Green Transition in the Euro Area: Domestic and Global Factors*

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Abstract

We analyze the economic impact of the green transition in the euro area by extending the Euro Area and Global Economy (EAGLE) model with green and brown energy sectors. Energy goods are consumed as final goods by households and as inputs by intermediate goods firms. A carbon tax manifests itself as a cost-push shock with stagflationary effects when fiscal interventions are not primary-balance neutral. Without subsidies to green energy firms, the green transition is limited to household expenditure switching towards green energy goods. When authorities direct subsidies to green energy firms, firms in the intermediate good sector also raise their demand for green energy inputs, strengthening the demand channel in the market for green energy and thus driving its price upwards. When carbon taxes are raised globally, the recession in the euro area deepens while inflationary pressures amplify, triggered partly by a weakening of the euro. Taxes on brown capital investment are also contractionary but lead to lower inflation. In this case, subsidies to investment in green energy capital can mitigate the recession. Overall though, taxes on brown capital investment are not successful in strengthening the green transition, unlike carbon taxes.

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1 Introduction

The green transition involves moving towards economic and energy sustainability by reducing dependence on fossil fuels and excessive natural resource use. This shift will impact the economy, leading, for example, to job and capital reallocation, changes in inflation dynamics, and probably short to medium-term output losses. Policymakers must therefore ensure the success of the green transition while safeguarding living standards. To this end, fiscal instruments and policies play a prominent role in climate change mitigation and adaptation. Carbon taxes and subsidies to green energy sources are considered key tools in this endeavor, for they are thought to be effective, efficient and easy to implement (Timilsina, 2022). However, successfully calibrating and implementing these tools requires a thorough understanding of their potential effects on the macroeconomy, not only in terms of aggregate output and inflation, but also at a more detailed level of disaggregation. Therefore, when designing climate change policies, important factors to take into account involve policy mix influencing wealth distribution and fiscal budget balance, as well as policy coordination. For instance, this includes consideration of their impacts on households (wealthy and hand-to-mouth) and across sectors (tradable and non-tradable; green and brown). Over the past seven years, EU has achieved only 20% emission reduction, therefore significant policy efforts at EU and national level are needed to achieve the ambitious targets set for 2030 and 2050.

In this paper, we rely on a large-scale microfounded model to analyze the macroeconomic implications of transition policies aimed at advancing the green transition, with a specific focus on carbon taxes and green subsidies. Specifically, we use the Euro Area and Global Economy (EAGLE) model (Gomes et al., 2012), a dynamic stochastic general equilibrium (DSGE) model representing the euro area (EA) within the global economy. With its detailed trade matrix and distinction between tradable and non-tradable sectors, the EAGLE model provides a comprehensive framework to evaluate both the effects of domestic environmental measures, as well as the spillovers and macroeconomic interdependencies resulting from climate policy across the EA, the US, and the rest of the world (RW).

To conduct our analysis, however, we need to extend the baseline EAGLE model with an environmental dimension. We achieve this by following existing studies, including Golosov et al.

(2014), Känzig (2023) and Coenen et al. (2023). Broadly speaking, we proceed as follows. On the supply side, monopolistically competitive brown (green) energy firms combine brown (green) capital and labour to produce a brown (green) energy good. The latter is then sold to domestic households for final consumption or to domestic intermediate tradable and non-tradable firms that use it as an input. On the demand side, households consume energy and non-energy goods using a constant elasticity of substitution (CES) aggregator. In addition, households with full access to asset markets can accumulate three types of physical capital: brown (fossil fuel-intensive), green (clean-energy intensive) and non-energy related. Importantly, accumulating new brown capital requires importing tradable goods, creating a direct channel through which foreign environmental policy affects domestic outcomes. Regarding environmental policies, the government in each region (i) imposes a carbon tax as a surcharge on the price of the brown energy; (ii) taxes households' brown capital income; and (iii) redistributes a share of these revenues to green energy producers and households.

Our first exercise evaluates the macroeconomic implications of a carbon tax implemented as a surcharge on the price of brown energy levied on both consumers and intermediate good producers. Specifically, we analyze the consequences of introducing a carbon tax exclusively within the EA, with no redistribution, alongside scenarios that incorporate the redistribution of carbon tax revenues to green energy-producing firms and financially constrained households. Furthermore, we explore the effects of globally increasing carbon taxes in a coordinated fashion.

In the absence of any redistribution and with only a domestic carbon tax, our findings align with those of Coenen et al. (2023). In this scenario, the carbon tax acts as a negative supply shock, resulting in reduced output and higher inflation. In response to this inflationary pressure, the monetary authority raises the policy rate, leading to the appreciation of the euro against the basket of currencies of its trading partners and a contraction in the trade balance. Furthermore, regarding energy usage and production, the carbon tax operates as expected: the higher price of brown energy post-tax reduces demand from both firms and households, resulting in decreased production, while green energy production increases in response.

Redirecting a share of carbon tax revenues to green energy-producing firms results in a less severe contraction in aggregate demand and output, while inflation rises less. Furthermore, compared to the scenario without subsidies, household consumption of brown energy declines, supporting the goal of promoting the transition to green energy. When redistributing a share of the carbon tax revenues to financially constrained households in addition to subsidizing green energy firms, we observe similar effects. In this case, the increase in disposable income for these households mitigates the decline in consumption and output. However, their consumption of brown energy decreases only as much as in the scenario with transfers solely to green energy firms. Consequently, this policy may not significantly accelerate the transition to green energy. Instead, a targeted subsidy aimed at encouraging the consumption of green energy goods may prove more effective.

We also consider a primary-balance-neutral policy intervention where all carbon tax revenues are redistributed equally to green energy firms and financially constrained households, leaving the government's primary balance unaffected. In this scenario, the nature of the carbon tax shock changes. The government more than offsets the downward pressures of the shock on economic activity, resulting in a mild expansion in the quarters following the shock, despite the rise in inflation. The transition to green energy by both firms in the intermediate goods sector and households is now more pronounced.

An important finding of ours relates to the demand and supply channels in the brown and green energy markets. We show that the demand channel always dominates in the brown energy market following a rise in the carbon tax, resulting in a decline in brown energy inflation before tax, despite a drop in output. Redistributive policies further strengthen the demand channel, amplifying the decline in brown energy inflation before tax. In the green energy market, without redistributive policies, the demand channel dominates, leading to a mild rise in green energy inflation after the carbon tax increase, driven mainly by rising household demand. However, this is reversed when redistributive policies are introduced. Green energy inflation falls considerably, indicating that redistributive policies strengthen the supply channel.

When carbon taxes are raised globally, the economic contraction within the EA is deeper and more prolonged compared to scenarios where carbon taxes are raised only within the EA. Additionally, the peak in inflation is slightly higher, and the overall inflationary impact is more persistent. This is partly due to the reversal in the response of the real effective exchange rate, which triggers higher non-energy inflation. In this global scenario, the real effective exchange rate depreciates for several quarters, contrasting sharply with the strong appreciation observed when carbon taxes are raised only within the EA. Consequently, the weaker euro reduces the purchasing power of households in the EA, leading to a greater decline in domestic aggregate demand when carbon taxes are raised globally.

Finally, we consider taxes on brown capital rental income accompanied by subsidies for green capital investment. We find that these measures are contractionary and deflationary, unlike the effects of a carbon tax. More importantly, they are not effective in enhancing the green transition as they fail to offset the negative impact of higher costs for brown capital on the marginal costs and output of intermediate goods firms. At the household level, this type of tax increases demand for green energy due to lower green energy prices, but to a much lesser extent compared to the impact of a carbon tax.

Literature review. Our research contributes to the expanding literature on environmental concerns within DSGE models. For instance, Golosov et al. (2014) derive an analytical expression for the optimal carbon tax, examining its sensitivity to critical factors like the discount rate and economic losses from carbon emissions. Extending this framework, Känzig (2023) incorporates nominal rigidities and household heterogeneity, emphasizing the tradeoff between reducing carbon emissions and the economic costs of climate policy.

Studies by Annicchiarico and Di Dio (2015, 2017) explore how polluting producers, facing nominal rigidities, manage abatement costs and environmental damage under government environmental policies. Additionally, Heutel (2012) suggests that emission taxation should be procyclical, aligning policy with GDP fluctuations. In a simplified Robinson Crusoe economy model, Fischer and Springborn (2011) evaluate the effectiveness of emissions cap, emissions tax, and intensity targets.

Further insights from Hassler et al. (2016) highlight technological choices and their environmental impacts, while Acemoglu et al. (2012) and Acemoglu et al. (2016) develop endogenous growth models with clean and dirty technologies, focusing on optimal carbon tax and green subsidies. Notably, Lanteri and Rampini (2023) present a stochastic overlapping generation model, demonstrating optimal investment decisions under financial constraints favoring old, dirty capital over new, clean capital.

In a closed-economy setup of a multi-sector DSGE model, Hinterlang et al. (2022) compare the effects of reducing labor taxes through increased consumption, energy taxes, or emission taxes, finding energy and emission taxes more effective in funding labor tax reductions, akin to a positive productivity shock.[1]

In contrast to these studies, we use a large, richer model, designed to assess the effects of environmental policies, both domestic and foreign, not only on real variables but also on nominal ones, notably inflation.

Our analysis aligns with research from leading policy institutions. For example, Varga et al. (2022) extend the canonical DSGE model by incorporating a finely disaggregated supply side, distinguishing between various types of energy and capital with different environmental footprints. Their model, calibrated to the European Union (EU), suggests that transitioning to a net-zero emissions economy can be facilitated by recycling carbon taxes to alleviate other distortive taxes or to subsidize clean energy sources.

Similarly, Bartocci et al. (2022) examine the macroeconomic effects within the EA economy of increased carbon taxes and subsidies for renewable energy sources, alongside interactions with central bank interventions in sovereign bond markets. Meanwhile, Del Negro et al. (2023) develop a multi-sector New Keynesian model and find that climate policies need not necessarily lead to inflation, but rather can create a tradeoff between inflation and output. This tradeoff depends significantly on the price flexibility within brown and green sectors relative to the broader economy, as well as the specific design of climate policies—whether they involve taxes or subsidies.

Other noteworthy contributions include studies by Ernst et al. (2022) and Carton et al. (2023), which employ multi-region multi-sector models to assess the impacts of climate policies such as carbon pricing and cross-border adjustments of taxation and subsidies. Erceg et al. (2024) investigate the conditions under which climate policies can mitigate inflation, highlighting that energy subsidies may effectively reduce inflation if applied regionally rather than globally.

[1] Other notable works include Airaudo et al. (2022); Angelopoulos et al. (2010); Bartocci and Pisani (2013); Carrattini et al. (2021); Economides and Xepapadeas (2018); Gallic and Vermandel (2020); Kharroubi and Smets (2023); McKibbin et al. (2020, 2021), among others.

Additionally, Ferrari and Nispi Landi (2022) identify dual effects of emission taxes, acting as a negative supply shock by raising firms' marginal costs and potentially inducing deflationary pressures as households reduce consumption and investment.

In contrast to these studies, we extend the EAGLE model, tailored for analyzing spillovers and macroeconomic interdependence among countries, to explore the international dimensions of environmental policy in detail.

A paper closely related to ours is Coenen et al. (2023), as we also assess the impact of transition policies on both inflation and economic activity and explore their interplay with fiscal and monetary policy.[2] However, there are key distinctions between our approach and Coenen et al. (2023). First, our use of the EAGLE model with its detailed trade matrix and inclusion of tradable and non-tradable sectors allows us to emphasize the open economy dimension of environmental policy. Second, we analyze different types of capital with varying environmental impacts—fossil fuel-intensive, clean energy-intensive, and non-energy-related—which enables us to examine the macroeconomic effects of taxing brown capital while subsidizing its green counterpart. Third, unlike Coenen et al. (2023), where a competitive firm combines brown and green energy into a single final energy good for production and consumption, we treat brown and green energy as distinct commodities, each subject to its own market-clearing condition. As will become evident, this enhanced level of disaggregation enables us to better trace the effects of environmental policy throughout the macroeconomy.

Lastly, our paper contributes to the literature using Integrated Assessment Models (IAMs) or Computable General Equilibrium frameworks to assess the impacts of carbon taxes. Among the earliest IAMs is the DICE/RICE family of models, which was recently reviewed by Nordhaus (2017). Other notable examples include the GCAM model of Calvin et al. (2019) and the MAgPIE model in Dietrich et al. (2019). In contrast to these studies, we employ a large-scale microfounded model, enabling us to investigate the transmission channels of climate change on the macroeconomy over the short to medium term. The aforementioned models, on the other hand, are better suited for examining the interactions between climate and the economy over

[2] Similarly, Ferrari Minesso and Pagliari (2023) conduct a three-country two-sector study on the cross-country implications of climate-related mitigation policies. They argue that an optimal policy mix should integrate fiscal measures focused on emissions reduction, adjust monetary policy in response to environmental transition costs, and promote international cooperation to minimize the economic losses from climate policies.

longer time horizons.

Organization of the paper. The paper is structured as follows. In Section 2 we provide the stylize facts with respect to fiscal and the related climate change policies. In Section 3 we provide the theoretical model extension of the EAGLE model. In Section 4 we discuss the calibration of the key structure parameters of the model, with focus on the energy sector. In Section 5 we discuss our quantitative results following carbon tax, carbon tax global coordination as well as taxes on brown capital investment. In Section 6 we conclude.

2 Fiscal instruments and policies

To shed some light on the matter we discuss the development of climate change related fiscal instruments and policies first. The EU has set ambitious long-term targets to reduce greenhouse gas (GHG) emissions and limit global warming in line with the Paris Agreement.[3] By 2030, the EU has committed to cut net GHG emissions by at least 55% compared to emissions produced in 1990, while by 2050, the EU aims to achieve carbon neutrality.

Based on current mitigation policies, significant additional policy efforts at EU and national level are needed to achieve the ambitious targets set for 2030 and 2050. As discussed by Avgousti et al. (2023), the EU has achieved its 20% GHG emission reduction target over the past seven years. Without any additional action, the European Environment Agency (EEA) projects carbon emissions to fall by around 35% by 2030, thereby falling significantly short of the reduction target of 55%. Therefore, an "effort-sharing" scheme has been put in place with binding national emission targets for 2020 and 2030 for the sectors not included in the EU Emissions Trading

[3]The Paris Agreement is a legally binding international treaty on climate change, adopted in 2015, with the goal is to limit global warning to well below 2 (preferably 1.5) degrees Celsius compared with pre-industrial levels.

System (the EU ETS). [4] [5] [6]

In order for the EU to reach its targets by 2030 and 2050, it requires additional efforts on the policy front, many of which will have a fiscal policy angle. In this respect, fiscal policy plays a prominent role in climate change mitigation and adaptation. On the expenditure side, most of the policies involve investing in clean energy sources and improving energy efficiency. On the revenue side, the EU ETS plays a prominent role, though there is a carbon price gap between the current policies and the price needed to substantially reduce GHG emissions. Last, an optimal combination of revenue policies, in particular taxes, and expenditure policies, such as subsidies and investment, is essential in order to achieve GHG emissions targets.

Focusing first on the expenditure side, public expenditure measures adopted to combat climate change are manifold and heterogeneous across countries. These measures include transfers to households and subsidies to firms to incentivize emission reductions and lower energy intensity, public expenditure to protect the environment, and public R&D spending to promote cleaner technologies and climate change mitigation. Most measures have been in place for several years and often reflect EU initiatives, such as those related to energy efficiency and a greater share of renewable energy, though green investment is below the level required to fulfil the target.

A second policy relating to the expenditure side is the elimination of environmentally harmful policies by distorting price signals. They can be beneficial for the environment, in addition to having positive budgetary effects. Among the environmentally harmful policies, reductions in energy tax obligations play a larger role than budgetary transfers in the EU. These reductions are

[4] The EU ETS is a form of environmental taxation that seeks to use the dynamics of supply and demand to reduce the EU's overall carbon emissions in line with its broader climate change reduction goals. The market price of carbon is set by cleaner firms trading allowances with more carbon-intensive firms while the overall cap on allowed emissions is reduced over time. The EU ETS works on the "cap and trade" principle and steers the carbon price through allowances for CO2 emissions that are traded at company level. Reducing the allowances has helped strengthen the price signalling effect of the EU ETS. Almost half of the CO2 emissions in the EU have been subject to the EU ETS and its provisions foresee that at least 50% of the revenues are spent on climate policies.

