ \ln \left(C_{i,t+s} - hC_{t+s-1} \right) - \psi \frac{N_{i,t+s}^{1+\varphi}}{1 + \varphi} \right\}, \tag{27}$$

and subject to the budget constraint

$$P_t C_{i,t} + I_{i,t} + B_{i,t} \leq W_{i,t} N_{i,t} + r_t^K K_{i,t} u_t + (1 + i_{t-1}) B_{i,t-1} + \Gamma_t + P_t T_t, \tag{28}$$

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[7] Symmetry across firms allows to drop index j.

where $C_{i,t}$ is consumption of household i and C_t is aggregate consumption, $I_{i,t}$ is investment, $B_{i,t}$ are risk-free nominal bonds, $K_{i,t}$ is the capital stock, Γ_t are profits of firms in all sectors and T_t are net transfers. Household utility is subject to habit formation, where the parameter h reflects the degree of dependence on past aggregate consumption. Given perfect risk sharing across households, the index i can be omitted. Utility maximization yields the Euler equation:

$$1 = \beta E_t \frac{1+i_t}{1+\pi_{t+1}} \frac{C_t - hC_{t-1}}{C_{t+1} - hC_t} \tag{29}$$

Households own the capital stock, which evolves according to

$$K_{t+1} = \mu_t I_t + (1-\delta) K_t, \tag{30}$$

where $\mu_t = 1 - \left(\frac{\kappa_I}{2}\frac{I_t}{I_{t-1}} - 1\right)$ represents investment adjustment cost and δ is the depreciation rate. Households rent capital to the production sector as well as to the brown and green energy sectors, such that

$$K_t = K_t^Y + K_t^{BR} + K_t^{GR}. \tag{31}$$

Households face a standard monopoly problem when selecting its wage to maximize their utility. Following Erceg et al. (2000), we assume that households experience Calvo-type frictions. In each period, the household can reset its wage $W_{l,t}^*$ with probability $1-\theta_w$. The household that can re-optimize its wage, and does so by maximizing the following objective function:

$$\max E_t \sum_{s=0}^{\infty} (\beta\theta_w)^s \left(\Lambda_{t+s} W_{l,t}^* N_{l,t+s} - \psi \frac{N_{l,t+s}^{1+\varphi}}{1+\varphi}\right) \tag{32}$$

3.5 Monetary policy and market clearing

Monetary policy follows a Taylor-type interest rate rule:

$$i_t = i^* + \phi_\pi (\pi_t - \pi) + \phi_y (\ln Y_t - \ln Y) \tag{33}$$

where i^* and π are the steady state nominal interest rate and inflation rate, respectively. We assume that government consumption is financed by raising debt and taxes,

$$G_t + (1+i_t)d_t = T_t + d_{t+1}, \tag{34}$$

where d_t is the stock of nominal debt. For bond market-clearing, we impose that $b_t = d_t$, meaning households hold the entire stock of government bonds. Substituting this condition into the aggregated household budget constraint leads to the aggregate accounting identity:

$$Y_t = C_t + S_t + I_t + G_t \tag{35}$$

Aggregate output is given by

$$v_t Y_t = A_t \left(K_t^Y\right)^{\alpha_y} N_t^{1-\alpha_y-\alpha_E} E_t^{\alpha_E}, \tag{36}$$

where $v_t \equiv \int_0^1 \left(\frac{P_{jt}}{P_t}\right)^{-\varepsilon} dj$ represents a measure of price dispersion that arises due to the presence of Calvo price rigidities.

All general equilibrium conditions are provided in the Appendix.

4 Transition dynamics

This section presents the main results. The energy transition is initiated by implementing a permanent brown energy tax, which increases the relative cost of brown energy production. This drives a gradual shift toward a new steady state with a higher share of green energy in the overall mix. Within this framework, we explore the role of monetary policy in influencing the transition dynamics.

4.1 Parameterization

Table 1 reports our baseline parameterization. For the household side, we set the discount factor β to 0.995, consumption habit formation h to 0.6, the labor disutility parameter ψ to 1 and labor demand elasticity χ to 6. These values are fairly standard in the literature (e.g., (Smets and Wouters, 2007)). We also set the share of non-wage-adjusting households ε^w to 0.55, a compromise between estimates provided in Smets and Wouters (2007) and Boehl and Strobel (2024).

On the goods-producing firms' side, the capital depreciation rate δ is set to 0.025 and the investment adjustment cost parameter κ_I is 4. The price elasticity of demand ε_y is 6 and the degree of price indexation ζ_p is 0.5, consistent with conventional parameterizations (e.g., (Smets and Wouters, 2007)). Two key parameters, the Calvo parameter θ and the factor share of capital α_y, are set to 0.85 and 0.2, respectively, based on estimates in Boehl and Strobel (2024). These values are derived from estimated medium-scale DSGE models using data up to 2019, fully accounting for the occasionally binding lower bound on interest rates. Using this recent data sample captures the effects of two important macroeconomic phenomena of recent decades: the effective binding lower bound on nominal interest rates and the flattening of the Phillips curve.

For the energy sector, we aim to align the parameters with standard values used in the literature. The share of energy inputs for goods-production α_E is set to 0.1, reflecting the average over the values reported in Kotlikoff et al. (2024). The substitution elasticities for brown and green energy ε_{BR} and ε_{GR} are both set to 6, consistent with standard values for substitution elasticities of intermediate goods. The parameters ϕ^m and ε_m are set to 0.95 and 0.1, following Comin and Gertler (2006) and Anzoategui et al. (2019). Finally, we treat χ^m as a free parameter to match $A_t^m = 1$ in the pre-tax steady state and set A_t^{GR} to 0.44 for all t, achieving a 25% share of green energy in the overall energy mix in the initial steady state[8]. A_t and A_t^{BR} are set to 1 for all t. Government spending G_t is set to 0.2 of output in the initial steady state for all t.

For monetary policy, the output stabilization parameter ϕ_y is set to its standard value of 0.125. In the analysis that follows, we will explore different values for the degree of inflation stabilization ϕ_π.

4.2 The brown energy tax and aggregate dynamics

We assume that the government implements a permanent brown energy tax in period 1, with $\tau_0 = 0$ and $\tau_t = \tau$ for $t > 0$. This tax triggers a transition from the initial steady state to a new one, characterized by a relatively larger share of green energy. Both the initial and new steady states lie on the balanced growth path, where $\frac{A_{t+1}^m}{A_t^m} = 1$. In this section, we focus on the aggregate dynamics in response to the brown energy tax. For now, we set the inflation stabilization parameter in the Taylor rule ϕ_π to 3. The implications of varying the degree of monetary responsiveness to inflation will be explored in the following section.

