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Macroeconomic effects of carbon transition policies: an assessment based on the ECB's New Area-Wide Model with a disaggregated energy sector

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Abstract

We use scenario analysis to assess the macroeconomic effects of carbon transition policies aimed at mitigating climate change. To this end, we employ a version of the ECB's New Area-Wide Model (NAWM) augmented with a framework of disaggregated energy production and use, which distinguishes between "dirty" and "clean" energy. Our central transition scenario is that of a permanent increase in carbon taxes, which are levied as a surcharge on the price of dirty energy. Our findings suggest that increasing euro area carbon taxes to an interim target level consistent with the transition to a net-zero economy entails a transitory rise in inflation and a lasting, albeit moderate decline in GDP. We show that the short and medium-term effects depend on the monetary policy reaction, on the path of the carbon tax increase and on its credibility, while expanding clean energy supply is key for containing the decline in GDP. Undesirable distributional effects can be addressed by redistributing the fiscal revenues from the carbon tax increase to low-income households.

JEL Classification System: C54, E52, E62, H23, Q43

Keywords: Climate change, carbon taxation, DSGE model, monetary policy, fiscal policy, euro area

Non-technical summary

In this paper, we use scenario analysis to assess the macroeconomic effects of transition policies aimed at reducing carbon emissions in the euro area, with a focus on tax policies that raise the price of carbon emissions. To carry out the analysis, we employ a version of the ECB's New Area-Wide Model (NAWM) which has been augmented with a framework of disaggregated energy production and use, where intermediate-good firms and households demand an energy composite for production and consumption purposes. The energy composite is produced by an energy provider which aggregates "dirty" and "clean" energy inputs. These inputs are in turn produced from imported fossil resources, the use of which causes carbon emissions, and from domestic renewable resources.

We use the augmented version of the NAWM to conduct simulation analyses around a central carbon tax transition scenario. The central scenario is empirically grounded in measures of Effective Carbon Rates (ECRs) provided by the OECD, which capture the price of carbon emissions at the sectoral and country level. Specifically, the scenario assumes a steady and linear increase in the average ECR for the euro area to a target rate of €140/tCO2 over the period from 2022 to 2030. This target rate is broadly consistent with estimates of the IEA, according to which advanced economies need to raise the price of carbon emissions to $140/tCO2 in 2030 in order to meet their longer-term net-zero commitments, provided that the prospective effects from additional non-price policy measures in their overall decarbonisation strategy as well as technological advances leading to an increase in the efficiency of clean energy production and energy use are achieved.

Our simulation results for the central carbon tax transition scenario suggest that the assumed increase in the price of carbon emissions has a limited overall impact on the economy. Consumer price inflation rises as higher energy prices feed both directly and indirectly into the price of the aggregate consumption bundle of households. The rise in annual inflation is gradual and hump-shaped, reaching a peak of around 0.2 percentage point in the course of 2023, before slowly receding by the end of 2030. On average, inflation increases by less than one-tenth of a percentage point over the scenario period from 2022 to 2030. At the same time, higher energy prices put only modest upward pressure on inflation excluding energy via their impact on intermediate-good production costs. On the real side, aggregate consumption falls moderately by about 0.7% over the medium to longer term. The fall in investment is markedly stronger, with a decline of close to 2.5% at the trough. The implied decline in aggregate demand translates into a gradual but lasting fall in GDP by around 1.2%, shaving off about one-eighth of a percentage point from GDP growth per annum over the scenario period. At the sectoral level, the increase in carbon prices operates by affecting relative energy prices. Hence, the aggregate energy provider is incentivised to substitute away from utilising more costly dirty energy and into utilising clean energy. Due to the lower use of dirty energy in aggregate energy production and the overall fall in aggregate energy use, carbon emissions are reduced by roughly 7% in the medium to longer term. Clearly, as the carbon tax increase in our central scenario is the only policy measure considered, this reduction must necessarily falls short of the targeted emissions levels of a comprehensive net-zero decarbonisation strategy.

Sensitivity analyses carried out around the central carbon tax transition scenario shows that the short and medium-term effects depend, inter alia, on the monetary policy reaction, on the path of the carbon tax increase and on its credibility. Expanding clean energy supply is key for containing the decline in GDP and the increase in inflation as well as accelerating the reduction in carbon emissions. Undesirable distributional effects can be addressed by redistributing the fiscal revenues from the carbon tax increase to low-income households by means of targeted transfers.