[5] The EU ETS was introduced in 2005 as a "cap and trade" principle and covers three sectors - (i) energy production, (ii) manufacturing and construction, and (iii) intra-EU aviation – which together account on average for around 40% of total GHG emissions in the EU. The number of GHG emission allowances was gradually reduced over time, although a significant proportion continues to be allocated freely. In fact, after hovering at very low levels for most of the first decade, the uniform carbon price increased steeply, especially during 2021 and reached more than EUR 90/tCO2 at the beginning of February 2022 (compared with an annual average of around EUR 25/tCO2 in 2020).

[6] The Effort Sharing Regulation (ESR) was set up in 2014 to complement the EU ETS via annual national targets for the non-EU ETS sectors and to support the economy-wide reduction of emissions by 2030. Discussion relating to the EU ETS will follow later in the same section.

defined as energy-related tax expenditure and can be measured by the differences in the effective tax rate across fossil fuel products and sectors. If there were no environmentally harmful tax expenditure in place, CO2 emissions from energy use would be taxed uniformly, at least when abstracting from other instruments such as the EU ETS. As discussed in Avgousti et al. (2023) on aggregate, direct budgetary transfers in support of fossil fuels in the EU peaked in 2012 but have been on a downward trend since 2016, mainly as a result of EU initiatives to foster climate change mitigation.

Turning now to the revenue side, all EU countries have environmental taxes in place, which are categorised into energy, transport, and pollution and resource taxes, with the former representing the largest share of total environmental tax revenue for all EU Member States. On average, energy taxes account for around three-quarters of environmental tax revenues in EU countries. The literature has identified carbon taxation as an effective incentive-based fiscal policy measure for climate change mitigation. Explicit carbon tax revenues in the EU are very low, as only a few EU Member States have an explicit carbon tax in place. In a few Member States, government revenues from carbon taxes are earmarked for economic activities that support climate change adaptation and mitigation. One important aspect for climate change mitigation relates to the level of and change in energy efficiency and how this determines the energy intensity of certain sectors across countries. Countries with higher implicit taxes on energy show a lower energy intensity of GDP. According to Avgousti et al. (2023), environmental tax revenues are small compared with EU countries' total tax burden, representing only 5.9% of total tax revenues in 2019 (2.4% of EU GDP). All in all, both their share of total tax revenues and the composition of environmental taxes have remained broadly stable since 2010.

Despite the recent stepping up of policy efforts mentioned above, current policy instruments, mainly financed by the Next Generation EU (NGEU) funding, may still be insufficient to encourage emission reduction through behavioural changes and increases in green energy and energy efficiency investments. Therefore, access to financing is a fundamental factor in fostering green investment policies, with green financing taking on greater significance at the national and European level.

Furthermore, carbon prices, both in the form of taxes and trading schemes, were relatively low in the EU in 2018. Due to the fact that the average explicit and implicit carbon taxes might be overestimated, the OECD developed the carbon pricing gap, which compares the percentile distribution of the actual carbon rate with a benchmark, this being EUR 60/tCO2. A high carbon pricing gap value points to only a low fraction of emissions being taxed.[7] This sizeable carbon pricing gaps suggest that carbon taxation in EU countries is too low and fragmented to achieve the EU emission reduction targets.

When designing climate change policy, an issue which is important to take into account is the policy mix and the impact of taxes and other instruments on wealth distribution. Such policies may have more of an impact on poorer households, leading to the need to compensate lower income groups that are more affected by climate change and the respective mitigation policies. All in all, the effects of a carbon tax on redistribution, as well as its political feasibility, ultimately depend on the way its revenue is rebated.

Last but not least, addressing climate change should involve a collective responsibility and no single country can tackle it alone. Policymakers must coordinate their efforts by setting minimum carbon prices, removing trade barriers, avoiding costly subsidy races, and developing an international architecture to crowd-in private financing. Such international coordination is required to minimize adverse spillovers and accelerate decarbonization. Any uncoordinated actions may pose significant risks by distorting trade and investment flows that could give rise to competitiveness concerns. Carbon taxation can entail a loss of competitiveness when it is not multilaterally imposed, discouraging climate change mitigation and adaptation efforts. These issues have informed recent discussions at EU level about the implementation of a Carbon Border Adjustment Mechanism (CBAM), as well as regarding the efficient recycling of carbon taxation revenues to mitigate the potentially adverse short-term effects of carbon taxes.

3 Modelling environment

The Euro Area and Global Economy (EAGLE) model is a multi-country DSGE model of the EA developed by the Bank of Italy, Bank of Portugal, and the ECB (Gomes et al., 2010, 2012). Like

[7]The implicit carbon tax combines the explicit carbon tax with EU ETS carbon pricing, weighted by the sectors' share of total emissions.

the ECB's New Area Wide Model (NAWM, Coenen et al., 2008) and the IMF's Global Economy Model (GEM, Laxton and Pesenti, 2003), the EAGLE model is micro-founded and includes nominal price and wage rigidities, capital accumulation, and international trade in goods and bonds. The EAGLE model extends the NAWM by introducing tradable and non-tradable sectors and a monetary union.

We extend the EAGLE model to include energy sectors, drawing on the works of Golosov et al. (2014), Känzig (2023) and Coenen et al. (2023). However, our model differs from Coenen et al. (2023) in several key aspects. Households consume final non-energy, brown energy, and green energy goods. The shares of energy goods in the consumption bundle are treated as preference parameters. Although this structure allows for different shares of energy goods for Ricardian and non-Ricardian households (as in Känzig, 2023), we assume equal weights for simplicity. Moreover, households invest in regular, brown, and green capital, allowing us to differentiate between taxes on brown capital and subsidies for green investment.

On the supply side, we distinguish between monopolistically competitive brown and green energy firms. Brown energy firms use brown capital and labor, while green energy firms use green capital and labor. The product of the energy firms is sold only domestically to households for final consumption or to domestic intermediate tradable and non-tradable goods firms that use it as an input. These intermediate goods firms are also monopolistically competitive and use regular capital, labor, and energy inputs with a Cobb-Douglas production function.

The central bank sets the short-term nominal interest rate using a standard Taylor-type rule, reacting to increases in consumer price inflation and real activity at the EA level. The US and the RW have their own nominal interest rates and nominal exchange rates. The government collects tax revenues through various taxes, including lump-sum taxes, VAT, labor income tax, payroll contributions, and dividend taxes. Regarding climate policy, the government in each region uses carbon taxes and taxes on brown capital investment. We consider different redistribution schemes, targeting green energy firms, financially constrained households, or both. In each block, the public debt is stabilized through a fiscal rule.

Each region's size is determined by the share of resident households and domestic sector-specific firms, both defined over a continuum of mass s. Our focus is on the Home country (H), with similar characterizations for other countries and the new features compared to the standard EAGLE model.

3.1 Firms

On the production side of the economy, we assume the following structure:

- Final Consumption Goods Producers: There is a continuum of perfectly competitive producers that bundle tradable and non-tradable goods to produce a final consumption good (see A.1).
- Final Investment Goods Producers: There is also a continuum of perfectly competitive producers for final investment goods. Our model includes three types of capital—general, brown, and green—resulting in three types of final investment goods producers:
  - Final general investment goods producers (see A.2).
  - Final brown investment goods producers.
  - Final green investment goods producers.

  Each type of producer bundles tradable and non-tradable goods to produce their respective final goods.
- Intermediate Tradable Goods Producers: These firms are monopolistically competitive, selling their goods both domestically and abroad. They employ general capital, labor, and both brown and green energy inputs using a Cobb-Douglas technology.
- Intermediate Non-Tradable Goods Producers: These firms are also monopolistically competitive but sell their goods only domestically. They follow a production technology similar to that of tradable goods firms.
- Energy Sector: This sector is monopolistically competitive, producing both brown and green energy goods. The energy goods are sold to consumers for final consumption and to intermediate goods firms as inputs. Brown energy producers combine brown capital and labor using a Cobb-Douglas technology, while green energy producers use green capital and labor with a similar technology.

The production structure is symmetric across all four regions of the model. For brevity, we present the home country only, with similar expressions holding for the other regions, and focus on the energy dimension of the model (the remaining part being close to the original EAGLE).[8]

3.1.1 Final goods sector: energy investment goods

Firms producing final non-tradable goods are symmetric, act under perfect competition and use non-tradable, domestic and imported tradable intermediate goods as inputs. The intermediate goods are assembled according to a constant elasticity of substitution (CES) technology. Final goods can be used for private consumption and investment.

Brown energy investment good. Each firm x ($x \in \left[0, s^H\right]$) produces a brown energy investment good $Q^{IB}(x)$ with the following CES technology:

$$Q_t^{IB}(x) = \left[v_{IB}^{\frac{1}{\mu_{IB}}} TT_t^{IB}(x)^{\frac{\mu_{IB}-1}{\mu_{IB}}} + (1 - v_{IB})^{\frac{1}{\mu_{IB}}} NT_t^{IB}(x)^{\frac{\mu_{IB}-1}{\mu_{IB}}} \right]^{\frac{\mu_{IB}}{\mu_{IB}-1}} \tag{1}$$

where:

$$TT_t^{IB}(x) = \left[v_{TIB}^{\frac{1}{\mu_{TIB}}} HT_t^{IB}(x)^{\frac{\mu_{TIB}-1}{\mu_{TIB}}} + (1 - v_{TIB})^{\frac{1}{\mu_{TIB}}} IM_t^{IB}(x)^{\frac{\mu_{TIB}-1}{\mu_{TIB}}} \right]^{\frac{\mu_{TIB}}{\mu_{TIB}-1}} \tag{2}$$

Two intermediate inputs are used in the production of the consumption good. A basket NT_t^{IB} of non-tradable intermediate goods and a composite bundle TT_t^{IB} of domestic (HT_t^{IB}) and imported (IM_t^{IB}) tradable goods. The parameter $\mu_{IB} > 0$ denotes the intra-temporal elasticity of substitution between tradable and non-tradable goods, while v_{IB} ($0 \leq v_{IB} \leq 1$) measures the weight of the tradable bundle in the production of the consumption good. For the bundle of tradable goods, the parameter $\mu_{TIB} > 0$ denotes the intra-temporal elasticity of substitution between the bundles of domestic and foreign tradable intermediate goods, while v_{TIB} ($0 \leq v_{TIB} \leq 1$) measures the weight of domestic tradable intermediate goods. Imports $IM_t^{IB}(x)$ are

[8] Implications on market clearing conditions are also shown in the Annex A.3.

a CES function of basket of goods imported from other countries:

$$IM_t^{IB}(x) = \left[\sum_{CO \neq H} \left(v_{IMIB}^{H,CO} \right)^{\frac{1}{\mu_{IMIB}}} \left(IM_t^{C,CO}(x) \left(1 - \Gamma_{IM^{IB}}^{H,CO}(\gamma_{IMIB}) \right) \right)^{\frac{\mu_{IMIB}-1}{\mu_{IMIB}}} \right]^{\frac{\mu_{IMIB}}{\mu_{IMIB}-1}} \quad (3)$$

where $\mu_{IMIB} > 0$ and the coefficients $v_{IMIB}^{H,CO}$ are such that:

$$0 \leq v_{IMIB}^{H,CO} \leq 1, \quad \sum_{CO \neq H} v_{IMIB}^{H,CO} = 1 \quad (4)$$

The term $\Gamma_{IM^{IB}}^{H,CO}(\gamma_{IMIB})$ represents adjustment costs on bilateral investment imports of country H from country CO.

Green energy investment good. Each firm x ($x \epsilon \left[0, s^H\right]$) produces a green energy investment good $Q^{IG}(x)$ with the following CES technology:

$$Q_t^{IG}(x) = \left[v_{IG}^{\frac{1}{\mu_{IG}}} HT_t^{IG}(x)^{\frac{\mu_{IG}-1}{\mu_{IG}}} + (1 - v_{IG})^{\frac{1}{\mu_{IG}}} NT_t^{IG}(x)^{\frac{\mu_{IG}-1}{\mu_{IG}}} \right]^{\frac{\mu_{IG}}{\mu_{IG}-1}} \quad (5)$$

Two intermediate inputs are used in the production of the green investment good. A basket NT_t^{IG} of non-tradable intermediate goods and a HT_t^{IG} of tradable goods. The parameter μ_{IG} > 0 denotes the intra-temporal elasticity of substitution between tradable and non-tradable goods, while v_{IG} ($0 \leq v_{IG} \leq 1$) measures the weight of the tradable bundle in the production of the green investment good.

3.1.2 Energy sector: Brown and green energy producers

Consistent with the data (see Dhyne et al. (2006)) and following Känzig (2023), we assume that final good firms in energy sectors are monopolistically competitive and produce their goods by adopting a technology, along the lines of Golosov et al. (2014). Similar to Coenen et al. (2023), we assume that brown and green energy firms set their prices infrequently in the spirit of Calvo (1983).

Each brown brand is produced by a firm b belonging to the continuum of mass s^H ($b \in [0, s^H]$).

Similarly, each green brand is produced by a firm g, also defined over the continuum of mass s^H ($g \in [0, s^H]$).

Technology. Each brown and green good, respectively b and g, is produced using a Cobb-Douglas technology:

$$Y_{B,t}^{S}(b) = z_{B,t} K_{B,t}^{D}(b)^{\gamma_B} N_t^D(b)^{1-\gamma_B} - \psi_B \tag{6}$$

$$Y_{G,t}^{S}(g) = z_{G,t} K_{G,t}^{D}(g)^{\gamma_G} N_t^D(g)^{1-\gamma_G} - \psi_G \tag{7}$$

where ψ_B and ψ_G are fixed costs taking the same values across firms belonging to the same sector. The inputs are homogeneous capital services, $K_{B,t}^D(b)$ and $K_{G,t}^D(g)$, and an index of differentiated labor services, $N_t^D(b)$ and $N_t^D(g)$. Capital and labor services are supplied by domestic households under perfect competition and monopolistic competition, respectively. In addition, $z_{B,t}$ and $z_{G,t}$ are sector-specific productivity shocks. The profits of the brown energy firms receive the following form:

$$P_{B,t} Y_{B,t}^S(b) - \left(1 + \tau_t^{W_F}\right) W_t N_t^D(b) - R_{B,t}^K K_{B,t}(b) \tag{8}$$

To support the green transition, firms in the green energy sector receive a subsidy, $\tau_t^{E_G}$. The variable $\tau_t^{W_F}$ is a payroll tax rate levied by the domestic government on wage payments. We assume it is the same across firms.

$$\left(1 + \tau_t^{E_G}\right) P_{G,t} Y_{G,t}^S(g) - \left(1 + \tau_t^{W_F}\right) W_t N_t^D(g) - R_{G,t}^K K_{G,t}(g) \tag{9}$$

Cost minimization. Firms belonging to the brown (green) sector take the rental cost of capital $R_{B,t}^K$ ($R_{G,t}^K$) and the aggregate wage index W_t as given. Firms belonging to the brown sector demand capital and labor services to minimize total input cost, $R_{B,t}^K K_{B,t}^D(b) + \left(1 + \tau_t^{W_F}\right) W_t N_t^D(b)$, subject to the production function, (6). Similarly, firms in the green sector minimize the cost $R_{G,t}^K K_{G,t}^D(g) + \left(1 + \tau_t^{W_F}\right) W_t N_t^D(g)$ subject to the production function (7).