What are the macroeconomic implications of the brown energy tax? Consider first a tax increase from 0% to 30%. This scenario is illustrated by the blue dashed lines in Figure 3. The transition dynamics are depicted as (percentage) deviations from the initial steady state, which is the long-run equilibrium before the energy transition. Upon implementation, the tax distorts the relative costs of producing the two energy types, making brown energy more expensive relative to green energy. This price distortion triggers a gradual shift in demand and resources from the brown sector to the green sector, leading to a transition towards a new steady state over the medium term.

This transition unfolds as follows. In the short run, the higher cost of producing brown energy drives up overall energy prices, which raises input costs for the goods-producing sector. This prompts firms to increase prices, leading to higher inflation. In response, the central bank raises the nominal interest rate to curb inflation. The resulting rise in the real interest rate reduces consumption through the Euler equation, as higher rates make borrowing more expensive and encourage saving. Consequently, the effects of the brown energy tax resemble those of a large supply-side shock.

Additionally, energy production shifts from the brown sector to the green sector. The use of brown energy declines immediately, while green energy usage increases. The initial rise in energy prices and demand for green energy boosts profits for green intermediate producers. This, in turn, has a significant impact on R&D efforts in the green sector: higher expected profits lead to increased R&D spending. Consequently, innovation accelerates, expanding the number of green intermediate firms in the market. This growth enhances resource allocation among these firms, resulting in higher overall productivity in the sector.

The developments in the energy and R&D sectors have important feedback effects on the broader economy. First, as energy production moves from the brown to the green sector, the capital stock in the brown sector declines, while green energy capital rises. However, this shift is not one-for-one,

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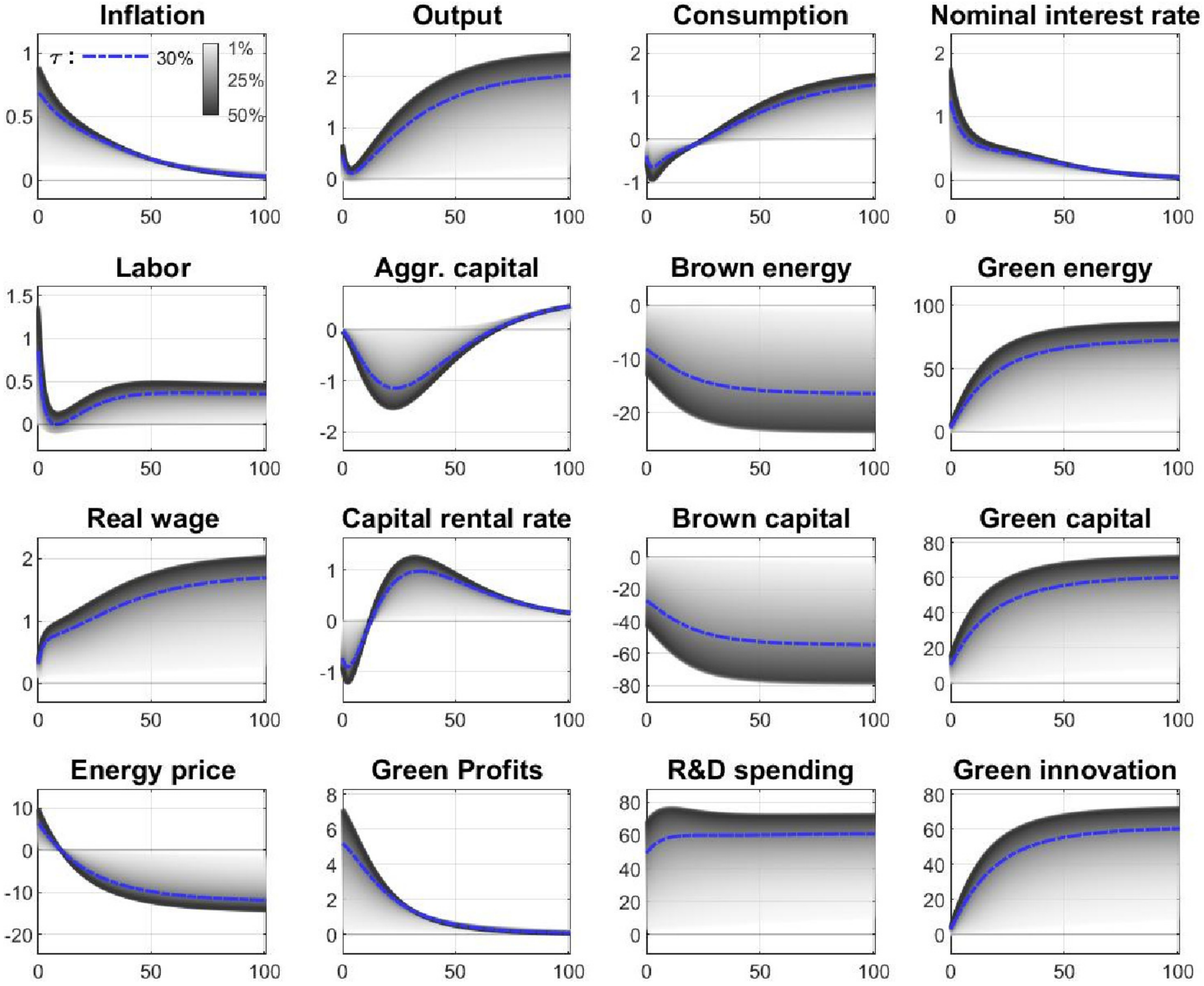
[8] This approximately corresponds to the share of green energy in the Euro Area in recent years.

Figure 3: Aggregate dynamics during the energy transition



Notes: Impulse responses shown in percentage deviation from initial steady state. Inflation and nominal interest rates are annualized. In quarters.