1 Introduction

The transition to a "net-zero" economy, as set out by the European Commission in the European Green Deal, constitutes a structural force that will be a possibly significant contributor to euro area macroeconomic dynamics over the next decades (see, e.g., Pisani-Ferry, 2021, Lane, 2022, and Schnabel, 2022).[1] The impact of the net-zero transition on inflation dynamics will depend on the transition pathway, notably for the price of carbon emissions, and evolve over time. Over the short to medium term, the transition is likely to add upward pressures on energy prices, which in turn will depend on the changing mix of fossil and renewable resources in energy production. As regards the real economy, the transition will be accompanied by marked structural shifts in aggregate supply and in the composition of aggregate demand, which in themselves will have an influence on inflation. Over the longer term, sizeable efficiency gains in the production and use of renewable energy are expected to materialise, reducing overall energy prices and thus easing or even reverting inflation pressures. These prospective macroeconomic developments will have a bearing on the conduct of monetary policy aimed at preserving price stability.

Against this background, we use scenario analysis to assess the macroeconomic effects of transition policies aimed at reducing carbon emissions in the euro area, with a focus on tax policies that raise the price of carbon emissions.[2] To carry out the analysis, we employ a version of the ECB's New Area-Wide Model (NAWM) which has been augmented with a framework of disaggregated energy production and use, where intermediate-good firms and households demand an energy composite for production and consumption purposes.[3] The energy composite is produced by a perfectly competitive firm, which combines "dirty" and "clean" energy inputs. These inputs are in turn produced by two sets of monopolistically competitive firms: firms in the dirty energy sector combine imported "fossil" resources, the use of which causes carbon emissions, with a capital-labour bundle, whereas firms in the

[1] The European Green Deal is a set of policy initiatives by the European Commission with the overarching aim of making the European Union climate neutral by achieving net-zero greenhouse gas emissions by 2050 (see European Commission, 2019).

[2] Compared to other instruments, carbon taxes are judged to be effective, efficient, easy to implement, and difficult to evade (see Timilsina, 2022, for a comprehensive review). They correct market distortions by taxing carbon emissions and thereby cause emitters to pay for the social costs which are generally excluded from the private costs of economic activities releasing carbon emissions.

[3] The original NAWM is a calibrated, non-linear, two-country DSGE model of the euro area and the United States; see Coenen, McAdam and Straub (2007, 2008).

clean energy sector combine domestic "green" renewable resources with a capital-labour bundle. The energy composite is then utilised as a distinct input in the production of intermediate goods, and as a separate good in households' aggregate consumption bundle. Importantly, our specification of imperfect competition across firms in the clean and dirty energy sectors allows for sectoral energy prices to be passed through to intermediate-good and aggregate consumption prices in a staggered fashion. Over and above carbon emissions from energy use, we have also introduced non-energy carbon emissions and related abatement efforts on the part of intermediate-good firms which are deemed a desirable feature for studying carbon transition policies.

Our modelling strategy differs from other climate change-related modelling approaches in that our model places emphasis on understanding the macroeconomic effects of transition policies in the short to medium term. While the incorporation of macroeconomic aspects of climate change are also an important part of Integrated Assessment Models (IGAMs) or Computable General Equilibrium (CGE) frameworks, these classes of models generally lack the economic micro-foundations and relevant economic frictions that enable a quantitative assessment of the transmission channels of climate change on the macro economy over the shorter term.[4] Instead, the strength of these models predominantly lies in their ability to capture sectoral reallocations over a longer time horizon and the two-way interaction between climate and the economy.

While the literature exploring the interactions between climate change and the economy within DSGE models is still nascent (see, e.g., Angelopoulos et al., 2010, Fischer and Springborn, 2011, Heutel, 2012, Annicchiarico and Di Dio, 2015, for early contributions), there are several recent DSGE model-based studies of climate policies which our analysis relates to, such as Känzig (2021), Ferrari and Nispi Landi (2022), Airaudo et al. (2022), Dupraz et al. (2022), Del Negro et al. (2023) and Priftis and Schoenle (2023). Compared to these studies, our analysis is based on a larger-scale model and tailored to provide quantitative prescriptions regarding the effectiveness of carbon transition policies. As such, our approach is closer to that of other model-based studies carried out at policy institutions, such

[4]Prominent examples of IGAMs are the DICE model (Nordhaus, 2017), the GCAM model (Calvin et al., 2019) and the REMIND-MagPIE model (Dietrich et al., 2019), whereas the IMF-ENV model (Rojas-Romagosa et al., 2022) is a recent example of CGE models developed for evaluating climate policies.

as Varga et al. (2021), Bartocci et al. (2022), Carton et al. (2022) and Ernst et al. (2022). Our focus however is on exploring the impact of transition policies on both inflation and economic activity and on examining the interplay of this impact with the conduct of fiscal and monetary policy, which is of particular relevance for central banks.