The first-order conditions of the firms' cost minimization problem with respect to capital and labor inputs - respectively $K_{B,t}^D(b)$ and $N_t^D(b)$ for the brown sector, $K_{G,t}^D(g)$ and $N_t^D(g)$ for the green sector - are sector-specific. Given that all firms face the same factor prices and all firms use the same technology, the nominal marginal cost is identical across firms within each sector (i.e., $MC_{B,t} = MC_t(b)$ and $MC_{G,t} = MC_t(g)$):

$$MC_{B,t} = \frac{1}{z_{B,t}(\gamma_B)^{\gamma_B}(1-\gamma_B)^{1-\gamma_B}}\left(R^K_{B,t}\right)^{\gamma_B}\left(\left(1+\tau^{W_F}_t\right)W_t\right)^{1-\gamma_B} \quad (10)$$

$$MC_{G,t} = \frac{1}{z_{G,t}(\gamma_G)^{\gamma_G}(1-\gamma_G)^{1-\gamma_G}}\left(R^K_{G,t}\right)^{\gamma_G}\left(\left(1+\tau^{W_F}_t\right)W_t\right)^{1-\gamma_G} \quad (11)$$

Price setting. Each firm in the energy goods sector sells its differentiated output under monopolistic competition. Brown and green energy-producing firms set their prices infrequently *à la* Calvo (1983). Specifically, brown energy-producing firms their price with probability $(1-\xi_B)$ maximize the discounted sum of their current and expected future nominal profits:

$$E_t\sum_{k=0}^{\infty}\Lambda_{I,t,t+k}\,\xi_B^k\left[\widetilde{P}_{B,t}(b)Y^S_{B,t+k}(b) - MC_{B,t+k}\left(Y^S_{B,t+k}(b)+\psi_B\right)\right] \quad (12)$$

subject to the total demand for energy brand b of firms in the intermediate goods sectors and households, each specified in detail below. In the expression above $\Lambda_{I,t,t+k}$ is the stochastic discount factor of the financially unconstrained households (type I) to be specified in section 3.2.1 and who are assumed to own brown energy producing firms. Since we assume that all brown energy-producing firms that reset their price choose the same price ($\widetilde{P}_{B,t}$), we drop index b in what follows. The first-order condition reads as follows:

$$\frac{\widetilde{P}_{B,t}}{P_{B,t}} = \frac{\theta_B}{\theta_B-1}\frac{F_{B,t}}{G_{B,t}} \quad (13)$$

where θ_B is the elasticity of substitution across brown energy good varieties. Furthermore, $F_{B,t}$ and $G_{B,t}$ are specified as follows:

$$F_{B,t} = \frac{MC_{B,t}}{P_{B,t}}Y^S_{B,t} + \xi_B\beta E_t\left[\frac{\Lambda_{I,t+1}}{\Lambda_{I,t}}\left(\frac{\pi_{B,t+1}}{\pi^{\chi_B}_{B,t}\pi_B^{1-\chi_B}}\right)^{1-\theta_B}F_{B,t+1}\right] \quad (14)$$

$$G_{B,t} = Y^S_{B,t} + \xi_B\beta E_t\left[\frac{\Lambda_{I,t+1}}{\Lambda_{I,t}}\left(\frac{\pi_{B,t+1}}{\pi^{\chi_B}_{B,t}\pi_B^{1-\chi_B}}\right)^{\theta_B-1}G_{B,t+1}\right] \quad (15)$$

The above recursive expressions also account for the possibility that producers that cannot optimally reset their price in the current period index their price, $P_{B,t-1}$ to a weighted average of past period's brown energy gross inflation, $\pi_{B,t-1} = P_{B,t-1}/P_{B,t-2}$ and its steady state counterpart, π_B. The degree of indexation is governed by parameter χ_B.

The aggregate brown energy price index is a weighted average of the price that is reset in a generic period t and the past price indexed to past and steady-state brown energy price inflation:

$$P_{B,t} = \left[\xi_B \left(P_{B,t-1}\pi_{B,t}^{\chi_B}\pi_B^{1-\chi_B}\right)^{1-\theta_B} + (1-\xi_B)\left(\widetilde{P}_{B,t}\right)^{1-\theta_B}\right]^{\frac{1}{1-\theta_B}} \tag{16}$$

Turning now to green energy-producing firms, as explained above, they receive a subsidy that is a fraction ς_E of the government's carbon tax revenues (specified in section 3.3.2) and reset their price with probability $(1-\xi_G)$. When instead they do not reset their price, they index the prevailing price of the previous period, $P_{G,t-1}$, to the previous period's green energy price inflation, $\pi_{G,t}$, and its steady state counterpart, π_G. Once re-setting the price, the energy good firm of brand g maximizes the expected discounted sum of its future nominal profits:

$$E_t \sum_{k=0}^{\infty} \Lambda_{I,t,t+k}\, \xi_G^k \left[\left(1+\tau_{t+k}^{E_G}\right)\widetilde{P}_{G,t}(g) Y_{G,t+k}^S(g) - MC_{G,t+k}\left(Y_{G,t+k}^S(g) + \psi_G\right)\right] \tag{17}$$

subject to the total demand for energy brand g of firms in the intermediate goods sectors and households, each specified in detail below. In the expression above, $\Lambda_{I,t,t+k}$, is again the stochastic discount factor of type I households (to be specified below) who are assumed to own green energy firms. The first order condition reads as follows:

$$\frac{\widetilde{P}_{G,t}}{P_{G,t}} = \frac{\theta_G}{\theta_G - 1}\frac{F_{G,t}}{G_{G,t}} \tag{18}$$

where θ_G is the elasticity of substitution across green energy good varieties. Furthermore, $F_{G,t}$

and $G_{G,t}$ are specified as follows:

$$F_{G,t} = \frac{MC_{G,t}}{P_{G,t}} Y_{G,t}^S + \xi_G \beta E_t \left[\frac{\Lambda_{I,t+1}}{\Lambda_{I,t}} \left(\frac{\pi_{G,t+1}}{\pi_{G,t}^{\chi_G} \pi_G^{1-\chi_G}} \right)^{1-\theta_G} F_{G,t+1} \right] \tag{19}$$

$$G_{G,t} = \left(1 + \tau_t^{E_G}\right) Y_{G,t}^S + \xi_G \beta E_t \left[\frac{\Lambda_{I,t+1}}{\Lambda_{I,t}} \left(\frac{\pi_{G,t+1}}{\pi_{G,t}^{\chi_G} \pi_G^{1-\chi_G}} \right)^{\theta_G - 1} G_{G,t+1} \right] \tag{20}$$

where parameter χ_G determines the degree of indexation to past green energy price inflation. Since we assume that all the green energy-producing firms that reset their prices choose the same price, we have dropped index g in the expressions above. The aggregate green energy price index is a weighted average of the price that is reset in a generic period t ($\widetilde{P}_{G,t}$) and the past price indexed to past and steady-state green energy price inflation:

$$P_{G,t} = \left[\xi_G \left(P_{G,t-1} \pi_{G,t}^{\chi_G} \pi_G^{1-\chi_G} \right)^{1-\theta_G} + (1 - \xi_G) \left(\widetilde{P}_{G,t} \right)^{1-\theta_G} \right]^{\frac{1}{1-\theta_G}} \tag{21}$$

3.1.3 Intermediate goods firms

There are firms producing tradable and non-tradable intermediate goods (brands) under a monopolistic competition regime. Each tradable brand is produced by a firm h belonging to the continuum of mass s^H ($h \in [0, s^H]$). Tradable goods firms sell their goods at home and abroad and engage in local currency pricing. Each non-tradable brand is produced by a firm n, also defined over the continuum of mass s^H ($n \in [0, s^H]$). Both sectors are using brown and green energy goods.

Technology. Each non-tradable and tradable intermediate good, respectively n and h, is produced using a Cobb-Douglas technology:

$$Y_{T,t}^S(h) = e^{-\lambda \mathcal{S}_{E,t}} z_{T,t} K_t^D(h)^{\alpha_{KT}} N_t^D(h)^{\alpha_{NT}} E_{B,t}^D(h)^{\alpha_{BT}} E_{G,t}^D(h)^{\alpha_{GT}} - \psi_T \tag{22}$$

$$Y_{N,t}^S(n) = e^{-\lambda \mathcal{S}_{E,t}} z_{N,t} K_t^D(n)^{\alpha_{KN}} N_t^D(n)^{\alpha_{NN}} E_{B,t}^D(n)^{\alpha_{BN}} E_{G,t}^D(n)^{\alpha_{GN}} - \psi_N \tag{23}$$

where ψ_T and ψ_N are fixed costs taking the same values across firms belonging to the same sector.[9] The function $e^{-\lambda \mathcal{S}_{E,t}}$ captures climate damages, where $\mathcal{S}_{E,t}$ is the atmospheric carbon concentration while λ is a scaling parameter. This term gives rise to a feedback loop between climate and the economy. Non-energy inputs are homogeneous capital services, $K_t^D(n)$ and $K_t^D(h)$, and an index of differentiated labor services, $N_t^D(n)$ and $N_t^D(h)$. Capital and labor services are supplied by domestic households under perfect competition and monopolistic competition, respectively. $z_{N,t}$ and $z_{T,t}$ are sector-specific productivity shocks, while $E_{B,t}^D(\cdot)$ and $E_{G,t}^D(\cdot)$ represent the demand for brown and green energy goods by intermediate goods firms, specified as follows:

$$E_{B,t}^D(h) = \alpha_{BT} MC_{T,t}(h) \frac{Y_{T,t}^S + \psi_T}{(1+\tau^{E_B})P_{B,t}} \tag{24}$$

$$E_{G,t}^D(h) = \alpha_{GT} MC_{T,t}(h) \frac{Y_{T,t}^S + \psi_T}{P_{G,t}} \tag{25}$$

where the corresponding demand functions of the non-tradable good firm producing variety n are defined in a similar manner. $MC_{T,t}(h)$ denotes the marginal cost of the tradable good firm, to be specified below. Tradable and non-tradable good producers face a carbon tax, $\tau_t^{E_B}$, which is levied as a surcharge on the price of the brown energy good.

Carbon emission. The current level of atmospheric carbon concentration in the production of tradables and non-tradables is introduced as in Golosov et al. (2014), and is a function of current and part emissions:

$$\mathcal{S}_{E,t} = \sum_{s=0}^{\infty} (1-\varpi_s) \frac{E_{B,t-s}}{E_{G,t-s}} \quad \text{with} \quad 1-\varpi_s = \phi_L + (1-\phi_L)\,\phi_0\,(1-\phi)^s . \tag{26}$$

where ϕ_L is the share of carbon emitted into the atmosphere staying in it forever while ϕ_0 is the remaining share of emissions that decay over time at a geometric rate $1-\phi$. ϖ_s represents the amount of carbon that is left in the atmosphere after s periods. We can thus re-write in recursive form as:

$$\mathcal{S}_{E,t} = (1-\phi)\,\mathcal{S}_{E,t-1} + \phi_0 \left(\frac{E_{B,t}}{E_{G,t}}\right) \tag{27}$$

[9] We assume constant returns to scale so that $\alpha_{KT} + \alpha_{NT} + \alpha_{BT} + \alpha_{GT} = 1$ and $\alpha_{KN} + \alpha_{NN} + \alpha_{BN} + \alpha_{GN} = 1$

Cost minimization. Firms of the intermediate sectors take the rental cost of capital R_t^K, the aggregate wage index W_t and (brown and green) energy prices ($P_{B,t}$ and $P_{G,t}$) and as given. They minimize total input cost: $R_t^K K_t^D(\cdot) + P_{B,t}E_{B,t}^D(\cdot) + P_{G,t}E_{G,t}^D(\cdot) + \left(1+\tau_t^{W_F}\right) W_t N_t^D(\cdot)$ subject to their respective production function, (22 and 23). Given that all firms face the same factor prices and all firms use the same technology, the nominal marginal cost is identical across firms within each sector (i.e., $MC_{N,t} = MC_t(n)$ and $MC_{T,t} = MC_t(h)$):

$$MC_{T,t} = \mathcal{A}_{T,t}^{-1} \left(R_t^K\right)^{\alpha_{KT}} \left(P_{B,t}\right)^{\alpha_{BT}} \left(P_{G,t}\right)^{\alpha_{GT}} \left[\left(1+\tau_t^{W_F}\right) W_t\right]^{1-\alpha_{KT}-\alpha_{BT}-\alpha_{GT}} \tag{28}$$

$$MC_{N,t} = \mathcal{A}_{N,t}^{-1} \left(R_t^K\right)^{\alpha_{KN}} \left(P_{B,t}\right)^{\alpha_{BN}} \left(P_{G,t}\right)^{\alpha_{GN}} \left[\left(1+\tau_t^{W_F}\right) W_t\right]^{1-\alpha_{KN}-\alpha_{BN}-\alpha_{GN}} \tag{29}$$

with

$$\mathcal{A}_{T,t} = e^{-\lambda \mathcal{S}_{E,t}} z_{T,t} \left(\alpha_{KT}\right)^{\alpha_{KT}} \left(\alpha_{BT}\right)^{\alpha_{BT}} \left(\alpha_{GT}\right)^{\alpha_{GT}} \left(1-\alpha_{KT}-\alpha_{BT}-\alpha_{GT}\right)^{1-\alpha_{KT}-\alpha_{BT}-\alpha_{GT}}$$

and

$$\mathcal{A}_{N,t} = e^{-\lambda \mathcal{S}_{E,t}} z_{N,t} \left(\alpha_{KN}\right)^{\alpha_{KN}} \left(\alpha_{BN}\right)^{\alpha_{BN}} \left(\alpha_{GN}\right)^{\alpha_{GN}} \left(1-\alpha_{KN}-\alpha_{BN}-\alpha_{GN}\right)^{1-\alpha_{KN}-\alpha_{BN}-\alpha_{GN}}.$$

Price setting. Firms in the tradable and non-tradable goods sectors operate under monopolistic competition setting their prices infrequently *à la* Calvo (1983). As mentioned above, tradable goods firms sell their goods domestically and abroad, opting for local currency pricing, meaning that they set a different price for their good according to the destination market. Firms in the non-tradable sector sell their goods domestically only. The full description of the maximization problem of tradable and non-tradable goods firms is identical to that in the original model of Gomes et al. (2012) and in order to save space we do not report them here, directing thus the reader to the relevant section of their paper.

3.2 Households

There are two types of households, I and J. I-type households are indexed by $i \in [0, s^H(1-\omega)]$. They have access to financial markets, where they buy and sell domestic government bonds and internationally traded bonds, accumulate physical capital (regular, brown or green) and rent its services to firms, hold money for transaction purposes. J-type households are indexed by $j \in (s^H(1-\omega), s^H]$. They cannot trade in financial and physical assets but they can intertemporally smooth consumption by adjusting their holdings of money. Both types of households supply differentiated labor services and act as wage setters in monopolistically competitive markets.

Both types of households consume energy and non-energy goods using a CES aggregator:

$$\mathbb{C}_t(z) = \left(\nu_{C,z}^{\frac{1}{\epsilon_C}} \quad C_t(z)^{\frac{\epsilon_C - 1}{\epsilon_C}} + (1 - \nu_{C,z})^{\frac{1}{\epsilon_C}} \quad C_{E,t}(z)^{\frac{\epsilon_C - 1}{\epsilon_C}} \right)^{\frac{\epsilon_C}{\epsilon_C - 1}}, \quad \text{for} \quad z = I, J \tag{30}$$

where ϵ_C is the intra-temporal elasticity between non-energy and energy consumption goods, $\nu_{C,z}$ is the share of non-energy consumption goods in the consumption bundle of type $z = I$ (wealthy) or type $z = J$ (hand-to-mouth) household. For simplicity, we assume that both types of households have the same shares of non-energy and energy goods in their baskets, so that $\nu_{C,I} = \nu_{C,J}$. The consumption of energy goods is further decomposed into:

$$C_{E,t}(z) = \left(\nu_{B,z}^{\frac{1}{\epsilon_{BG}}} \left(C_{B,t}(z)\right)^{\frac{\epsilon_{BG} - 1}{\epsilon_{BG}}} + (1 - \nu_{B,z})^{\frac{1}{\epsilon_{BG}}} \left(C_{G,t}(z)\right)^{\frac{\epsilon_{BG} - 1}{\epsilon_{BG}}} \right)^{\frac{\epsilon_{BG}}{\epsilon_{BG} - 1}}, \quad \text{for} \quad z = I, J \tag{31}$$

where $C_{B,t}$ and $C_{G,t}$ represent consumption in brown and green energy goods while $\nu_{B,z}$ is the share of brown energy goods in the energy bundle of household I and J, respectively. For simplicity, we assume that both household types have the same shares of brown and green energy goods in their baskets, so that $\nu_{B,I} = \nu_{B,J}$. ϵ_{BG} is the intra-temporal elasticity of substitution between brown and green energy goods.

Given that household types have the same shares of non-energy and energy goods in their consumption bundles, the **aggregate price index** is defined as:[10]

$$\mathcal{P}_{\mathbb{C},t} = \left(\nu_C P_{C,t}^{1-\epsilon_C} + (1 - \nu_C) P_{C_E,t}^{1-\epsilon_C} \right)^{\frac{1}{1-\epsilon_C}} \tag{32}$$

where $\nu_C = \nu_{C,I} = \nu_{C,J}$. $P_{C,t}$ is the price of non-energy consumption goods and $P_{C_E,t}$ is the aggregate price index of energy goods. Consumers face a tax, $\tau_t^{E_B}$, which is levied as a surcharge on the price of the brown energy good.[11] Hence, the aggregate price index of energy goods is

[10]Notice that the reference price (*numéraire*) set to unity in the model is now the total consumption deflator including energy goods ($\mathcal{P}_{\mathbb{C},t} = 1$), implying $P_{C,t} = \left[\upsilon_C \left(P_{T^C,t}\right)^{1-\mu_C} + (1 - \upsilon_C) \left(P_{NT,t}\right)^{1-\mu_C} \right]^{\frac{1}{1-\mu_C}}$ where $P_{T^C,t}$ and $P_{NT^C,t}$ represent the price of total tradable consumption goods and the price of non-tradable consumption goods respectively, as defined in the original EAGLE model.