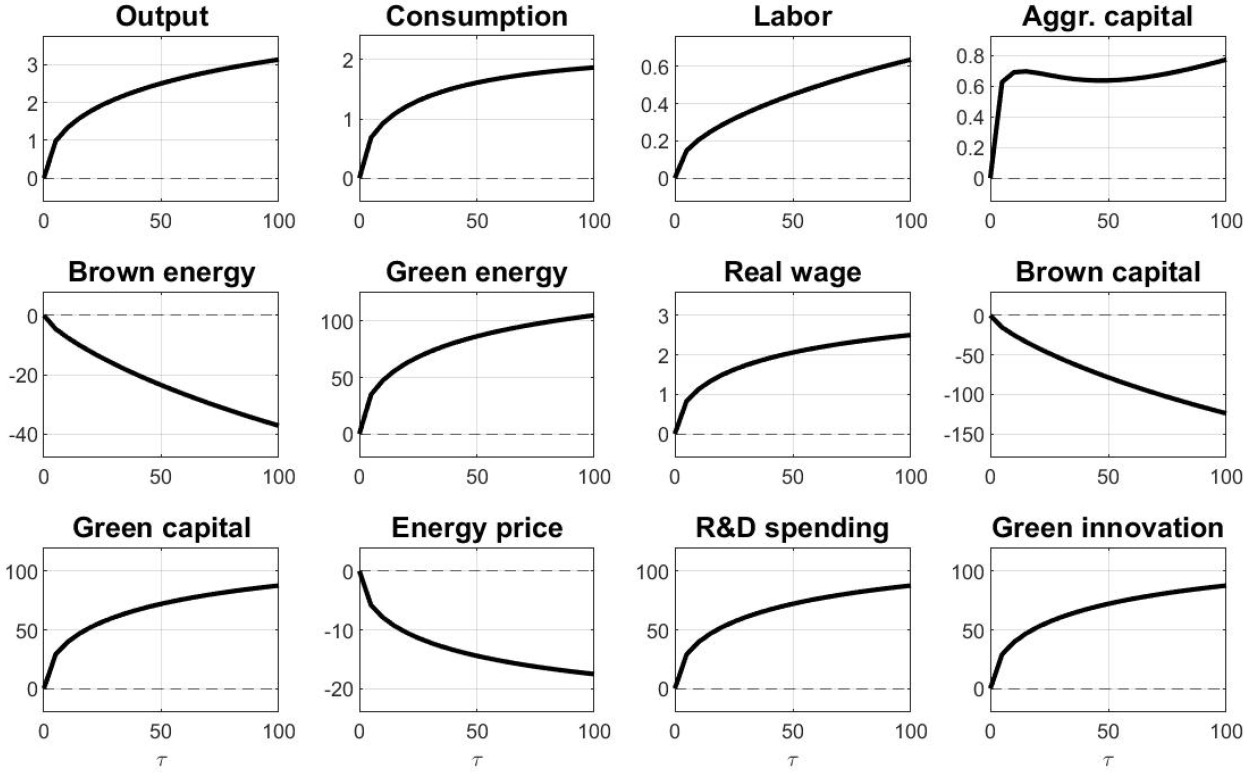
as the productivity gains in the green sector enable the production of a given amount of green energy with less capital than before. As a result, overall aggregate capital – and, hence, investment – declines in the early stages of the energy transition.

Second, output slightly increases on impact. According to the market-clearing condition in Eq. (35), the goods produced in the economy are allocated toward household consumption, investment, government consumption, and R&D activities. Both consumption and investment decline in response to the tax, while government consumption is assumed to remain constant. However, aggregate production rises overall to accommodate the increased demand for R&D. This additional demand for goods drives up the need for production inputs, leading to a rise in labor demand and real wages. The associated increase in input costs further elevates goods prices and inflation.

Over time, the economy converges to a new long-run equilibrium. Inflation returns to its steady state, consistent with the central bank's target. In contrast, output and consumption are permanently higher than in the initial steady state. Two key factors drive this outcome. First, R&D spending remains elevated. In equilibrium, this necessitates higher output levels, which, in turn, increase the demand the production inputs labor, capital and energy. Second, innovation reduces energy costs over time, lowering input costs for goods producers and increasing energy usage in production. As a result, the combination of higher labor and capital income, increased goods production driven by R&D, and reduced energy costs boosts household consumption in the long run.

Figure 3 also illustrates the impulse responses for a range of tax rates, with darker shades representing higher rates. The tax rates range from 1% to 50%. The level of the tax significantly impacts both the transition dynamics and the new steady-state levels. Generally, lower tax rates produce more subdued dynamics. Specifically, at very low values of τ, the distortion in the relative costs of producing brown and green energy is small, resulting in limited effects on energy prices and inflation. Consequently, the responses in other sectors, particularly the R&D sector, remain relatively muted.

Figure 4: The brown energy tax and new steady states

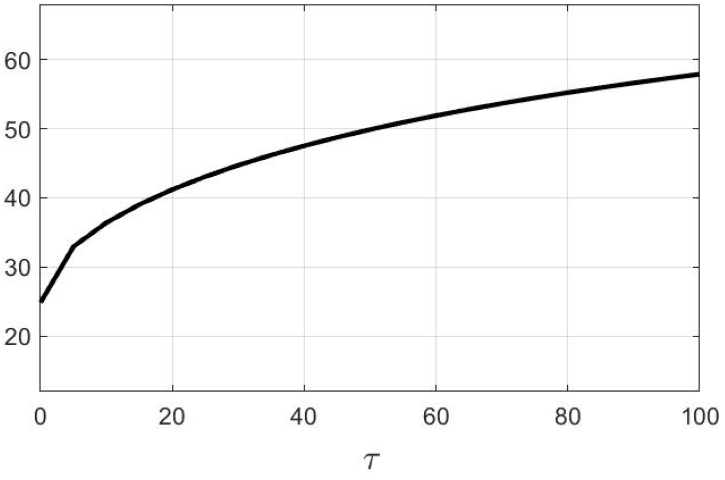


Notes: New steady states are shown in percentage deviations from initial steady state levels. Tax rates are schon in percent.

Furthermore, smaller taxes lead to smaller changes in the steady-state levels of aggregate variables. Figure 4 shows the new long-run equilibria for various tax rates, expressed as percentage changes relative to the old steady-state levels.The relationship between the tax rate and the change in the new steady state is nonlinear. For example, the increase in output at the new steady-state level is concave in τ. This indicates that the effectiveness of the tax in boosting long-run output is particularly high when τ is low but diminishes gradually as tax rates increase. A similar pattern is observed for other aggregate variables, including consumption, green energy, and R&D spending.

Similarly, Figure 5 depicts the share of green energy in the final energy mix as a function of the tax rate. Starting at around 25% when $\tau = 0$, this share increases to nearly 60% as the tax rises to 100%. This indicates that even with a full tax, a complete shift to green energy cannot not achieved in this model. The primary reason is the diminishing productivity of capital in the energy sector's production functions. Consequently, brown energy continues to play a role in the overall energy mix.

Figure 5: Steady state shares of green energy



Notes: Shares are calculated as percentage of total energy in new steady state. Tax rates are schon in percent.