We use the augmented version of the NAWM to conduct simulation analyses around a central carbon tax transition scenario, which extends the short-term assessment in Ferdinandusse et al. (2022). The central scenario is empirically grounded in measures of Effective Carbon Rates (ECRs) provided by the OECD, which capture the price of carbon emissions at the sectoral and country level. Specifically, the scenario assumes a steady and linear increase in the average ECR for the euro area to a target rate of €140/tCO2 over the period from 2022 to 2030. This target rate is broadly consistent with estimates of the IEA, according to which advanced economies need to raise the price of carbon emissions to \$140/tCO2 in 2030 in order to meet their longer-term net-zero commitments, provided that the prospective effects from additional non-price policy measures in their overall decarbonisation strategy as well as technological advancements leading to an increase in the efficiency of clean energy production and energy use are achieved.[5]

Our simulation results for the central carbon tax transition scenario suggest that the assumed increase in the price of carbon emissions has a limited overall impact on the economy. Consumer price inflation rises as higher energy prices feed both directly and indirectly into the price of the aggregate consumption bundle of households. The rise in annual inflation is gradual and hump-shaped, reaching a peak of around 0.2 percentage point in the course of 2023, before slowly receding by the end of 2030. On average, inflation increases by less than one-tenth of a percentage point over the scenario period from 2022 to 2030. At the same time, higher energy prices put only modest upward pressure on inflation excluding energy via their impact on intermediate-good production costs. On the real side, aggregate consumption falls moderately by about 0.7% over the medium to longer term. The fall in investment is markedly stronger, with a decline of close to 2.5% at the trough. The implied decline in aggregate demand translates into a gradual but lasting fall in GDP

[5]Concerning the implementation of the European Green Deal, a comprehensive set of climate policy measures needed to reach the European Union's intermediate target of reducing emissions in 2030 by 55%, compared to 1990 levels, is detailed in the so-called "Fit for 55" package (see European Commission, 2021).

by around 1.2%, shaving off about one-eighth of a percentage point from GDP growth per annum over the scenario period. At the sectoral level, the increase in carbon prices operates by affecting relative energy prices. Hence, the aggregate energy producer is incentivised to substitute away from utilising more costly dirty energy and into utilising clean energy. Due to the lower use of dirty energy in aggregate energy production and the overall fall in aggregate energy use, carbon emissions are reduced by roughly 7% in the medium to longer term. Clearly, as the carbon tax increase in our central scenario is the only policy measure considered, this reduction must necessarily fall short of the targeted emissions levels of a comprehensive net-zero decarbonisation strategy.

We explore the sensitivity of our quantitative findings by first analysing the role of monetary policy in managing the inflation-output trade-off entailed by the carbon transition scenario. Under a version of the Taylor (1993) rule with an interest-rate reaction to inflation excluding energy, like the default interest-rate rule of our model, but with a reaction to the output gap instead of the GDP growth gap, both overall inflation and inflation excluding energy rise more strongly, while the output gap, measuring the shortfall of GDP below trend GDP, is mitigated. By contrast, under a Taylor rule which reacts to overall inflation and hence the carbon tax-induced direct effect of higher energy prices, the inflation effects are noticeably reduced, compared to the effects under the Taylor rule reacting to inflation excluding energy. At the same time, the GDP shortfall is larger. Hence, a policy-maker who has a strong preference to mitigate the shortfall of GDP would want to "look through" the direct inflation effect of the carbon tax and stabilise inflation excluding energy at the expense of tolerating higher overall inflation.

We next use our model to carry out sensitivity analyses on alternative schemes for distributing the carbon tax-related fiscal revenues, namely transfers and subsidies. First, our model features a time-invariant form of household heterogeneity, with a subset of households facing liquidity constraints because of limited access to asset markets. Hence, the way in which carbon tax revenues are distributed across households influences their individual consumption responses. If the tax revenues are transferred evenly to households, the constrained households are not sufficiently compensated for the reduction in real disposable income due to the carbon tax increase, and their individual consumption declines compared to that of the unconstrained households, resulting in an increase in consumption inequality. Instead, if the constrained households receive proportionately more of the revenues relative to the unconstrained households, i.e., targeted transfers, this allows them to eventually sustain their initial consumption position. Although the individual responses of consumption do not meaningfully impact the response of aggregate consumption, the choice of revenue distribution scheme by the government has important distributional implications, which are masked by an aggregate analysis of the effects of carbon taxes. Second, under a revenue distribution scheme whereby the government subsidises the production of clean energy, the aggregate effects are again very limited. This reflects the presence of two countervailing forces. On the one hand, as the availability of green resources is inelastic in our central scenario, the subsidy translates basically into a sustained increase in the profits of clean energy firms. These profits are paid as dividends to the unconstrained households, who accordingly expand consumption. On the other hand, granting the subsidy to clean energy firms comes along with a corresponding reduction in carbon tax-related transfers to households. This results in an off-setting fall in income and thus consumption, especially on the part of the unconstrained households.