[11]For simplicity, we assume that the carbon tax rate imposed on consumers is equal to that on tradable and non-tradable goods firms.

defined as:

$$P_{C_E,t} = \left(\nu_B \left((1+\tau_t^{E_B})P_{B,t}\right)^{1-\epsilon_{BG}} + (1-\nu_B)\left(P_{G,t}\right)^{1-\epsilon_{BG}}\right)^{\frac{1}{1-\epsilon_{BG}}} \tag{33}$$

where $\nu_B = \nu_{B,I} = \nu_{B,J}$. Since we restrict ourselves to identical shares energy and non-energy goods and identical shares of brown and green energy goods in the consumption bundles across households, the energy price indices in (32) and (33) are common for Ricardian and non-Ricardian ones. Expenditure minimization yields the demand schedules for non-energy consumption and energy goods:

$$C_{B,t}(z) = \left(\frac{\left(1+\tau_t^{E_B}\right)P_{B,t}}{P_{C_E,t}}\right)^{-\epsilon_{BG}} \left(\frac{P_{C_E,t}}{\mathcal{P}_{\mathbb{C},t}}\right)^{-\epsilon_e} \nu_{B,z}\left(1-\nu_{C,z}\right)\mathbb{C}_t(z), \tag{34}$$

$$C_{G,t}(z) = \left(\frac{P_{G,t}}{P_{C_E,t}}\right)^{-\epsilon_{BG}} \left(\frac{P_{C_E,t}}{\mathcal{P}_{\mathbb{C},t}}\right)^{-\epsilon_e} \left(1-\nu_{B,z}\right)\left(1-\nu_{C,z}\right)\mathbb{C}_t(z), \tag{35}$$

$$C_t(z) = \left(\frac{P_{C,t}}{\mathcal{P}_{\mathbb{C},t}}\right)^{-\epsilon_e} \nu_{C,z}\mathbb{C}_t(z), \qquad \text{for} \quad z = I, J \tag{36}$$

3.2.1 I-type households

Household i gains utility from consumption $\mathbb{C}_t(i)$ and disutility from working $N_t(i)$. In particular, there is external habit formation in consumption, which means that its utility depends positively on the difference between the current level of individual consumption, $\mathbb{C}_t(i)$, and the lagged average consumption level of households of type I, $\mathbb{C}_{I,t-1}$.

Each household i maximizes its lifetime utility by choosing the consumption and investment goods, $\mathbb{C}_t(i)$ and $I_t(i)$ respectively, the level of the general physical capital stock, $K_{t+1}(i)$ and its utilization rate $u_t(i)$, the level of the brown capital stock, $K_{B,t+1}(i)$ and its utilization rate $u_{B,t}(i)$, the level of the green capital stock, $K_{G,t+1}(i)$ and its utilization rate $u_{G,t}(i)$ holdings of domestic government bonds and internationally traded bonds, $B_{t+1}(i)$ and $B^*_{t+1}(i)$ respectively, and holdings of money, $M_t(i)$. We refer to these households as financially unconstrained.

Household i lifetime utility function is then:

$$E_t\left[\sum_{k=0}^{\infty}\beta^k\left(\frac{1-\kappa}{1-\sigma}\left(\frac{\mathbb{C}_{t+k}(i)-\kappa\mathbb{C}_{I,t+k-1}}{1-\kappa}\right)^{1-\sigma} - \frac{1}{1+\zeta}N_{t+k}(i)^{1+\zeta}\right)\right] \tag{37}$$

where β $(0 < \beta < 1)$ is the discount rate, σ $(\sigma > 0)$ denotes the inverse of the intertemporal elasticity of substitution and ζ $(\zeta > 0)$ is the inverse of the elasticity of work effort with respect to the real wage (Frisch elasticity). The parameter κ $(0 \leq \kappa \leq 1)$ measures the degree of external habit formation in consumption.

The individual budget constraint for household i is:

$$
\begin{aligned}
& \left(1+\tau_t^C+\Gamma_v\right) \mathcal{P}_{\mathbb{C},t} \mathbb{C}_t(i) + P_{I,t} I_t(i) + P_{IB,t} I_{B,t}(i) + P_{IG,t} I_{G,t}(i) + R_t^{-1} B_{t+1}(i) \\
& + \left(\left(1-\Gamma_{B^*,t}\right) R_t^*\right)^{-1} S_t^{H,US} B_{t+1}^*(i) + M_t(i) + \Phi_t(i) + \Xi_t \\
= & \left(1-\tau_t^N-\tau_t^{W_H}\right) W_t(i) N_t(i) + \left(1-\tau_t^D\right)\left(D_t(i)+D_t^B(i)+D_t^G(i)\right) + TR_t(i) - T_t(i) \\
& + \left(1-\tau_t^K\right)\left(R_t^K u_t(i) - \Gamma_u\left(\gamma_u\right) P_{I,t}\right) K_t(i) + \tau_t^K \delta P_{I,t} K_t(i) \\
& + \left(1-\tau_t^{K_B}\right)\left(R_{B,t}^K u_{B,t}(i) - \Gamma_{u_B}\left(\gamma_{u_B}\right) P_{IB,t}\right) K_{B,t}(i) + \tau_t^{K_B} \delta_B P_{IB,t} K_{B,t}(i) \\
& + \left(1+\tau_t^{K_G}\right)\left(R_{G,t}^K u_{G,t}(i) - \Gamma_{u_G}\left(\gamma_{u_G}\right) P_{IG,t}\right) K_{G,t}(i) + \tau_t^{KG} \delta_G P_{IG,t} K_{G,t}(i) \\
& + B_t(i) + S_t^{H,US} B_t^*(i) + M_{t-1}(i)
\end{aligned} \tag{38}
$$

where $\mathcal{P}_{\mathbb{C},t}$ and $P_{I,t}$ are the prices of a unit of the private consumption good and the (non-energy) investment good, respectively. $P_{IB,t}$ and $P_{IG,t}$ are brown and green investment deflators. R_t and R_t^* denote, respectively, the risk-less returns on domestic government bonds, $B_{t+1}(i)$, and internationally traded bonds, $B_{t+1}^*(i)$. Domestically traded bond are denominated in domestic currency (euro). Internationally traded bonds are denominated in US dollars. $S_t^{H,US}$ is the nominal exchange rate, expressed in terms of units of Home currency per unit of the US dollars. The term Γ_{B^*} represents a financial intermediation premium that the household must pay when taking a position in the international bond market. The incurred premium is rebated in a lump-sum manner (see variable Ξ_t in the budget constraint) to domestic I-type households, that own firms. The term $M_t(i)$ represents domestic money holdings.

The fiscal authority levies taxes on the household's gross income and spending. In particular, τ_t^C denotes the consumption tax rate levied on consumption purchases, τ_t^N, τ_t^K (respectively $\tau_t^{K_B}$) and τ_t^D represent tax rates levied respectively on wage income, rental capital (respectively brown) income and dividends from firms ownership, while $\tau_t^{W_H}$ is an additional pay-roll tax rate levied on household wage income that represents the household contribution to social security.

Following Coenen et al. (2008) we assume that the utilization cost of physical capital and physical capital depreciation are exempted from taxation. Notice that green investment is subsidized at τ^{K_G}. The variable $TR_t(i)$ represents lump-sum transfers received from the government and $T_t(i)$ lump-sum taxes. The generic household i holds state-contingent securities, $\Phi_t(i)$, which are traded amongst I-type households and provide insurance against individual income risk.

The household provides labor services, $N_t(i)$, at wage rate $W_t(i)$ and rents general capital services $u_t(i) K_t(i)$, at the rental rate R_t^K, to domestic firms, brown capital services $u_{B,t}(i) K_{B,t}(i)$, at the rental rate $R_{B,t}^K$, to domestic firms and green capital services $u_{G,t}(i) K_{G,t}(i)$, at the rental rate $R_{G,t}^K$, to domestic firms. Varying the intensity of capital utilization is subject to a proportional cost Γ_u, Γ_{u_B} and Γ_{u_G}, respectively. The law of motion for the three types capital stock (owned by household i) is:

$$K_{t+1}(i) = (1-\delta) K_t(i) + (1-\Gamma_I(\gamma_I)) I_t(i) \tag{39}$$

$$K_{B,t+1}(i) = (1-\delta_B) K_{B,t}(i) + (1-\Gamma_{IB}(\gamma_{IB})) I_{B,t}(i) \tag{40}$$

$$K_{G,t+1}(i) = (1-\delta_G) K_{G,t}(i) + (1-\Gamma_{IG}(\gamma_{IG})) I_{G,t}(i) \tag{41}$$

where $\delta > 0$ is the depreciation rate and Γ_I represents an adjustment cost. The purchases of the consumption good are subject to a proportional transaction cost, Γ_v. The variables $D_t(i), D_t^B(i), D_t^G(i)$ in the budget constraint represents the dividends paid by intermediate good firms and brown and green energy-producing firms to I-type households.

Each household i acts as wage setter for its differentiated labor services $N_t(i)$ in monopolistically competitive markets. It is assumed that wages are determined by staggered nominal contracts *à la* Calvo (1983).

3.2.2 J-type households

In each country there is a continuum of J-type households indexed by $j \in [s^H(1-\omega), s^H]$. Even though J-type households do not have access to capital and bond markets (financially-constrained), they can intertemporally smooth consumption by adjusting their holdings of money. The household j chooses purchases of the consumption good $\mathbb{C}_t(j)$ and holdings of money $M_t(j)$

that maximize its lifetime utility function (that is assumed to be similar to that of I-type households), subject to its budget constraint:

$$\begin{aligned} & \left(1+\tau_t^C+\Gamma_{v,t}\right) \mathcal{P}_{\mathbb{C},t}\mathbb{C}_t\left(j\right)+M_t\left(j\right)+\Phi_t\left(j\right) \\ = \; & \left(1-\tau_t^N-\tau_t^{W_H}\right) W_t\left(j\right) N_t\left(j\right)+TR_t\left(j\right)+T_t^{E_G}-T_t\left(j\right)+M_{t-1}\left(j\right) \end{aligned} \quad (42)$$

where the transaction cost $\Gamma_{v,t}$ depends on consumption-based velocity. $TR_t\left(j\right)$ and $T_t^{E_G}$ are general transfers and transfers from redistribution of carbon taxes by the government, respectively, all lump-sum. Similarly to I-type households, J-type households act as wage setters for their differentiated labor services. Similarly to I-type households, J-type households act as wage setters for their differentiated labor services.

3.3 Monetary and fiscal authorities

3.3.1 Monetary policy

The monetary authority faces a Taylor-type interest rate rule specified in terms of annual CPI inflation, $\Pi_{\mathbb{C},t}^4 \equiv \mathcal{P}_t/\mathcal{P}_{t-4}$ and quarterly output growth, $\dot{Y}_t \equiv Y_t/Y_{t-1}$:

$$\left(R_t\right)^4 = \phi_R\left(R_{t-1}\right)^4+\left(1-\phi_R\right)\left[\left(\overline{R}\right)^4+\phi_\Pi\left(\Pi_{\mathbb{C},t}^4-\overline{\Pi}^4\right)\right]+\phi_{g_Y}\left(\dot{Y}_t-1\right)+\varepsilon_{R,t} \quad (43)$$

where $\left(\overline{R}\right)^4 = \beta^{-4}\;\overline{\Pi}$ is the equilibrium nominal interest rate, $\overline{\Pi}$ is the monetary authority's inflation target and the term $\varepsilon_{R,t}$ is a serially uncorrelated monetary policy shock. In the specific case of the EA, a similar equation holds for the (single) monetary authority, that targets a weighted (by regional size) average of regional annual CPI inflation and real quarterly output growth.

3.3.2 Fiscal policy

Fiscal instruments for climate policy. The government in each region imposes a carbon tax, $\tau_t^{E_B}$, as a surcharge on the price of the brown energy input/good on tradable and non-tradable goods firm as well as on households, provides labor subsidies to the green energy sector($\tau_t^{E_G}$) and imposes taxes on household's brown capital income ($\tau_t^{K_B}$). At the same time, it uses fraction

μ_B^I of the revenues to subsidize wealthy household's green capital income ($\tau_t^{K_G}$). The remaining fraction, $1-\mu_B^I$, is devoted to financing debt or other government expenditures. Specifically, the distribution of revenues from taxing brown capital reads as follows:

$$\tau_t^{K_G}\left(R_{G,t}^K u_{G,t}-\Gamma_{u_G}\left(\gamma_G\right)P_{IG,t}\right)K_{G,t}=\mu_B^I\,\tau_t^{K_B}\left(R_{B,t}^K u_{B,t}-\Gamma_{u_B}\left(\gamma_B\right)P_{IB,t}\right)K_{B,t} \tag{44}$$

where assume that carbon taxes are set according to the following rule: $\tau_t^{K_B}=(1-\rho_{\tau^{K_B}})\tau^{K_B}+\rho_{\tau^{K_B}}\tau_{t-1}^{K_B}+\varepsilon_{\tau^{K_B},t}$ The subsidy that the green energy firms receive represents a fraction, ς_E, of the government's carbon tax revenues such that:

$$\begin{aligned}\varsigma_E^Y&\left[\tau_t^{E_B}\left(\int_0^{s^H}P_{B,t}E_{B,t}^D(h)dh+\int_0^{s^H}P_{B,t}E_{B,t}^D(n)dn\right)+\tau_t^{E_B}P_{B,t}\left(C_{B,t}(I)+C_{B,t}(J)\right)\right]\\&=\tau_t^{E_G}\int_0^{s^H}P_{G,t}E_{G,t}(g)dg\end{aligned} \tag{45}$$

where $0\leq\varsigma_E^Y\leq1$ and $\int_0^{s^H}P_{B,t}E_{B,t}^D(h)dh$ and $\int_0^{s^H}P_{B,t}E_{B,t}^D(n)dn$ represent the aggregate expenditure of domestic tradable goods firms and non-tradable goods firms on brown energy. $\int_0^{s^H}P_{G,t}E_{G,t}(g)$ represents the aggregate revenues, net of subsidies, of green energy producers residing in the domestic economy. s^H captures the continuum of the mass of green energy firms in the domestic economy. Energy firms of each sector choose the price that maximizes their profits subject to the total demand they are facing (brown or green energy goods).

Furthermore, the government may choose to transfer an additional fraction of its carbon tax revenues to financially-constrained (type-J) households. In this case, we have:

$$\begin{aligned}\varsigma_E^C&\left[\tau_t^{E_B}\left(\int_0^{s^H}P_{B,t}E_{B,t}^D(h)dh+\int_0^{s^H}P_{B,t}E_{B,t}^D(n)dn\right)+\tau_t^{E_B}P_{B,t}\left(C_{B,t}(I)+C_{B,t}(J)\right)\right]\\&=T_t^{E_G}\end{aligned} \tag{46}$$

where $0\leq\varsigma_E^C\leq1$. In general, we will assume that $\varsigma_E^Y+\varsigma_E^C<1$, so that not all carbon tax revenues are redistributed. As in Känzig (2023), we assume that carbon taxes are set according to the following rule: $\tau_t^{E_B}=(1-\rho_{\tau^{E_B}})\tau^{E_B}+\rho_{\tau^{E_B}}\tau_{t-1}^{E_B}+\varepsilon_{\tau^{E_B},t}$.

Government budget constraint. In each country the fiscal authority purchases G, a final good which is a composite of non-tradable intermediate goods only. The fiscal authority also makes transfer payments to households, TR_t, issues bonds to refinance its debt, B_t, earns seigniorage on outstanding money holdings, M_{t-1}, and levies taxes. As previously said, there are tax rates on consumption purchases (τ_t^C) and on wage, capital and dividend income (τ_t^N, τ_t^K, τ_t^D, respectively). There are also pay-roll tax rates levied on household wage income ($\tau_t^{W_H}$) and on wages paid by firms (social contributions, $\tau_t^{W_F}$). Therefore the fiscal authority's period-by-period budget constraint is:

$$
\begin{aligned}
& P_{G,t}G_t + TR_t + \tau_t^{E_G} W_t N_{G,t} + \tau_t^{K_G}\left(R_{G,t}^K u_{G,t} - \left(\Gamma_{u_G}\left(\gamma_G\right) + \delta_G\right) P_{IG,t}\right) K_{G,t} + B_t \\
= \; & \tau_t^C C_t + \left(\tau_t^N + \tau_t^{W_H}\right)\left(W_{I,t}N_{I,t} + W_{J,t}N_{J,t}\right) + \tau_t^{W_F} W_t N_t \\
& + \tau_t^K \left(R_t^K u_t - \left(\Gamma_u\left(\gamma_u\right) + \delta\right) P_{I,t}\right) K_t + (1-\mu_B^I)\tau_t^{K_B}\left(R_t^{KB} u_{B,t} - \left(\Gamma_{u_B}\left(\gamma_B\right) + \delta_B\right) P_{IB,t}\right) K_{B,t} \\
& + \tau_t^D D_t + T_t + R_t^{-1} B_{t+1} + \Delta M_t \\
& + (1 - \varsigma_E^Y - \varsigma_E^C)\tau_t^{E_B} P_{B,t}\left(E_{B,t}^D + E_{B,t}^D + C_{B,t}(I) + C_{B,t}(J)\right)
\end{aligned}
\tag{47}
$$

Lump-sum taxes as a fraction of steady-state nominal output, $\tau_t \equiv \frac{T_t}{P_Y Y}$, are adjusted to make public debt stable according to the following rule:

$$
\tau_t = \phi_{B_Y}\left(\frac{B_t}{\overline{P_Y Y}} - \overline{BY}\right) \tag{48}
$$

where $\overline{B_Y}$ is the fiscal authority's target for the ratio of government debt to output and $\phi_{B_Y} > 0$ is a parameter.