The insights so far naturally raise the question of the optimal tax rate. To evaluate the welfare implications of the brown energy tax, we evaluate households' lifetime utility as defined in Eq. (27). Welfare can be decomposed in terms of the consumption and the labor components:[9]

$$W_t = E_t \sum_{s=0}^{\infty} \beta^s \ln\left(C_{i,t+s}(\tau_t) - hC_{t+s-1}(\tau_t)\right) - E_t \sum_{s=0}^{\infty} \beta^s \psi \frac{N_{i,t+s}(\tau_t)^{1+\varphi}}{1+\varphi},$$

where $(\{C(\tau)\}_t^\infty, \{N(\tau)\}_t^\infty)$ are i's equilibrium sequences of consumption and labor for a given tax rate τ. This expression helps to highlight the short-term and long-term implications of the brown tax. In the short run, a higher tax reduces consumption and increases labor hours, causing a decline in welfare. In the long run, however, steady-state consumption increases, boosting welfare. Nevertheless, this long-term benefit is accompanied by an increase in labor hours, leading to higher

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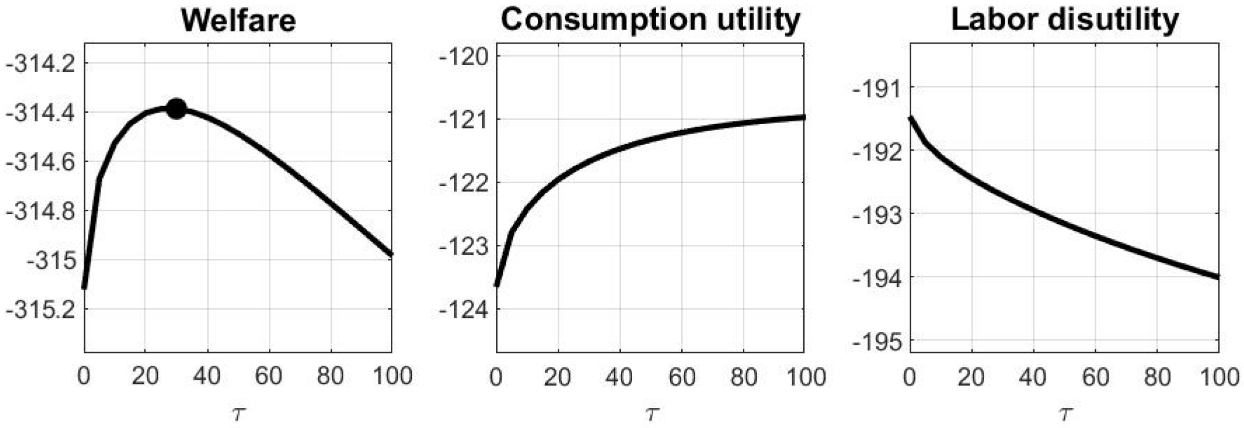
[9] For simplicity, we focus on the perfect foresight path and disregard the uncertainty introduced by business cycle shocks.

labor disutility.

These trade-offs suggest the existence of an optimal tax rate. Figure 6 illustrates welfare and its individual components as functions of the tax rate. The left panel displays overall welfare, which follows a nonlinear relationship with the tax rate. Specifically, welfare increases sharply at lower tax levels, peaking when the tax rate τ reaches 30% (black dot). Beyond this point, welfare begins to decline again. This nonlinear pattern arises from the dynamics of the consumption and labor components, as shown in the other panels. While consumption utility exhibits a concave relationship with the tax rate, labor disutility is convex. As a result, at higher tax rates, the utility gains from increased consumption are offset by the disutility associated with longer working hours.

Figure 6: The brown energy tax and welfare



Notes: Black dot in left panel indicates optimal tax rate. Tax rates are shown in percent.

4.3 The role of monetary policy

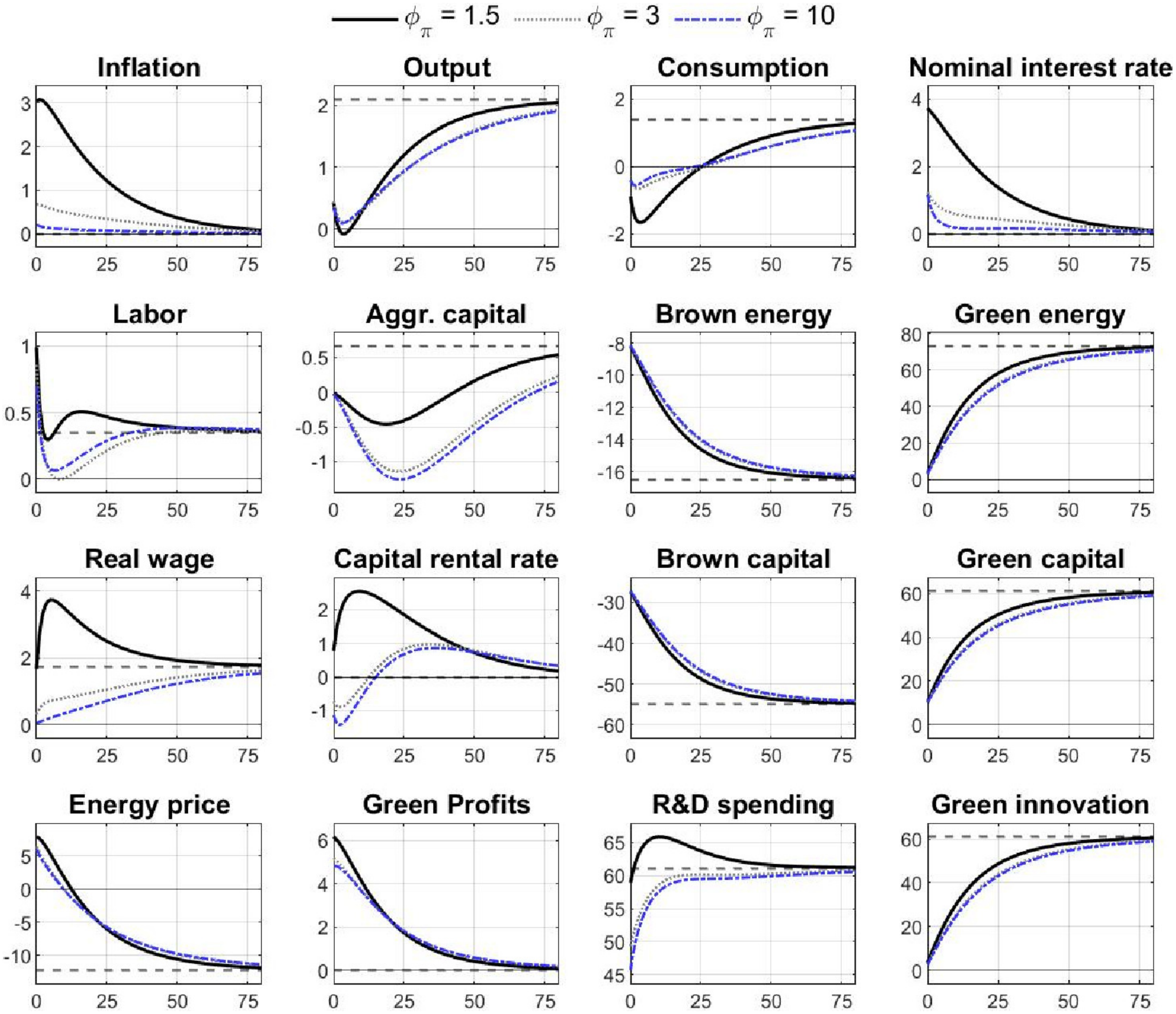
This section explores the impact of monetary policy on the transition dynamics following the implementation of a brown energy tax. Figure 7 displays the impulse responses to a permanent tax increase of 30% starting in period 1 (i.e., $\tau_0 = 0$ and $\tau_t = 30\%$ for $t > 0$) under different levels of inflation stabilization ϕ_π in the monetary policy rule. It is curcial to note that monetary policy does not affect the new long-run equilibrium, as it is neutral in the long run. Consequently, all models in Figure 7 start from the same pre-tax steady state and ultimately converge to the same post-tax long-run equilibrium.

This setup allows us to examine the implications of monetary policy for the transition dynamics. Consider a baseline scenario where $\phi_\pi = 1.5$, represented by the black solid lines in Figure 7. This reflects a central bank with a relatively weak inflation stabilization motive compared to the alternative cases where $\phi_\pi = 3$ or $\phi_\pi = 10$. Following the tax shock, energy prices rise, triggering an increase in inflation. In the baseline scenario with weaker inflation stabilization, inflation spikes more sharply than in the alternative scenarios, reaching up to 3% annually on impact.

This outcome has important implications for the shift from the brown to the green sector.

Specifically, in the baseline case, energy prices remain elevated in the short run. Combined with increased demand for green energy, this gives firms in the green sector a significant boost in profits. These higher profits, in turn, fuel R&D spending on green innovation. Notably, R&D spending exceeds its long-run steady-state level during the initial periods of the transition.

Figure 7: Transition dynamics and monetary policy



Notes: Impulse responses shown in percentage deviation from initial steady state. Inflation and nominal interest rates are annualized. In quarters.

The surge in R&D spending has several important implications for the short- and medium-term dynamics of the economy. Initially, the increased R&D efforts require additional resources in the form of produced goods. This scaling-up of production crowds out private demand, resulting in a significant drop in consumption in the first periods following the tax hike. At the aggregate level, output increases on impact, but the rise in output is smaller in the baseline scenario compared to policies with stronger inflation stabilization motives. One key factor contributing to this outcome is the higher profitability of green energy in the baseline case. Green intermediate firms demand significantly more capital for production, driving a sharp increase in the capital rental rate. This, in turn, raises the cost of goods production, limiting the overall rise in output.

In the medium run, green innovation becomes a key driver of economic dynamics. The surge in R&D spending in the baseline scenario significantly accelerates the growth of new green firms. This expansion has two major effects: it increases the efficiency of green energy production and lowers energy prices, keeping them below the levels observed in alternative scenarios for the rest of the transition process.

These factors are crucial in accelerating the broader economic transition. For instance, while output is initially lower in the baseline scenario compared to alternative policies, it begins to grow rapidly after approximately 10 periods, eventually surpassing the output levels of the other scenarios in the medium run. A similar pattern is observed for consumption: though initially lower in the baseline case, it exceeds the levels of the alternative scenarios after about 25 periods. This accelerated growth in output and consumption enables the economy to reach its new long-run equilibrium faster. In the baseline scenario, these steady-state levels are achieved after roughly 80 periods, whereas output and consumption in the alternative cases remain below their respective steady-state levels at that point.

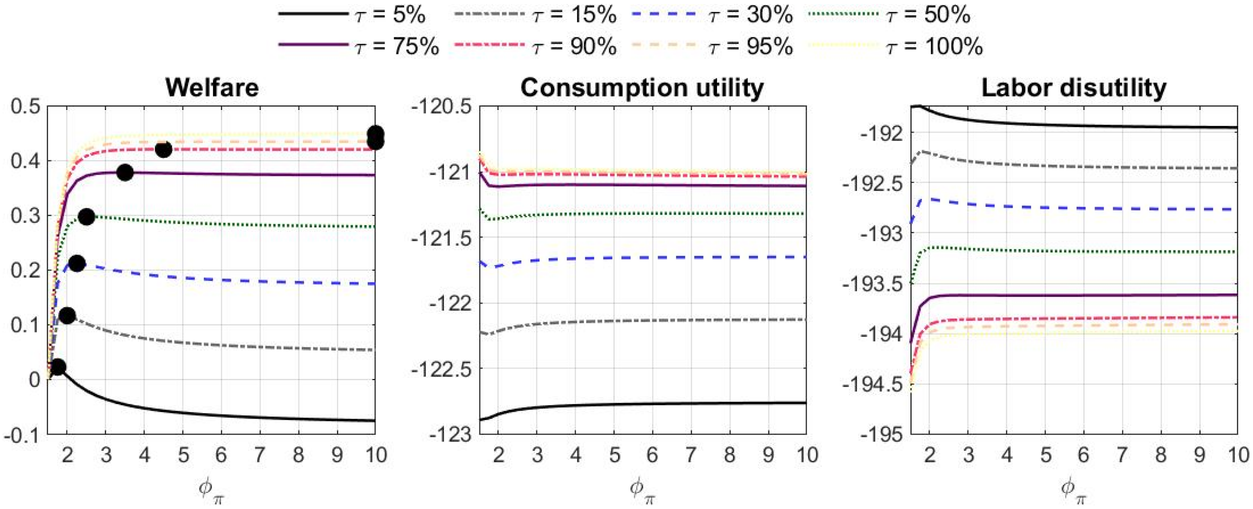
In summary, monetary policy involves a non-trivial trade-off between short-run and medium-run effects. A policy with weaker inflation stabilization results in higher inflation, increased production input costs, and lower output and consumption in the short run. However, it also fosters faster innovation, driving stronger output and consumption growth and enabling a quicker transition in the medium run.

We conduct a welfare analysis to evaluate the trade-offs. Figure 8 illustrates welfare and its consumption and labor components as functions of the degree of inflation stabilization (ϕ_π) for selected tax rates. To facilitate comparison, the left panel presents welfare relative to the welfare level when $\phi_\pi = 1.5$ for a given tax rate. The black dots represent the optimal value of ϕ_π for each level of τ. The other panels show the consumption utility and labor disutility components are shown as actual levels.

The analysis reveals that the optimal degree of inflation stabilization (ϕ_π) depends on the tax rate. As the tax rate increases, the optimal value of ϕ_π also rises. This result reflects the differing effects on consumption and labor across the scenarios. Specifically, consumption utility is generally higher for all values of ϕ_π when tax rates are higher. However, labor disutility also rises with higher tax rates. These findings are consistent with the results from the previous section. Overall, both consumption and labor components exhibit nonlinear relationships with ϕ_π and τ.