4 Calibration

Key parameters such as real and nominal rigidities, Calvo price stickiness, indexation price parameters for non-energy sectors, leverage ratios, and policy rules are derived from the standard EAGLE model (see Gomes et al. (2010)). Moving to parameters specific to our current extension, we start with those pertaining to the energy sector.

4.1 Energy sectors

The dataset employed for the calibration of the energy sector originates from the OECD Input/Output table.[12] This database is organized with column and row labels denoting the name of each country followed by the industry code, adhering to the International Standard Industry Classification (ISIC) Rev 4.

The data analysis conducted to generate Table 1 proceeds as follows. Initially, the Input/Output (IO) table is aggregated based on regions and sectors. Specifically, the regions considered in our analysis include the EA, the US, and the RW. In our analysis, each region is treated as a closed economy, wherein exports and imports are excluded from consideration. Consequently, the sectoral results pertaining to the economy are computed based on the proportion of intermediate goods utilized from a particular sector relative to the total intermediate goods used as inputs. Regarding consumption, investment, and government expenditures, only internal transactions are accounted for, with imports and exports disregarded. The values represent the share of internal consumption, investment, or government expenditure within a specific sector, relative to the total consumption, investment, or expenditure. Furthermore, concerning the breakdown of energy-related data into brown and green portions, following Coenen et al. (2023) a fixed ratio is applied, designating 71.7% of the energy as brown (the implied share of dirty energy as defined by Coenen et al. (2023)), with the remaining portion classified as green.[13]

As the structure of the IO table is too detailed to match the simpler structure of our model, production sectors are aggregated in a way such that the IO table is reduced to a 3-sector economy. Aggregation is performed according to the following categorization:

- Energetic sector: B05_06, C19 and D.
- Tradable sector: A, B (except B05_06), C (except C19) and G.
- Non-tradable sector aggregates all the industries from E to T.

[12] Link: *OECD database*

[13] In the literature there is no common distinction between brown and green energy sectors, however we try to summarize some of the shares that are used by the following papers. For example, Diluiso et al. (2020) distinguish between low-carbon and fossil energy, accounting for 25% and 75% of total energy sector, respectively. Auclert et al. (2023) report 69% share of different types of fossil fuel in gross available energy consumption. Combining oil, gas and coal shares, they account for 71.2% in firms' production costs and households' consumption in total energy consumption in Bartocci et al. (2022). Airaudo et al. (2022) report energy shares only for the production side of the economy, which stands at 53% of brown energy in total energy production.

Against this backdrop, in Table 1 we calculate the values of target variables that we want to match in our model. From the OECD IO data we observe that the RW is more energy intensive than the EA and US. On the other hand, US and EA have a similar energy sector structure size. As a consequence, the size of the energy sector in total production expressed as a share of GDP accounts for 6.9% in EA, 5.1% in US and 12.6% in RW. The shares of energy goods used to produce intermediate goods stand at 2.2% in EA, 1.9% in US and 3.3% in RW in the tradable sector and 2.3% in EA, 2.9% in US and 4.4% in RW in the non-tradable sector. In final goods consumption, the energy goods take up 4.7% in EA, 2.9% in US and 4.1% in RW of private consumption, 0.8% in EA, 2.0% in US and 1.2% in RW in private investment, while the energy goods component in government expenditures is negligible for EA and US, while in RW it stands at 2.9%.

In Tables 2 and 3 we give an overview of key structural parameters of energy sectors in our model. The total energy consumption and the size of energy sector expressed as a share of GDP account for 6.7% in EA, 3.6% in US and 4.9% in RW and 6.4% in EA, 4.5% in US and 7.1% in RW, respectively, thus proxying the targeted values from the OECD IO data extraction as well as the relevant literature (for exapmple Coenen et al. (2023)). The share of energy in the final goods consumption basket $1 - \nu_C$ accounts for 5% in EA, 2.9% in US and 4.1% for RW. Comparing to the Coenen et al. (2023) fixed ratio of brown energy (71.7%) we obtain the model based brown energy ratio of 85.1% in total energy consumption and 66.1% in total energy production.

Turning to the calibration of other structural parameters that determine the use and production of energy sectors, we mostly follow the values set in Coenen et al. (2023), Golosov et al. (2014) and Känzig (2023) papers. Mark-up price values are set at 1.1 in both, brown and green energy sectors, across all three regions. These values are lower than in the non-energy part of the economy. The Calvo price stickiness and price indexation parameters for both types of energy sectors are calibrated to 0.5. Following Känzig (2023) value of the implied carbon tax rate calculated from the EU emissions allowances, we set the steady state rate to 3.9%. The tax on brown capital income is set to 19% in EA and 16% in US and RW. The fraction of subsidies, that go to green energy firms and the hand-to-mouth households are set to 0.15, while for the fraction subsidies to green investment takes a slightly larger share at 0.25, equal for all three regions. With respect to the substitution elasticity between brown and green energy in aggregate energy production, we set the substitution parameter between the brown and green energy ϵ_{BG} at 2.5, implying that the brown and green energy goods are by characteristics more of an imperfect substitute rather than a complement. It is consequently set in the middle of the range estimated by Papageorgiou et al. (2017) (1.8 and 3). Further on, the current level of atmospheric carbon concentration depends on past emissions as well as on the share of carbon emissions that cannot immediately exit the atmosphere and on the decay parameter. Following the proposed values from Golosov et al. (2014) with respect to the carbon emissions depreciation, we set the carbon decay parameter ϕ at 0.0228 for all three regions. The share of carbon staying (forever) in the atmosphere ϕ_L is set at 0.2 while the share of carbon ϕ_0 that can exit immediately is set at 0.393. The scaling parameter λ takes up the value of 5.31×10^{-5}. The production function responsiveness parameters γ_B and γ_G, which denote the biases in the brown and green capital in both energy sectors respectively, slightly differ. The bias towards the brown capital takes up a value close to one fourth in all regions and is somewhat lower compared to the green sector, where the value is set close to one third. Lastly, the biases towards brown and green energy in the intermediate goods production functions (the αs) for both the tradable and the non-tradable sector take up the values in the range of 0.005 to 0.05, implying the targeted value of the share of energy utilization as an input in the production process. The responsiveness bias towards the regular capital in both sectors is substantially higher in a range between 0.25 and 0.3 for all three regions.

4.2 Non-energy sectors

Table 4 reports the great ratios and rigidities. Markups in the EA non-tradable sector and labor market are higher than the corresponding values in the US and the RW. In all regions the markup in the tradable sector has the same value and the markup in the non-tradable sector is higher than that in the labor market. Specifically, the net price markup in of the EA is 20% in the tradable sector, 30% in the labor market and 50% in the non-tradable sector. In the US and the RW we set these markups respectively to 20%, 20% and 30%. Regarding nominal and real rigidities, Calvo price parameters in the domestic tradable and non-tradable sector equal to 0.90

in the EA and 0.75 outside the euro. Calvo wage parameters and price parameters in the export sector are equal to 0.75 in all the regions. The indexation parameters on prices and wages are equal respectively to 0.50 and 0.75. For real rigidities, adjustment costs on investment are set to 6 in the EA and to 4 in the case of the US and the RW while adjustment costs on consumption and investment imports (identical across regions) are equal to 2 and 1, respectively. Finally, region sizes are set to match their respective shares of world GDP.

Table 5 reports parameters in the monetary rules and fiscal rules. The interest rate reacts to the its lagged value (inertial component of the monetary policy), annual inflation and quarterly output growth. In the monetary union, monetary policy reacts to EA wide variables. For fiscal rules, lump-sum taxes stabilize public debt. Steady-state ratios of government debt over output are equal to 2.40 in all the regions (0.6 in annual terms). Steady-state tax rates on consumption and labor income are respectively equal to 0.183 and 0.122 in the EA; and to 0.077 and 0.154 outside the EA. The rates on social contributions paid by firms are equal to 0.219 in the EA and 0.071 outside the EA while those paid by households are equal to 0.118 and 0.071 in the EA and outside the EA, respectively.

5 Quantitative Analysis

In the sections that follow, we consider the responses of the variables of interest to an increase in the carbon tax, $\tau_t^{E_B}$, that leads to an increase in the price of total energy by 1 percent on impact, similar to Känzig (2023). We assume the degree of persistence in the law of motion of the carbon tax, $\rho_{\tau^{E_B}} = 0.90$, which is equivalent to a mean reversion of approximately 20 quarters.

We consider the following scenarios:

- Implementation of a carbon tax solely within the EA, without any redistribution of tax revenues.
- Implementation of a carbon tax within the EA with two types of redistribution: one where revenues are directed to subsidize green energy-producing firms, and another where revenues are also directed to financially constrained households.
- Implementation of globally raised carbon taxes in a symmetric manner.

- Introduction of taxes on brown capital rental income accompanied by subsidies to green capital investment.

For clarity and focus, our analysis is primarily centered on the EA.

5.1 Increase of carbon tax without redistribution

In this section, we look at the case where a carbon tax as a surcharge on the price of brown energy is levied on consumers and intermediate goods producers in the EA only. In this first simulation, we abstract from subsidies to the green energy sector, implying $\varsigma_E = 0$. We display the impulse responses (blue solid lines) in Figures 1, 2 and 3 below.

Looking first at the energy-related variables displayed in Figure 2, the increase in the carbon tax leads to a decline in the output of brown energy and a rise in the output of green energy. The higher after-tax price of energy output leads to an expenditure switching effect by households towards green energy consumption goods as illustrated in Figure 3. Looking at the tradable and non-tradable sectors instead, their demand for green energy goes down given the weak substitution between the two types of energy inputs. It is important thus to note that a carbon tax alone without a redistribution scheme does not necessarily boost green transition in all segments of the economy. However, the expenditure-switching effect by households is strong enough to drive the output of green energy upwards. Given the absence of a redistribution scheme, green energy-producing firms do not absorb the decline in the demand for brown energy goods.

Turning to investment in energy (see blue solid lines in Figure 2), investment in both brown and green energy decline due to the decrease in the demand for brown and green energy inputs by the tradable and non-tradable goods sectors in the EA. This results in a decline in the rental rate of brown by a percentage point approximately, offsetting the mild rise in the rental rate of green capital and adding further downward pressures to financially unconstrained households' wealth, suppressing thereby further their consumption.

With respect to intermediate goods sectors, output declines in the tradable goods sector due to the higher price of brown energy inputs and the weak substitutability with the green energy input. Output in the non-tradables sector experiences a mild increase in the first quarters after the shock owing to the fact that it is more labor intensive than the tradables sector, benefiting thereby more from the decline in wages. However, once wages start to adjust the impact of the persistent rise in the price of brown energy input starts to kick-in driving output downwards.

Focusing now on the greater macroeconomic effects of the carbon tax, illustrated in Figure 1 a couple of observations stand out. The carbon tax shock in the absence of subsidies, even though featuring direct demand-side and supply-side effects, resembles the effects of a supply-side or a price mark-up shock. Specifically, output contracts, inflation rises, total investment, and the rental rate of capital drop, while total private consumption and hours also decrease. The rise in inflation is triggered by the rise in the after-tax price of brown energy and hence of total energy, and by the persistent decline in the supply of tradables and non-tradables. The rise in inflation triggers a persistent overshooting of the real interest rate in the medium-run that squeezes the present discounted value of wealth of the financially unconstrained households, adding thereby to the downward pressures on total consumption from the higher energy prices.

Broadening the picture to the international variables, the increase in the policy rate due to the jump in inflation leads to an appreciation of the euro *vis à vis* the basket of currencies of its trade partners.[14] This explains the initial decline in the trade balance. Given the weak exchange rate pass-through due to local currency pricing, the currency appreciation does not undo the inflationary impact of the carbon tax on inflation. The appreciation of the euro also explains why tradable goods output falls more compared to that of non-tradable goods (see Figure 2).

5.2 Subsidies to green energy firms

We now turn to the scenario where the fiscal authority redistributes a part of the carbon tax revenues to green energy-producing firms only, which we assume to receive a third ($\varsigma_E^Y = 1/3$) of total carbon tax revenues. The remaining part (66%) of the carbon tax revenues are used to finance the government debt or expenditures. The impulse responses are displayed by the red-dashed lines in Figures 1, 2, and 3, respectively.

Starting again with the energy-related variables, the demand for green energy by both types of households now increases more owing to the lower green energy price. Importantly, the lower

[14] A decline in the exchange rate corresponds to an appreciation.

green energy price explains why the sign of the response of the green energy input employed in the tradables and non-tradables sectors is now reversed. At the same time, the demand for brown energy goods by households declines now more compared to case without subsidies. The impact on the demand for brown energy by the firms in the intermediate goods sector is negligible compared again to the case without subsidies. Therefore, the subsidy towards the green energy sector serves in boosting green transition throughout the economy, namely at the household-level and the firm-level.

The increased total demand for green energy now justifies the amplified response of green energy production. The latter effect increases the demand for green capital which triggers a reversal in the sign (now positive) in the response of green investment relative to the case of no-subsidies, as Figure 2 shows. Cheaper green energy input yields a milder decline now in tradable and non-tradable goods output. The subsidy also results in a milder drop in total consumption, another reason why tradable and non-tradable output decline less. Interestingly, the weak substitutability between brown and green energy has some positive externality on brown investment, as its decline is now milder as well.

Looking at GDP, the subsidy to green energy firms leads to substantially softer contraction. This is driven primarily by the milder contractions in private consumption and total investment (see Figure 1). Given that tradable and non-tradable output now decline less, and accounting for the fact that general capital, K_t, has an important weight in their technology, the decline in total investment becomes even more benign. Looking finally at the international variables the impact of the subsidy to green energy firms is negligible compared to the scenario without subsidies.

5.3 Subsidies to green energy firms and to financially-constrained households

This scenario features a lump-sum subsidy to financially constrained households, on top of the subsidy to green energy firms. We assume that the carbon tax revenues are split equation among the green energy firms, the financially constrained households and the government, each party receiving a third of total revenues. The impulse response are displayed in the black-starred lines in Figures 1, 2, and 3.

The subsidy to financially constrained households has a limited effect on the effects of the carbon tax overall relative to the previous case with subsidies to green energy firms only. The major change is the milder contraction in total consumption, as expected. The same happens to the rental rate of general capital, R_t^K, and to hours. Looking at Figure 3, the impact on demand for green energy goods by financially constrained households, it follows a path that is identical to that in the scenario with subsidies to green energy firms only (red-dashed lines overlapping with black dashed-dotted). Although the subsidy to financially constrained households seems to mitigate the negative effects of the carbon tax on their consumption, it does not seem to add further impetus to green transition apart from that already put in place by the subsidy to green energy firms alone. A targeted subsidy towards the consumption of green energy goods might thus work better on that front. As regards the rest of the energy-related variables in Figure 3, the impact of the subsidy to financially constrained households has negligible to no effects relative to the case where subsidies are provided to green energy firms only.

Looking at the responses in Figure 2, the introduction of the subsidy to financially constrained households results now to slightly more amplified increase in the non-tradable output relative to the other two cases already. This is due to the way financially constrained households distribute their consumption. Given the implied higher share of non-tradable goods in their consumption basket, they devote a higher share of the transfer they receive to non-tradable goods. This explains why non-tradables output now increases more and stays above its steady state longer (see Figure 2). Given that this sector is more labor intensive than the tradable goods sector and given its higher share in total output in the EA (see Table 1), non-tradable goods firms try to accommodate the higher demand by increasing relatively more their demand for labor. This is the reason behind the slightly milder decline now of hours in Figure 1. Consequently, the contraction in economic activity is now marginally softer.