Even though the optimal level of ϕ_π increases with the tax rate, it remains relatively low for most values of τ, even at very high tax levels. For instance, the optimal ϕ_π is 3.5 for a 90% tax hike. Strong inflation stabilization only becomes the preferred policy when the tax rate exceeds 95%.

Figure 8: Welfare and the degree of inflation stabilization



Notes: Total welfare (left panel) is shown as difference to welfare when $\phi_\pi = 1.5$ for a given tax rate. Black dots represent the optimal value of ϕ_π for a given tax rate.

Table 1: **Parameterization**

Parameter	**Value**	**Economic interpretation**
		Households
β	0.995	Subjective discount factor
h	0.6	Consumption habit formation
ψ	1	Labor disutility parameter
χ	1	Inverse labor supply elasticity
ε^w	6	Elasticity of labor demand
θ_w	0.55	Share of households per period keeping wage unchanged
		Firms
δ	0.025	Constant capital depreciation rate
κ_I	4	Investment adjustment cost parameter
ε_y	6	Price elasticity of demand
α_y	0.2	Share of capital
α_E	0.1	Share of energy inputs
θ	0.85	Share of firms per period keeping prices unchanged
ξ_p	0.5	Price indexation
A	1	Productivity of goods production
		Energy subsectors
ε_{BR}	6	Brown inputs substitution elasticity
ε_{GR}	6	Green inputs substitution elasticity
α_{BR}	0.3	Production function brown energy
α_{GR}	0.3	Production function green energy
ϕ^m	0.95	Innovation survival probability
ε_m	0.1	Innovation spillover
χ^m	1.28	Constant conversion probability
A_{BR}	1	Productivity of brown energy production
A_{GR}	0.44	Productivity of green energy production
		Monetary policy
ϕ_y	0.125	Taylor rule output reaction

5 Sensitivity analysis

In this section, we examine key factors that influence the transition process in more detail. Specifically, we focus on (i) the extent of spillover effects in the innovation process, (ii) the degree of price rigidities in the goods-producing sector and (iii) the role of output gap stabilization in the monetary policy rule.

5.1 Innovation process

Despite the substantial progress made in the invention and adoption of green technologies in recent years, there remains significant uncertainty about the trajectory of future technological advancements. In this section, we explore a scenario in which R&D investments are less effective in producing new technologies. To capture this, we modify the endogenous conversion probability from R&D as follows:

$$\xi_t = \chi^m \left(A_t^m\right)^{\mu^m} \left(\frac{1}{S_t}\right)^{\varepsilon^m} \tag{37}$$

Previously, we assumed a spillover effect parameter of $\mu^m = \varepsilon^m = 0.1$. Now, assume that $\mu^m = 0.05$, indicating that the spillover effects from existing technologies are smaller. Conversely, ε^m remains at 0.1. This scenario reflects a situation where the marginal gains from inventing new green technologies are relatively low.

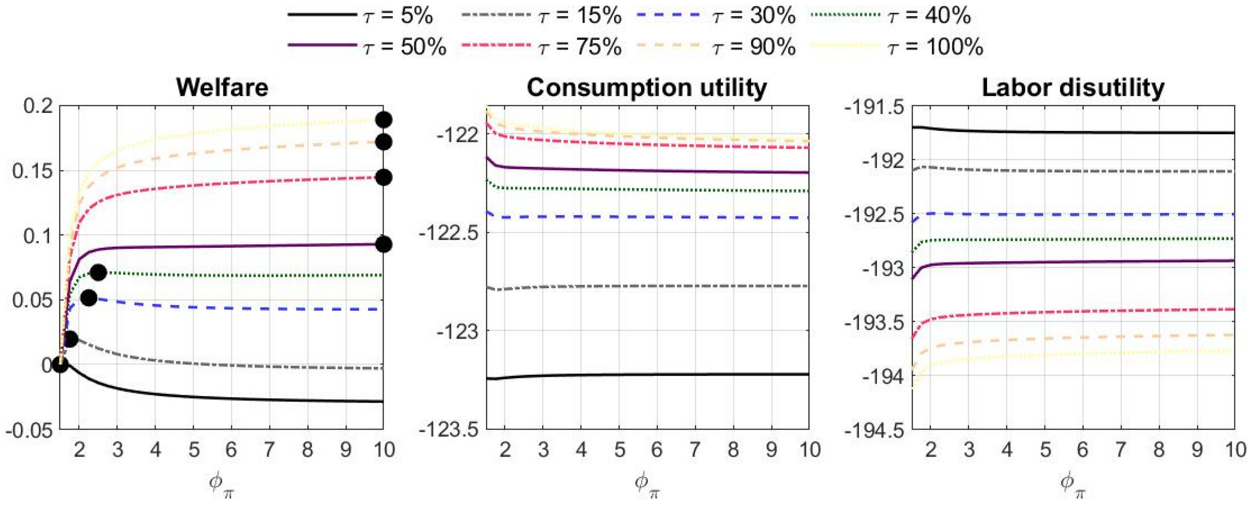
A less efficient innovation process has important implications for optimal monetary policy. Figure 9 illustrates welfare outcomes for varying degrees of inflation stabilization in the monetary policy rule at selected rates of the brown tax. Compared to the case in the previous section, the central bank would now prefer stronger inflation stabilization, even at lower tax rates. This shift occurs because, with smaller innovation gains, monetary policy becomes less effective in accelerating the transition process. However, the tax rate at which strong inflation stabilization ($\phi_\pi = 10$) becomes optimal remains relatively high. For tax rates below 50%, a low ϕ_π continues to be optimal.

5.2 Price rigidities

We also analyze how price rigidities influence the impact of monetary policy during the transition process. In a scenario with fully flexible prices, monetary policy would have no real effects, and the transition dynamics would be governed entirely by changes in real variables.

To investigate this, we consider a scenario with lower degrees of wage and price rigidities, setting $\theta_w = 0.25$ and $\theta = 0.5$, respectively. Figure 10 illustrates the transition dynamics for this case. Similar to the baseline scenario, inflation remains higher under a monetary policy with weaker inflation stabilization. However, the differences in output, R&D spending, and green innovation dynamics are now significantly smaller. This finding highlights that the effectiveness of monetary policy during the transition process depends critically on the degree of price rigidities. With more

Figure 9: Welfare under low weak innovation dynamics



Notes: Total welfare (left panel) is shown as difference to welfare when $\phi_\pi = 1.5$ for a given tax rate. Black dots represent the optimal value of ϕ_π for a given tax rate.

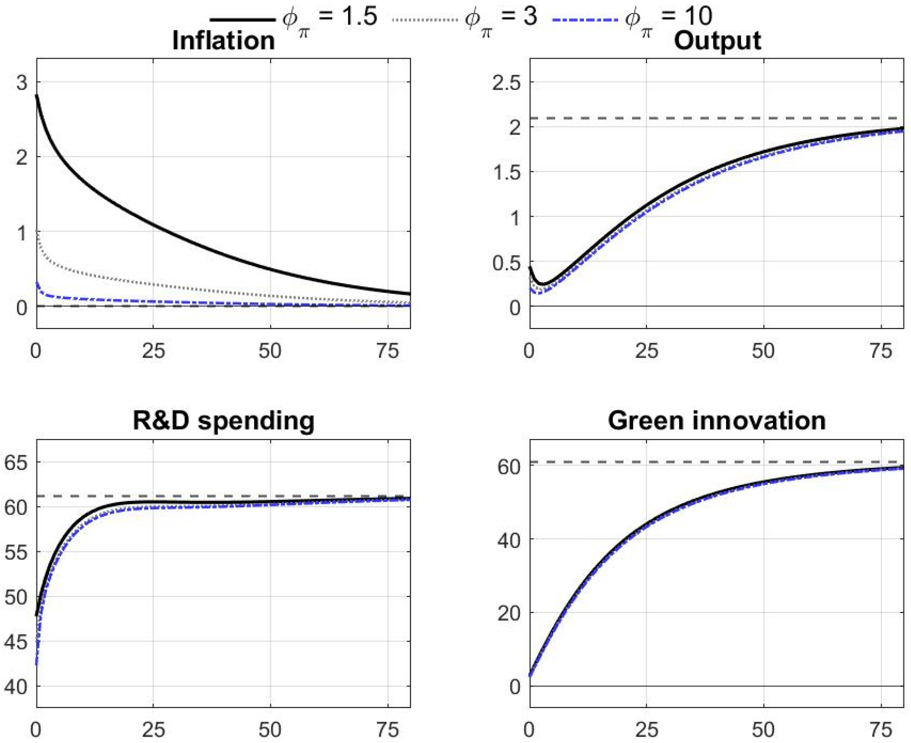
flexible prices, the scope for monetary policy intervention diminishes significantly.

5.3 Output gap targeting

In this section, we analyze the role of output gap targeting in monetary policy. In the baseline scenario, the output gap parameter in the Taylor rule ϕ_y is set to 0.125. Here, we explore different levels of ϕ_y while keeping the inflation stabilization parameter ϕ_π fixed at 3.

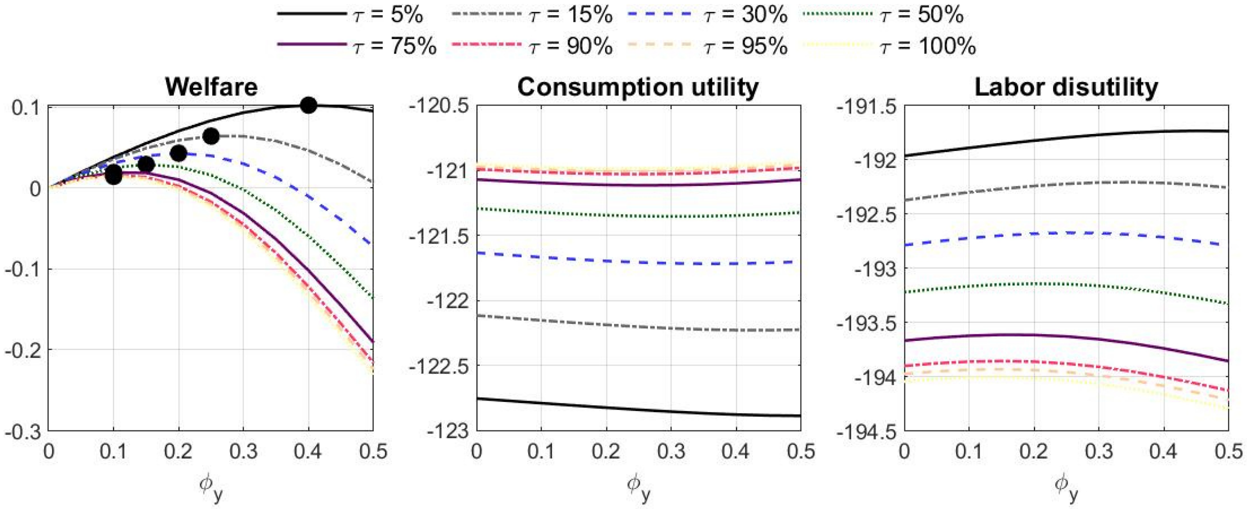
The welfare analysis reveals that the optimal level of ϕ_y depends on the brown energy tax rate. Figure 11 illustrates welfare and its individual components for varying degrees of ϕ_y across different tax rates. For lower tax rates, a higher degree of ϕ_y is optimal. This finding complements the results from the previous section: emphasizing output stabilization bolsters goods production and sustains energy demand, thereby increasing profits in the green sector and encouraging investment in green R&D. However, as the tax rate rises, the optimal degree of output gap stabilization decreases. The consumption gains from higher output become relatively smaller compared to the increased disutility from additional labor hours, making a stronger focus on inflation stabilization more desirable.

Figure 10: Transition dynamics under less rigid prices



Notes: Impulse responses shown in percentage deviation from initial steady state. Inflation and nominal interest rates are annualized. In quarters.

Figure 11: Welfare and output gap targeting



Notes: Total welfare (left panel) is shown as difference to welfare when $\phi_y = 0$ for a given tax rate.

6 Conclusion

We present a framework to analyze the macroeconomic implications of an energy transition from brown to green energy production. Using a medium-scale DSGE model with distinct green and brown energy sectors and endogenous innovation in green technologies, we examine the transition from an economy with a low share of green energy to one with a higher share, triggered by the implementation of a tax on brown energy. Our findings suggest that the energy transition resembles a significant supply-side shock, leading to a surge in inflation and energy prices alongside a decline in consumption. Simultaneously, energy production shifts from brown to green sources, fueling R&D efforts in green technologies. These innovations improve the efficiency of green energy production, leading to a gradual reduction in energy prices over time. In this context, monetary policy plays a pivotal role, even when the energy transition is not explicitly incorporated into the policy rule. A monetary policy with less emphasis on inflation stabilization leads to higher inflation and energy prices, but also provides stronger incentives for green R&D. Higher innovation efforts help speed up the transition process, ultimately improving overall welfare.