Finally, a glance at the international variables reveals that the real effective exchange rate is as appreciated as in the case with transfers to green energy-producing firms, while the trade balance-to-GDP stays overshoots now less. This is due to the milder decline in the consumption of financially constrained households. The appreciated currency (and the induced improved terms of trade) along with the injection of the subsidy by the government improve their purchasing power boosting thereby their demand for imports.

5.4 Primary-balance-neutral policy

In this section, we consider the case where the government redistributes the entire carbon tax revenues to the green energy-producing firms and to financially constrained households equally, i.e. $\varsigma_E^Y = \varsigma_E^C = 0.5$. We consider this policy to be primary-balance-neutral, namely leaving the primary balance unaffected as opposed to the previous cases that allowed for a reduction of the primary balance. The impulse responses are displayed by the green-circled lines in Figures 1, 2 and 3, respectively.

This policy changes the nature of the carbon tax shock. In particular, economic activity mildly expands even though inflation rises. The government thus manages to more than offset the downward pressures on economic activity avoiding a contraction, at least in the first quarters after the initial increase of the tax. Total consumption, total investment and hours, all contract now by less, while the effective exchange rate experiences now a weaker appreciation.

This policy is very effective at promoting green transition since it boosts green investment and the production of green energy considerably as shown in Figure 2 while the demand for green energy goods or inputs share a similar pattern (see Figure 3). It seems though that the supply effect in the green energy sector dominates the demand effect, which results in a decline in green energy inflation. On the other hand, the decline in demand for brown energy by firms in the intermediate goods sector and by households seems to dominate the decline in the supply of brown energy leading to a decline in brown energy inflation before carbon tax. This effect becomes now slightly stronger, with the trough of brown energy inflation before carbon tax pushed a bit lower.

Overall, redistribution policy seems to create a stronger supply channel in the market for green energy leading to a decline in green energy inflation and to a stronger demand channel in the market for brown energy resulting to a decline in brown energy inflation before carbon tax.

5.5 Policy coordination

In this section, we consider a scenario where carbon taxes are raised jointly in all regions. The shock to carbon taxes in each region is such that domestic energy inflation increases by 1 percent on impact. Since in the sections above we have established that the scenario with transfers to green energy firms only leads to very similar conclusions to that with subsidies to green energy firms and financially constrained households, here and to save space we restrain ourselves to the latter case. We display the impulse responses in Figures 4.

The contraction in economic activity in the EA is deeper when the carbon tax rises globally and symmetrically (black-dashed lines) relative to the scenario where the carbon tax is raised only in the EA (blue-solid lines). The peak in the inflation response is now slightly amplified with the overall inflationary impact being also more persistent. This is fueled by the stronger increase in non-energy inflation when carbon taxes are raised globally. The reversal in the response of the real effective exchange rate mainly triggers the higher non-energy inflation. Imported goods constitute a non-negligible part of non-energy inflation. When carbon taxes are raised globally, the real effective exchange rate depreciates for at least a year, even mildly. This sharply contrasts the strong appreciation when carbon taxes are raised in the EA only. The implied mild effective exchange rate dynamics also explain the substantially muted effect of higher carbon taxes globally on the trade balance in the EA.

Looking at the interest rate spreads globally provides an answer to the real effective exchange rate dynamics when carbon taxes are raised globally. Following the shock, the spread between the policy rate in the EA and the US increases persistently, while that between the policy rate in the EA and the RW declines for a number of quarters in the aftermath of the shock. Given the higher weight of the RW as a trade partner of the EA, the EA-RW interest rate spread casts a more important role in determining the value of the euro *vis à vis* the basket of currencies of its trade partners. Consequently, the euro loses value globally for about a year following the rise in carbon taxes globally and starts gaining ground once the spread with the policy rate in the RW reverses sign.

The weaker euro results in a deterioration of the purchasing power of households in the euro, which explains why total consumption declines slightly more when carbon taxes are raised globally. Given the weaker demand domestically for tradables and non-tradables but also from the US due to the positive interest rate spread that appreciates the euro *vis à vis* the dollar, the demand for, and thereby by the output of, especially, tradables but also of non-tradables in the EA declines more persistently, dampening more the demand for general and brown capital reflecting on a deeper contraction in brown and total investment (black-dashed lines). This also contributes to a muted increase in the demand for green capital, which gives rise to a dampened response of green investment relative to the scenario with carbon taxes raised in the EA only.

5.6 Taxing brown capital investment

We now turn to the case of taxes on brown capital investment. As described in section 3.3.2, the government imposes a tax, $\tau_t^{K_B}$, on the rental brown capital income of financially unconstrained (type-I) households. We consider again three cases, namely one where the government does not redistribute the revenues, one where it distributes the revenues subsidizing rental green capital income, and one where it redistributes the revenues subsidizing both green capital income and lump-sum transfers to financially constrained households. The shock to the tax on brown capital rental income is scaled such that it has an identical effect on the government's primary balance as the carbon tax, on impact. To save space we consider two cases, one without subsidies to green capital investment and one where all the revenues from the tax on brown capital investment are redistributed to green capital investment (i.e. μ_B^I). We display our results in Figures 5, 6 and 7 below.

The introduction of the brown capital leads to a contraction in economic activity. Although the effect on inflation is small, the tax is deflationary as opposed to the carbon tax. The tax has a contractionary effect because brown capital has a higher share in the production process and brown investment occupies a higher share of GDP than green investment. Hence, the resulting rise in the rental rate of brown capital (see Figure 6), puts upward pressure on the marginal costs of intermediate goods firms. Comparing the two cases displayed, when subsidies to green capital rental income are introduced (red-dashed lines), the contraction in economic activity is milder while the drop in inflation is deeper, driven by a deeper dive in non-energy inflation.

To gain more insight let us discuss the energy-related variables displayed in figures 6 and

7, respectively. Clearly, the subsidies to green capital rental income boost green investment as the red-dashed impulse response peaks higher than the solid-blue in Figure 6. This results in a decline in the rental price of green capital that bolsters green energy output. The resulting supply effect is strong enough to decrease the price of green energy further below the case of no subsidies. However, the demand for green energy of financially unconstrained households rises mildly, while that of constrained ones stays unchanged. At the same time, the drop in the demand for green energy input by intermediate goods firms declines now less owing to the lower price of green energy but does not reverse sign turning to positive territory at all.

All in all, the brown capital rental income tax and the associated subsidy to green capital investment do not contribute to green transition strong enough. The effect of the tax towards boosting demand for green energy is weak while the benefits from subsidies are mild.

6 Conclusion

In this paper, we explore the impact of climate policies on the EA economy *via* scenario analysis. Developing an augmented energy sector EAGLE model, we assess the global perspective of introducing carbon taxes for brown energy sector and subsidies for green energy sector. Several key findings emerge.

First, our research stresses the importance of considering redistributive measures in the design of climate policies. By reallocating a share of carbon tax revenues to green energy-producing firms and financially constrained households, we observe more favorable macroeconomic outcomes. Importantly, these redistributive measures do not necessarily hinder the progress of the green transition. Second, we show that, following a rise in carbon taxes, the demand channel always dominates in the market for brown energy, resulting in a decline in brown energy inflation, despite the drop in its output. Moreover, redistributive policies strengthen the demand channel, amplifying the decline in brown energy inflation. Third, when carbon taxes increase globally, the economic downturn within the EA intensifies and persists longer compared to scenarios where carbon taxes are raised only within the EA. Furthermore, we observe an amplification in the peak of the non-energy inflation response, contributing to a more persistent overall inflationary impact.

Finally, we also consider taxes on brown capital rental income accompanied by subsidies to green capital investment. We find that these measures are contractionary and deflationary, unlike the effects of a carbon tax. Most notably, they are not effective in supporting the green transition adequately, as they fail to counterbalance the adverse effects of increased costs for brown capital on the marginal costs and output of intermediate goods firms.

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Table 1. Input / Output Table (target variables)

	EA	US	RW
Sectors of the economy (share of GDP)			
Tradable sector in total production	0.3697	0.2425	0.6275
Non-tradable sector in total production	0.4959	0.4584	0.3427
Energy sector in total production	0.0688	0.0508	0.1256
— *Brown*	0.0494	0.0364	0.0901
— *Green*	0.0195	0.0144	0.0355
Energy goods			
Intermediate goods (share of total input)			
— Tradable sector	0.0221	0.0192	0.0328
— *Brown*	0.0159	0.0138	0.0235
— *Green*	0.0063	0.0054	0.0093
— Non-tradable sector	0.0227	0.0292	0.0443
— *Brown*	0.0163	0.0210	0.0317
— *Green*	0.0064	0.0083	0.0125
Final goods (share of each component)			
— Private consumption	0.0470	0.0287	0.0405
— *Brown*	0.0337	0.0206	0.0291
— *Green*	0.0133	0.0081	0.0115
— Private investment	0.0083	0.0202	0.0121
— Government expenditures	0.0009	0.0000	0.0294
Tradable goods			
— Private consumption	0.3543	0.2246	0.4258
— Private investment	0.3351	0.3481	0.3405
— Government expenditures	0.0355	0.0042	0.0250
Non-tradable goods			
— Private consumption	0.5987	0.7467	0.5337
— Private investment	0.6567	0.6317	0.6473
— Government expenditures	0.9637	0.9958	0.9457

TABLE 2. Energy economy (I)

	EA	US	RW
Share of GDP			
Total energy consumption	0.0667	0.0360	0.0490
Brown energy consumption	0.0568	0.0307	0.0411
Imports brown investment	0.007	0.008	0.0028
Sizes of energy sectors (share of GDP)			
Share brown energy sector	0.0426	0.0282	0.0437
Share green energy sector	0.0218	0.0170	0.0277
Mark-up			
Prices – brown energy goods	1.10	1.10	1.10
Prices – green energy goods	1.10	1.10	1.10
Real rigidities			
Brown energy investment (γ_{IB})	5.00	5.00	5.00
Green energy investment (γ_{IG})	5.00	5.00	5.00
Import of brown energy investment (γ_{IMIB})	2.00	2.00	2.00
Utilization of brown capital (γ_{uB})	1.00	1.00	1.00
Utilization of green capital (γ_{uG})	1.00	1.00	1.00
Nominal rigidities			
Brown energy goods sector			
Price stickiness (Calvo)	0.50	0.50	0.50
Price indexation	0.50	0.50	0.50
Green energy goods sector			
Price stickiness (Calvo)	0.50	0.50	0.50
Price indexation	0.50	0.50	0.50
Fiscal instruments (Steady state values)			
Carbon tax (τ^{E_B})	0.039	0.039	0.039
Tax on I-households brown capital income (τ^{K_B})	0.19	0.16	0.16
Fraction of subsidy to green energy firms (ς_E^Y)	0.33	0.33	0.33
Fraction of subsidy to J-type households (ς_E^C)	0.33	0.33	0.33
Fraction of subsidy to green investment (μ_B)	0.33	0.33	0.33

EA = Euro Area; US = United States; RW = Rest of World

Table 3. Energy economy (II)

	EA	US	RW
Consumption basket			
Substitution btw non-energy and energy (ϵ_C)	0.40	0.40	0.40
Substitution btw brown and green energy (ϵ_{BG})	2.50	2.50	2.50
Share of non-energy (ν_C)	0.9502	0.9714	0.9595
Share of brown energy in total energy consumption (ν_B)	0.90	0.90	0.90
Intermediate-good firms: tradable sector			
Bias towards capital (α_T)	0.30	0.30	0.30
Bias towards brown energy (α_{BT})	0.015	0.015	0.015
Bias towards green energy (α_{GT})	0.005	0.005	0.05
Intermediate-good firms (non-tradable sector)			
Bias towards capital (α_N)	0.25	0.25	0.25
Bias towards brown energy (α_{BN})	0.01	0.01	0.05
Bias towards green energy (α_{GN})	0.01	0.01	0.01
Carbon emission			
Scaling parameter (λ)	5.31×10^{-5}	5.31×10^{-5}	5.31×10^{-5}
Share of carbon staying forever (ϕ_L)	0.20	0.20	0.20
Share of carbon exiting immediately (ϕ_0)	0.393	0.393	0.393
Decay (ϕ)	0.0228	0.0228	0.0228
Brown energy sector			
Bias towards brown capital (γ_B)	0.258	0.267	0.243
Green energy sector			
Bias towards brown capital (γ_G)	0.332	0.335	0.319
Final brown investment-good firms			
Substitution btw. domestic and imported trad. goods (μ_{TIB})	2.50	2.50	2.50
Bias towards domestic tradables goods (υ_{TIB})	0.31	0.21	0.65
Substitution btw. tradables and nontradables (μ_{IB})	0.50	0.50	0.50
Bias towards tradable goods (υ_{IB})	0.45	0.45	0.35
Substitution btw. domestic and imported goods (μ_{IMIB})	2.50	2.50	2.50
Final green investment-good firms			
Substitution btw. tradables and nontradables (μ_{IG})	0.50	0.50	0.50
Bias towards tradable goods (υ_{IG})	0.75	0.75	0.75

EA = Euro Area; US = United States; RW = Rest of World

Table 4. Non-energy economy: Great ratios and rigidities

	EA	US	RW
Share in percentage of GDP			
Private consumption	60	63	64
Private investment	20	20	20
Public expenditure	20	16	16
Imports total	26	11	15
Imports consumption	19	7	9
Imports investment	7	4	6
Mark-up			
Wages – households	1.30	1.20	1.20
Prices – domestic tradable goods	1.20	1.20	1.20
Prices – domestic non-tradable goods	1.50	1.30	1.30
Real rigidities			
Capital utilisation	2000	2000	2000
Investment	6.00	4.00	4.00
Imports – consumption	2.00	2.00	2.00
Imports – investment	1.00	1.00	1.00
Nominal rigidities			
Households			
Wage stickiness	0.75	0.75	0.75
Wage indexation	0.75	0.75	0.75
Tradable goods sector			
Price stickiness (domestic goods)	0.90	0.75	0.75
Price indexation (domestic goods)	0.50	0.50	0.50
Non-tradable goods sector			
Price stickiness (domestic goods)	0.90	0.75	0.90
Price indexation (domestic goods)	0.50	0.50	0.50
Share in precentage of world GDP	24	30	46

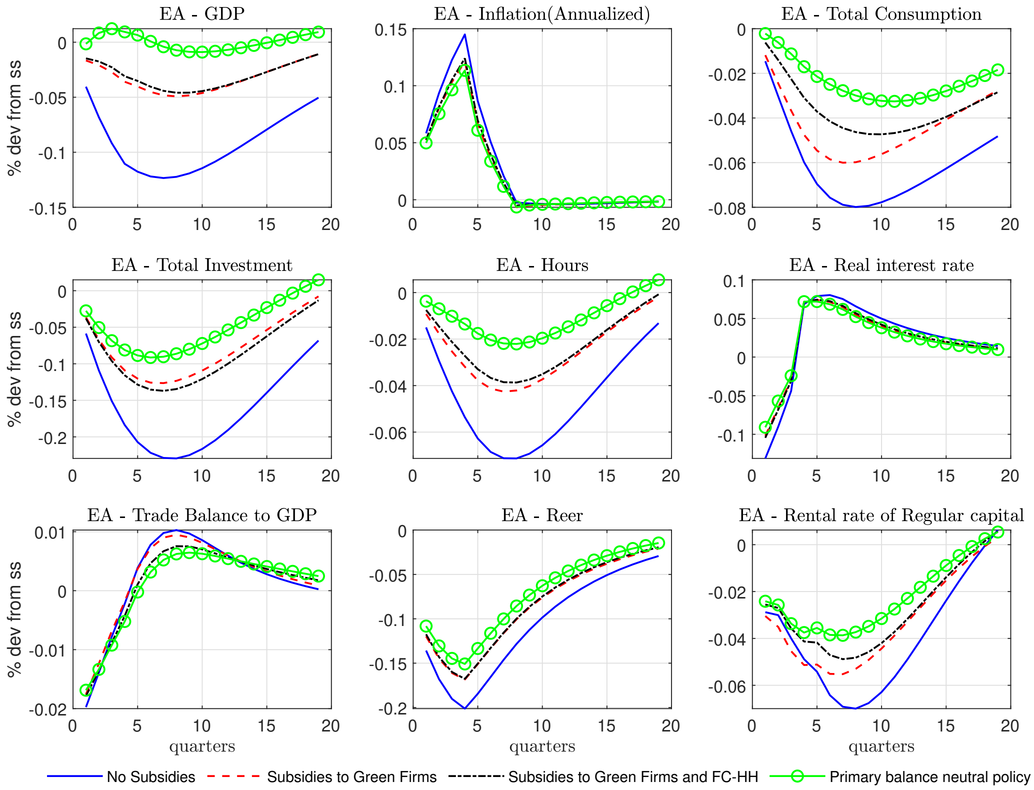
EA = Euro Area; US = United States; RW = Rest of World