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Appendix

A General equilibrium conditions

1. Energy sectors

$$E_t = BR_t + GR_t \tag{A.1}$$

$$BR_t = A_t^{BR} \left(K_t^{BR}\right)^{\alpha_{BR}} \tag{A.2}$$

$$q_t^E = \frac{\varepsilon_{BR}}{\varepsilon_{BR}-1} \frac{(1+\tau_t) r_t^k}{\alpha_{BR} A_t^{BR} \left(K_t^{BR}\right)^{\alpha_{BR}-1}} \tag{A.3}$$

$$GR_t = A_t^{GR} \left(A_t^m\right)^{\frac{\varepsilon_{GR}}{\varepsilon_{GR}-1}-\alpha_{GR}} \left(K_t^{GR}\right)^{\alpha_{GR}} \tag{A.4}$$

$$q_t^E = \frac{\varepsilon_{GR}}{\varepsilon_{GR}-1} \frac{r_t^k}{\alpha_{GR} A_t^{GR} \left(A_t^m\right)^{\frac{\varepsilon_{GR}}{\varepsilon_{GR}-1}-\alpha_{GR}} \left(K_t^{GR}\right)^{\alpha_{GR}-1}} \tag{A.5}$$

$$BR_t = \left(\frac{q_t^{BR}}{q_t^E}\right)^{-\varepsilon_E} \omega E_t \tag{A.6}$$

$$GR_t = \left(\frac{q_t^{GR}}{q_t^E}\right)^{-\varepsilon_E} (1-\omega) E_t \tag{A.7}$$

2. The green R&D sector

$$A_{t+1}^m = \xi_t S_t + \phi^m A_t^m \tag{A.8}$$

$$\xi_t = \chi^m \left(\frac{A_t^m}{S_t}\right)^{\varepsilon^m} \tag{A.9}$$

$$\frac{1}{\xi_t} = \beta \phi^m E_t \Lambda_{t,t+1} J_{t+1} \tag{A.10}$$

$$J_t = \Pi_{jt}^{GR} + \beta \phi^m E_t \Lambda_{t,t+1} J_{t+1} \tag{A.11}$$

$$\Pi_{jt}^{GR} = \left(q_{jt}^{GR} GR_{jt} - r_t^k K_{jt}^{GR}\right) \tag{A.12}$$

3. Consumption goods producing sector

$$v_t Y_t = A_t \left(K_t^Y\right)^{\alpha_y} N_t^{1-\alpha_y-\alpha_E} E_t^{\alpha_E} \tag{A.13}$$

$$K_t^Y = \alpha_y \frac{mc_t}{r_t^k} v_t Y_t \tag{A.14}$$

$$N_t = (1-\alpha_y-\alpha_E) \frac{mc_t}{w_t} v_t Y_t \tag{A.15}$$

$$E_t = \alpha_E \frac{mc_t}{q_t^E} v_t Y_t \tag{A.16}$$

4. Capital accumulation

$$K_{t+1} = \left(1 - \left(\frac{\kappa_I}{2}\frac{I_t}{I_{t-1}} - 1\right)\right) I_t + \left(1 - \delta(u_t)\right) K_t \tag{A.17}$$

$$q_t \frac{1+i_t}{E_t 1 + \pi_{t+1}} = E_t r^k_{t+1} + (1-\delta) E_t q_{t+1} \tag{A.18}$$

$$1 = q_t \left(1 - \frac{\kappa_I}{2}\frac{I_t}{I_{t-1}} - 1\right)^2 - \kappa_I \left(\frac{I_t}{I_{t-1}} - 1\right)\frac{I_t}{I_{t-1}} + E_t \frac{1+\pi_{t+1}}{1+i_t} q_{t+1} \kappa_I \left(\frac{I_{t+1}}{I_t} - 1\right)\left(\frac{I_{t+1}}{I_t}\right)^2 \tag{A.19}$$

where q_t is the price of capital.

5. Households

$$\lambda_t = \left(C_t - hC_{t-1}\right)^{-1} \tag{A.20}$$

$$\lambda_t = \beta E_t \lambda_{t+1} \frac{1+i_t}{1+\pi_{t+1}} \tag{A.21}$$

$$x^N_{1,t} = \psi \left(\frac{w_t}{w^*_t}\right)^{\varepsilon_w(1+\varphi)} N_t^{1+\varphi} + \theta_w \beta (1+\pi_{t+1})^{\varepsilon_w(1+\varphi)} \left(\frac{w^*_{t+1}}{w^*_t}\right)^{\varepsilon_w(1+\varphi)} x^N_{1,t+1} \tag{A.22}$$

$$x^N_{2,t} = \lambda_t \left(\frac{w_t}{w^*_t}\right)^{\varepsilon_w} N_t + \theta_w \beta E_t (1+\pi_t)^{\varepsilon - 1} \left(\frac{w^*_{t+1}}{w^*_t}\right)^{\varepsilon_w} x^N_{2,t+1} \tag{A.23}$$

$$\left(\varepsilon_w - 1\right) w^*_t = \varepsilon \frac{x^N_{1,t}}{x^N_{2,t}} \tag{A.24}$$

$$w_t^{1-\varepsilon} = \left(1 - \theta_w\right)\left(w^*_t\right)^{1-\varepsilon_w} + \theta_w (1-\pi_t)^{\varepsilon_w - 1} w_{t-1}^{1-\varepsilon_w} \tag{A.25}$$

6. Consumption goods price setting

$$\frac{1+\pi^*_t}{1+\pi_t} = \frac{\varepsilon_y}{\varepsilon_y - 1}\frac{x_{1,t}}{x_{2,t}} \tag{A.26}$$

$$x_{1,t} = \lambda_t mc_t Y_t + \beta\theta E_t (1+\pi_{t+1})^{\varepsilon_y} (1+\pi_t)^{-\varepsilon_y \xi_p} x_{1,t+1} \tag{A.27}$$

$$x_{2,t} = \lambda_t Y_t + \beta\theta E_t (1+\pi_{t+1})^{\varepsilon_y - 1} (1+\pi_t)^{(1-\varepsilon_y)\xi_p} x_{2,t+1} \tag{A.28}$$

$$(1+\pi_t)^{1-\varepsilon_y} = (1-\theta)\left(1+\pi^*_t\right)^{1-\varepsilon_y} + \theta \tag{A.29}$$

$$v_t = (1-\theta)\frac{1+\pi^*_t}{1+\pi_t}^{-\varepsilon_y} + (1+\pi_t)^{\varepsilon_y} \theta v_{t-1} \tag{A.30}$$

7. Monetary policy and market clearing

$$i_t = i + \phi_\pi \left(\pi_t - \pi\right) + \phi_y \left(\ln Y_t - \ln Y\right) \tag{A.31}$$

$$Y_t = C_t + I_t + S_t + G_t \tag{A.32}$$

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