Table 5. Monetary and Fiscal Policy

	EA	US	RW
Monetary authority			
Inflation target ($\overline{\Pi}^4$)	1.02	1.02	1.02
Interest rate inertia (ϕ_R)	0.87	0.87	0.87
Interest rate sensitivity to inflation gap (ϕ_Π)	1.70	1.70	1.70
Interest rate sensitivity to output growth (ϕ_Y)	0.10	0.10	0.10
Fiscal authority			
Government debt-to-output ratio ($\overline{B_Y}$)	2.40	2.40	2.40
Sensitivity of lump-sum taxes to debt-to-output ratio (ϕ_{B_Y})	0.10	0.10	0.10
Consumption tax rate (τ^C)	0.183	0.077	0.077
Dividend tax rate (τ^D)	0.00	0.00	0.00
Capital income tax rate (τ^K)	0.19	0.16	0.16
Labor income tax rate (τ^N)	0.122	0.154	0.154
Rate of social security contribution by firms (τ^{W_F})	0.219	0.071	0.071
Rate of social security contribution by households (τ^{W_H})	0.118	0.071	0.071

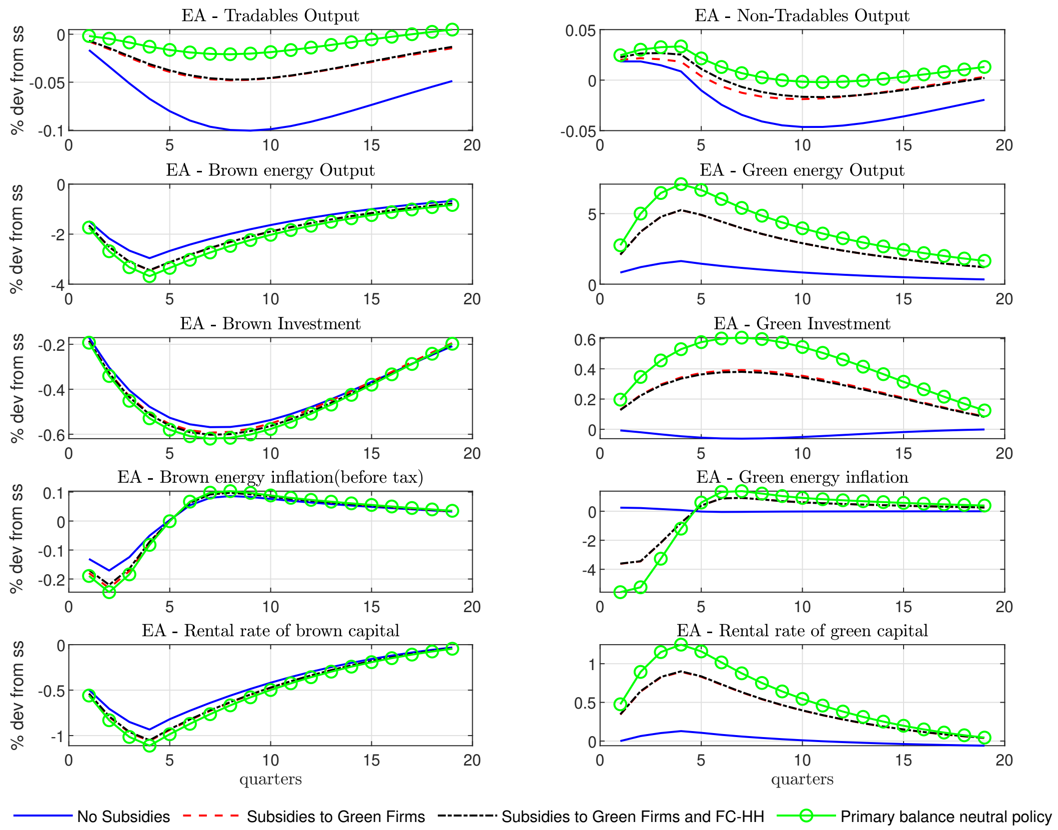
Note: EA = Euro Area; US = United States; RW = Rest of World

FIGURE 1. Impulse Responses to a carbon tax shock in the EA



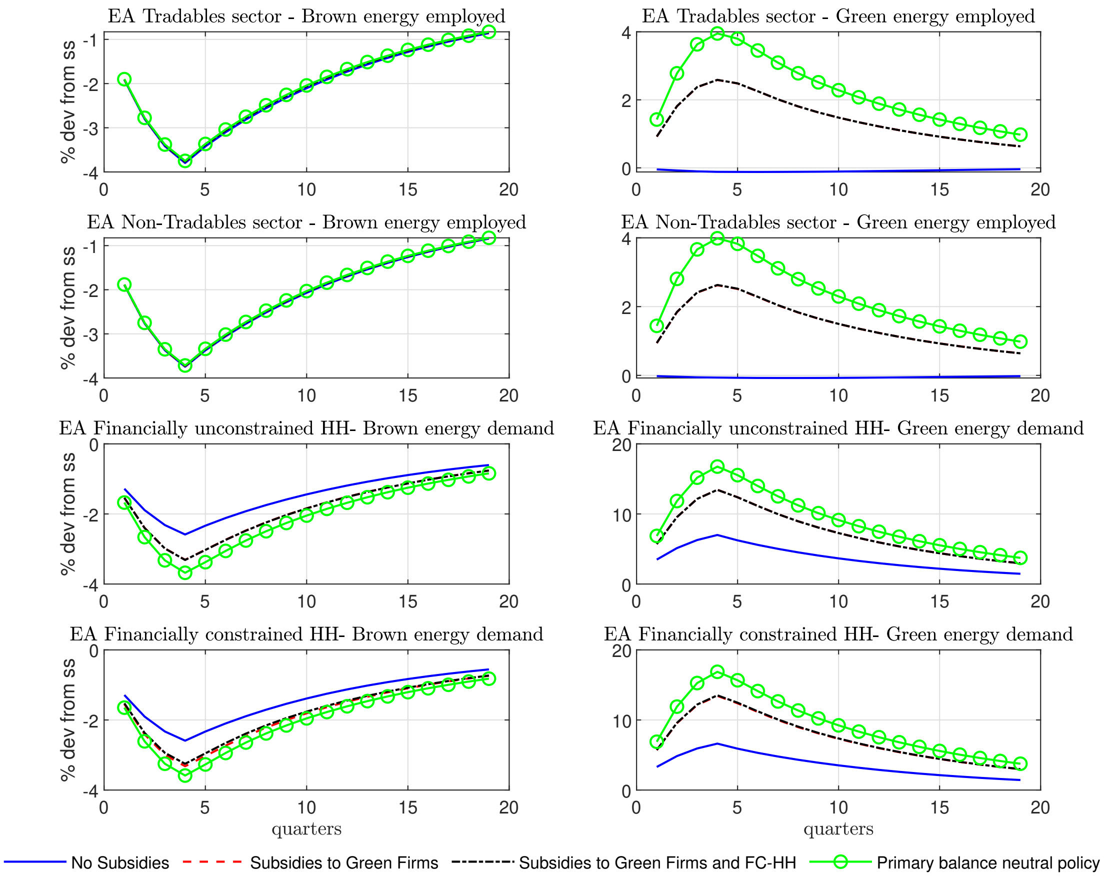
Notes: Impulse responses to a rise in carbon tax in the EA that raises the price of total energy by 1% on impact. Horizontal axis: quarters. Vertical axis: percentage deviations from the baseline, except for inflation and interest rates (annualized percentage-point deviations), and the trade balance-to-GDP ratio (percentage-point deviations). GDP and its components are reported in real terms. Blue-solid lines represent impulse responses after a carbon tax shock without subsidies. Red-dashed lines represent impulse responses after a carbon tax shock with subsidies to green energy-producing firms with $\varsigma_E^Y = 0.33$. Black-dashed-dotted lines represent impulse responses after a carbon tax shock with subsidies to green energy-producing firms and financially constrained households (FC-HH) with $\varsigma_E^Y = \varsigma_E^C = 0.33$. Green-circled lines represent impulse responses after a carbon tax shock with subsidies to green energy-producing firms and financially constrained households (FC-HH) under a primary balance neutral policy, i.e. $\varsigma_E^Y = \varsigma_E^C = 0.5$.

FIGURE 2. Impulse Responses to a carbon tax shock in the EA



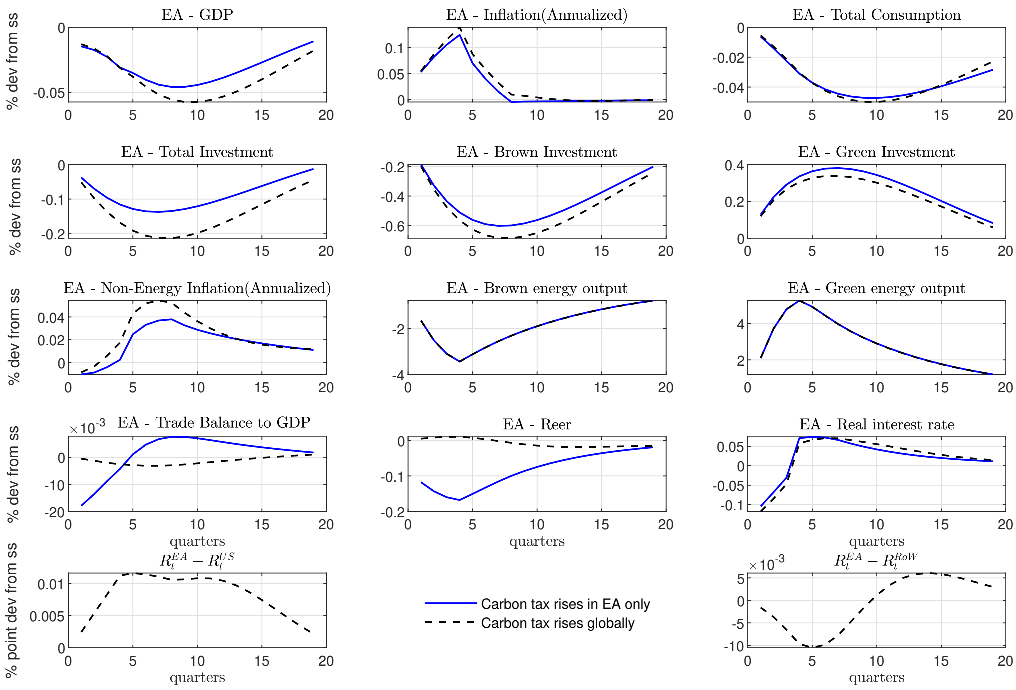
Notes: Impulse responses to a rise in carbon tax in the EA that raises the price of total energy by 1% on impact. Horizontal axis: quarters. Vertical axis: percentage deviations from the baseline, except for inflation and interest rates (annualized percentage-point deviations), and the trade balance-to-GDP ratio (percentage-point deviations). GDP and its components are reported in real terms. Blue-solid lines represent impulse responses after a carbon tax shock without subsidies. Red-dashed lines represent impulse responses after a carbon tax shock with subsidies to green energy-producing firms with $\varsigma_E^Y = 0.33$. Black-dashed-dotted lines represent impulse responses after a carbon tax shock with subsidies to green energy-producing firms and financially constrained households (FC-HH) with $\varsigma_E^Y = \varsigma_E^C = 0.33$. Green-circled lines represent impulse responses after a carbon tax shock with subsidies to green energy-producing firms and financially constrained households (FC-HH) under a primary balance neutral policy, i.e. $\varsigma_E^Y = \varsigma_E^C = 0.5$.

Figure 3. Impulse Responses to a carbon tax shock in the EA



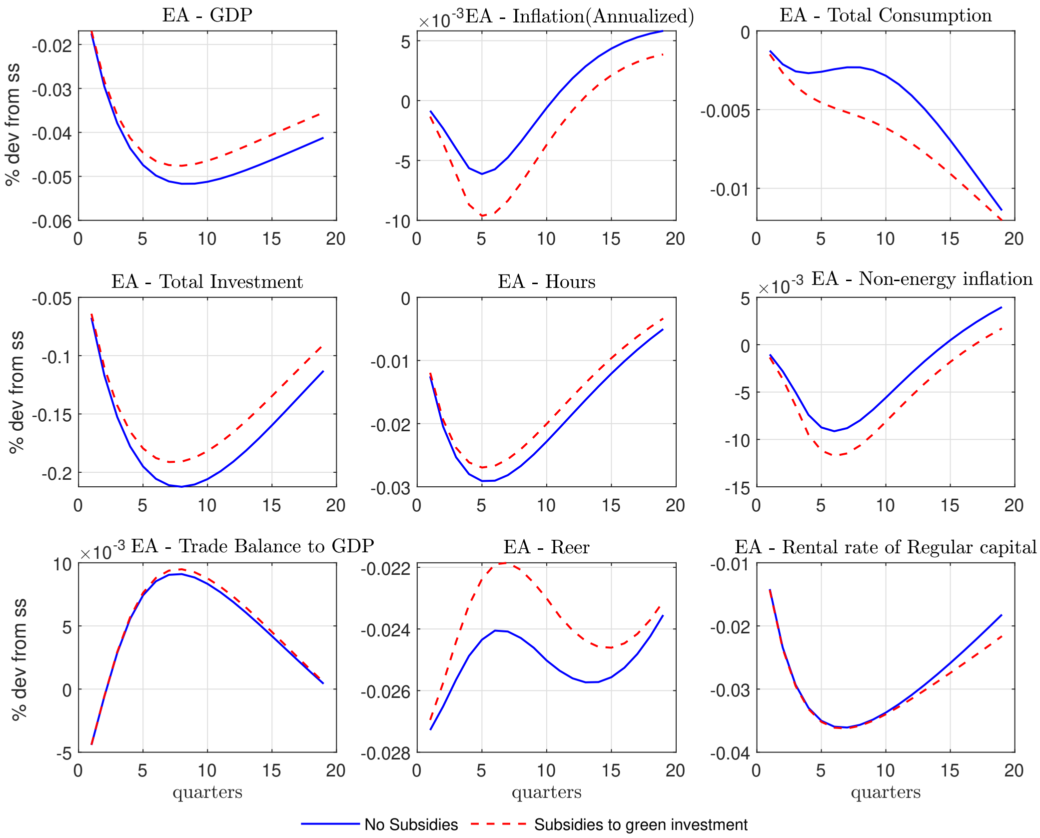
Notes: Impulse responses to a rise in carbon tax in the EA that raises the price of total energy by 1% on impact. Horizontal axis: quarters. Vertical axis: percentage deviations from the baseline, except for inflation and interest rates (annualized percentage-point deviations), and the trade balance-to-GDP ratio (percentage-point deviations). GDP and its components are reported in real terms. Blue-solid lines represent impulse responses after a carbon tax shock without subsidies. Red-dashed lines represent impulse responses after a carbon tax shock with subsidies to green energy-producing firms with $\varsigma_E^Y = 0.33$. Black-dashed-dotted lines represent impulse responses after a carbon tax shock with subsidies to green energy-producing firms and financially constrained households (FC-HH) with $\varsigma_E^Y = \varsigma_E^C = 0.33$. Green-circled lines represent impulse responses after a carbon tax shock with subsidies to green energy-producing firms and financially constrained households (FC-HH) under a primary balance neutral policy, i.e. $\varsigma_E^Y = \varsigma_E^C = 0.5$.

Figure 4. Impulse Responses to a Global Carbon Tax Shock with subsidies to green energy firms only



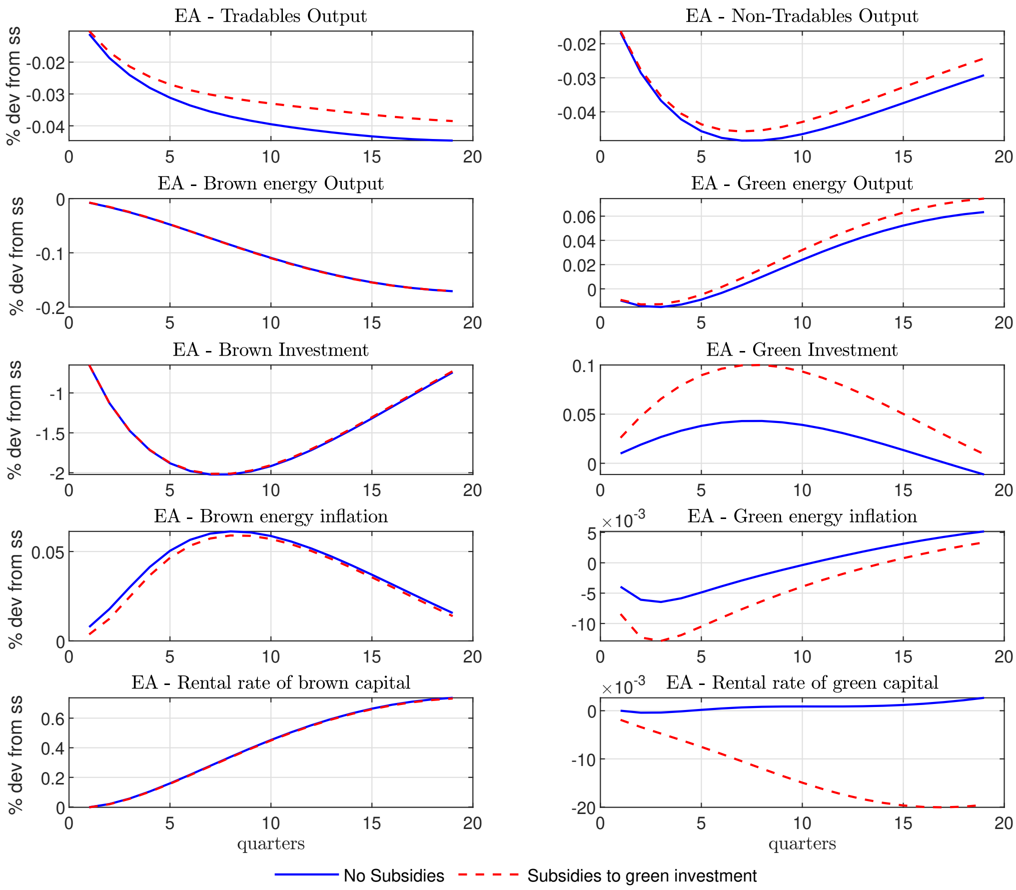
Notes: Impulse responses to a rise in carbon tax in the EA, the US and the RW that raises the price of total energy by 1% on impact, when all regions implement transfers to green energy firms only. $R_t^{EA} - R_t^{US}$ and $R_t^{EA} - R_t^{RW}$ denote the spread between the policy rate in the EA and the US and the spread between the policy in the EA and the RW, respectively. Horizontal axis: quarters. Vertical axis: percentage deviations from the baseline, except for inflation and interest rates (annualized percentage-point deviations), and the trade balance-to-GDP ratio (percentage-point deviations). GDP and its components are reported in real terms.

FIGURE 5. Impulse Responses to a brown-capital rental income tax shock in the EA



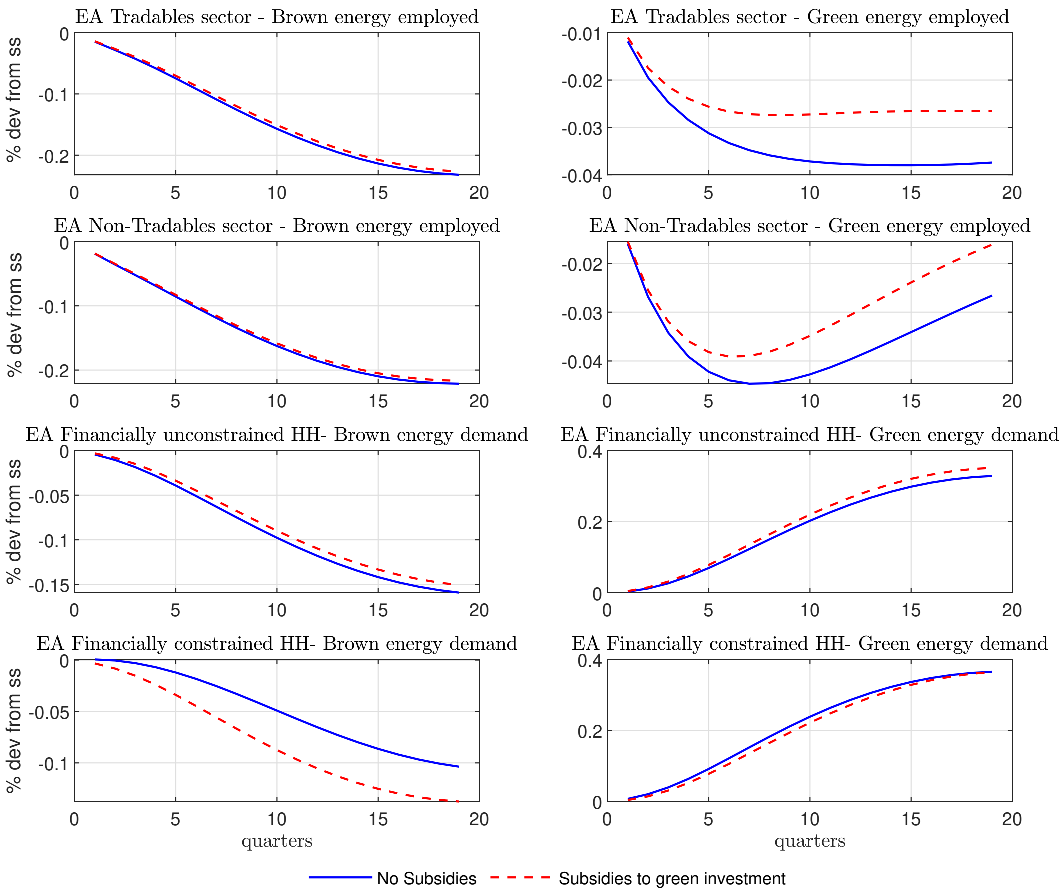
Notes: Impulse responses to a rise in tax on rental brown capital income in the EA. Horizontal axis: quarters. Vertical axis: percentage deviations from the baseline, except for inflation and interest rates (annualized percentage-point deviations), and the trade balance-to-GDP ratio (percentage-point deviations). GDP and its components are reported in real terms.

FIGURE 6. Impulse Responses to a brown-capital rental income tax shock in the EA



Notes: Impulse responses to a rise in tax on rental brown capital income in the EA. Horizontal axis: quarters. Vertical axis: percentage deviations from the baseline, except for inflation and interest rates (annualized percentage-point deviations), and the trade balance-to-GDP ratio (percentage-point deviations). GDP and its components are reported in real terms.

Figure 7. Impulse Responses to a brown-capital rental income tax shock in the EA



Notes: Impulse responses to a rise in tax on rental brown capital income in the EA. Horizontal axis: quarters. Vertical axis: percentage deviations from the baseline, except for inflation and interest rates (annualized percentage-point deviations), and the trade balance-to-GDP ratio (percentage-point deviations). GDP and its components are reported in real terms.

A Technical Annex

A.1 Final goods sector: non-energy consumption goods

Each perfectly competitive final non-energy consumption good firm x $(x \in [0, s^H])$ produces a non-energy consumption good, $Q_t^C(x)$, with the following CES technology:

$$Q_t^C(x) = \left[\nu_C^{\frac{1}{\mu_C}} TT_t^C(x)^{\frac{\mu_C - 1}{\mu_C}} + (1 - \nu_C) NT_t^C(x)^{\frac{\mu_C - 1}{\mu_C}} \right]^{\frac{\mu_C}{\mu_C - 1}} \tag{49}$$

where

$$TT_t^C(x) = \left[\nu_{TC}^{\frac{1}{\mu_{TC}}} HT_t^C(x)^{\frac{\mu_{TC} - 1}{\mu_{TC}}} + (1 - \nu_{TC}) IM_t^C(x)^{\frac{\mu_{TC} - 1}{\mu_{TC}}} \right]^{\frac{\mu_{TC}}{\mu_{TC} - 1}} \tag{50}$$

In the expressions above, $TT_t^C(x)$ and $NT_t^C(x)$ denote the tradable and non-tradable goods, respectively, used to produce the final non-energy consumption good. Parameter ν_C $(0 \leq \nu_C \leq 1)$ captures the share of tradables in the production process while parameter $\mu_C > 0$ denotes the elasticity of substitution between tradables and non-tradables in production. Subsequently, $HT_t(x)$ and $IM_t^C(x)$ in the tradable goods aggregator (50) denote the home and the imported tradable goods used in the production of the final non-energy consumption good. The parameter ν_{TC} $(0 \leq \nu_{TC} \leq 1)$ captures home bias while parameter $\mu_{TC} > 0$ is the trade elasticity. Imports $IM_t^C(x)$ are a CES function of basket of goods imported from other countries:

$$IM_t^C(x) = \left[\sum_{CO \neq H} \left(v_{IMC}^{H,CO} \right)^{\frac{1}{\mu_{IMC}}} \left(IM_t^{C,CO}(x) \left(1 - \Gamma_{IM^C}^{H,CO}(\gamma_{IMC}) \right) \right)^{\frac{\mu_{IMC} - 1}{\mu_{IMC}}} \right]^{\frac{\mu_{IMC}}{\mu_{IMC} - 1}} \tag{51}$$

where $\mu_{IMC} > 0$ and the coefficients $v_{IMC}^{H,CO}$ are such that:

$$0 \leq v_{IMC}^{H,CO} \leq 1, \quad \sum_{CO \neq H} v_{IMC}^{H,CO} = 1 \tag{52}$$

The term $\Gamma_{IM^C}^{H,CO}(\gamma_{IMC})$ represents adjustment costs on bilateral investment imports of country H from country CO.

A.2 Final goods sector: non-energy investment goods

Similar to the non-energy final consumption good firm above, the competitive final non-energy investment good firm l $(l \in [0, s^H])$ produces a non-energy investment good, $Q_t^I(l)$, with the following CES technology:

$$Q_t^I(l) = \left[\nu_I^{\frac{1}{\mu_I}} TT_t^I(l)^{\frac{\mu_I - 1}{\mu_I}} + (1-\nu_I) NT_t^I(l)^{\frac{\mu_I - 1}{\mu_I}}\right]^{\frac{\mu_I}{\mu_I - 1}} \tag{53}$$

where

$$TT_t^I(l) = \left[\nu_{TI}^{\frac{1}{\mu_{TI}}} HT_t^I(l)^{\frac{\mu_{TI} - 1}{\mu_{TI}}} + (1-\nu_{TI}) IM_t^I(l)^{\frac{\mu_{TI} - 1}{\mu_{TI}}}\right]^{\frac{\mu_{TI}}{\mu_{TI} - 1}} \tag{54}$$

In the expressions above, $TT_t^I(l)$ and $NT_t^I(l)$ denote the tradable and non-tradable goods, respectively, used to produce the final non-energy consumption good. Parameter ν_I $(0 \leq \nu_I \leq 1)$ captures the share of tradables in the production process while parameter $\mu_I > 0$ denotes the elasticity of substitution between tradables and non-tradables in production. Subsequently, $HT_t(l)$ and $IM_t^I(l)$ in the tradable goods aggregator (54) denote the home and the imported tradable goods used in the production of the final non-energy investment good. The parameter ν_{TI} $(0 \leq \nu_{TI} \leq 1)$ captures home bias while parameter $\mu_{TI} > 0$ is the trade elasticity. The imported goods aggregator $IM_t^I(l)$ are a CES function defined in a similar fashion as in (51) above.

A.3 Market clearing conditions

The market clearing condition for **non-tradable** intermediate good n is :

$$Y_{N,t}^S(n) = NT_t^C(n) + NT_t^I(n) + G_t(n), \ \forall n \tag{55}$$

Aggregating over the continuum of firms (s^H is the size of the domestic economy):

$$\begin{aligned} Y_{N,t}^S &= \frac{1}{s^H}\int_0^{s^H} Y_{N,t}^S(h)\,dh \\ &= \frac{1}{s^H}\left(\int_0^{s^H} \left(NT_t^C(n) + NT_t^I(n) + NT_t^{IB}(n) + NT_t^{IG}(n) + G_t(n)\right) dn\right) \\ &= NT_t^C + NT_t^I + NT_t^{IB} + NT_t^{IG} + G_t \end{aligned} \tag{56}$$

For each **tradable** intermediate good, aggregating across firms, the following market clearing condition holds:

$$\begin{aligned} Y^S_{T,t}(h) &= HT^C_t(h) + HT^I_t(h) + HT^{IB}_t(h) + HT^{IG}_t(h) \\ &+ \sum_{CO \neq H} IM^{C,CO}_t(h) + \sum_{CO \neq H} IM^{I,CO}_t(h) + \sum_{CO \neq H} IM^{IB,CO}_t(h), \qquad \forall h \end{aligned} \tag{57}$$

Aggregating across firms:

$$\begin{aligned} Y^S_{T,t} &= \frac{1}{s^H} \int_0^{s^H} Y^S_{T,t}(h)\, dh \\ &= \frac{1}{s^H} \left(\int_0^{s^H} \left(HT^C_t(h) + HT^I_t(h) + HT^{IB}_t(h) + HT^{IG}_t(h) \right) dh \right) \\ &+ \frac{1}{s^H} \left(\int_0^{s^H} \sum_{CO \neq H} \left(IM^{C,CO}_t(h) + IM^{I,CO}_t(h) + IM^{IB,CO}_t(h) \right) dh \right) \end{aligned} \tag{58}$$

Total supply of the composite **labor** bundle equals total demand by firms in tradables and non-tradables intermediate sectors:

$$\begin{aligned} N_t &= \frac{1}{s^H} \left(\int_0^{s^H} N^D_t(n)\ dn + \int_0^{s^H} N^D_t(h)\ dh + \int_0^{s^H} N^D_t(b)\ db + \int_0^{s^H} N^D_t(g)\ dg \right) \\ &= N^D_{N,t} + N^D_{T,t} + N^D_{B,t} + N^D_{G,t} \end{aligned} \tag{59}$$

The market clearing conditions, jointly with the budget constraints of the households and the fiscal authority, imply the following aggregate resource constraint:

$$\begin{aligned} P_{Y,t} Y_t &= P_{C,t}\ Q^C_t + P_{I,t}\ Q^I_t + P_{IB,t}\ Q^{IB}_t + P_{IG,t}\ Q^{IG}_t + P_{N,t}\ G_t \\ &+ \sum_{CO \neq H} \frac{\sigma^{CO}}{\sigma^H}\ \mathcal{X}^{H,CO}_t P^{H,CO}_{X,t} IM^{CO,H}_t - \sum_{CO \neq H} P^{H,CO}_{IM,t} IM^{H,CO}_t \end{aligned} \tag{60}$$

or identically:

$$\begin{aligned} P_{Y,t} Y_t &= P_{C,t}\left(C_t + \Gamma_{v,t}\right) + P_{I,t}\left(I_t + \Gamma_{u,t} K_t\right) + P_{IB,t}\left(I_{B,t} + \Gamma_{u_B,t} K_{B,t}\right) + P_{IG,t}\left(I_{G,t} + \Gamma_{u_G,t} K_{G,t}\right) \\ &+ P_{N,t} G_t + \sum_{CO \neq H} \frac{\sigma^{CO}}{\sigma^H}\ \mathcal{X}^{H,CO}_t P^{H,CO}_{X,t} IM^{CO,H}_t - \sum_{CO \neq H} P^{H,CO}_{IM,t} IM^{H,CO}_t \end{aligned} \tag{61}$$

where σ, $\mathcal{X}_t$ and $P_{X,t}$ are the size of the country (domestic H or foreign CO), the real exchange rate (euro-dollar) and the export deflator, respectively. Total imports of country H from country CO are defined as:

$$IM_t^{H,CO} \equiv IM_t^{C,CO} \frac{1-\Gamma_{IM^C}^{H,CO}(\cdot)}{\Gamma_{IM^C}^{H,CO\dagger}(\cdot)} + IM_t^{I,CO} \frac{1-\Gamma_{IM^I}^{H,CO}(\cdot)}{\Gamma_{IM^I}^{H,CO\dagger}(\cdot)} + IM_t^{IB,CO} \frac{1-\Gamma_{IM^{IB}}^{H,CO}(\gamma_{IMB})}{\Gamma_{IM^{IB}}^{H,CO\dagger}(\gamma_{IMIB})} \quad (62)$$

Domestic holdings of foreign bonds, denominated in foreign currency, evolve according to:

$$R_t^{*-1} B_{t+1}^* = B_t^* + \frac{TB_t^H}{S_t^{H,US}} \quad (63)$$

where TB_t^H stands for the Home economy's trade balance:

$$TB_t^H \equiv \sum_{CO \neq H} \frac{s^{CO}}{s^H} S_t^{H,CO} P_{X,t}^{H,CO} IM_t^{CO,H} - \sum_{CO \neq H} P_{IM,t}^{H,CO} IM_t^{H,CO} \quad (64)$$

Finally, the aggregate output is defined as follows:

$$P_{Y,t} Y_t = P_{T,t} Y_{T,t}^S + P_{N,t} Y_{N,t}^S + P_{B,t} Y_{B,t}^S + P_{G,t} Y_{G,t}^S \quad (65)$$

where the price indices have been defined in the sections above.