We also investigate the consequences of alternative tax paths in implementing the carbon transition scenario and the impact of an imperfectly credible implementation of the scenario. Compared to the linear tax increase in the central scenario, a front-loaded tax increase implies that GDP falls faster because of a stronger carbon tax-induced decline in households' real income and in the profitability of firms, resulting in lower consumption and investment. Instead, a back-loaded and delayed tax increase implies that households and firms benefit from an initially lower carbon tax burden but anticipate the continued and eventually accelerating increase in the carbon tax in the more distant future. Overall, this helps to sustain both consumption and investment and thus GDP in the short to medium term. The inflationary effects of the carbon tax increase are more drawn out under the back-loaded and delayed implementation, and they diminish faster under the front-loaded implementation, whereas the short-term impacts are by and large similar, reflecting the forward-looking price-setting behaviour of firms. Under the assumption of imperfect credibility households and firms do not believe in future carbon tax increases until they are actually observed. In this case, the intertemporal forward-looking element of decision-making is missing. As a consequence, there are no visible front-loading effects and the implied increase in inflation is contained but very persistent, while GDP declines more slowly.

We finally illustrate the importance of enhancing the supply of clean energy as a means to accelerate the carbon transition. If the efficiency of clean energy production improves, or if the availability of green resources increases, then households and firms will benefit from lower energy prices. Efficiency improvements can be related to the adoption of new technologies, and the increase in green resource availability can result from a government policy that allows issuance of additional production permits for the use of larger natural territories (e.g., increased land or sea surface use). In the same vein, these favourable supply effects can be expanded by a government policy aimed at enhancing clean energy production capacity (e.g., by undertaking "green" investments).

Across the different types of sensitivity analyses, the carbon reduction paths are found to be broadly similar, except for the cases of imperfect credibility and enhanced clean energy supply. In the first case the reduction of carbon emissions is materially delayed, and in the second case the emission reduction is substantially strengthened. These findings underline the importance of making credible commitments to meet the announced carbon reduction targets and the necessity of technological innovations and appropriate government policies to enhance the efficiency and capacity of clean energy production.

Lastly, our model also features an additional policy instrument aimed at mitigating carbon emissions, namely a tax on non-energy-related carbon emissions of intermediate-good firms. This instrument can be interpreted as a shadow price of environmental regulation, aimed at lowering the amount of emissions per unit of output produced. In practice, firms are incentivised to engage in costly abatement through, e.g., the installation of new pollution filters, in an effort to reduce the tax burden from non-energy emissions. Our results show that this margin of adjustment produces very modest inflationary effects, while contributing moderately to the overall decline in GDP due to carbon taxes.

When compared to the model-based studies referred to above, our analysis is closest to Varga et al. (2021), Bartocci et al. (2022), and Carton et al. (2022), who all investigate the impact of carbon taxes on the economy by employing larger-scale DSGE models suitable for performing quantitative analysis. While there are broad similarities with our analysis in terms of methodology and exercises performed, there are also differences in scope and predictions. Varga et al. (2021) use a DSGE model of the European Union and the rest of the world with a more granular disaggregation of energy for production and consumption purposes to explore the impact of alternative carbon policies on real activity. In line with our results, they find that carbon taxes lead to a fall in GDP, although the negative GDP effect of carbon taxes can be mitigated when fiscal revenues are recycled to reduce other distortive taxes or to subsidise clean energy production. Their analysis however does not speak to the effects on nominal variables, notably inflation. Bartocci et al. (2022) investigate the macroeconomic effects of carbon taxes using a two-country model of the euro area and the rest of the world with a disaggregated energy sector as we do. Similar to our results, they find that an increase in carbon taxes reduces GDP. However in contrast to us, they find that carbon taxes are disinflationary because, in their model, the negative effect of carbon taxes on aggregate demand and, thereby, on inflation prevails over the direct inflation effect. Carton et al. (2022) employ a global model with several energy sectors, including a "back up capacity" for electricity production which captures intermittent energy generation of renewable resources. They use the model to provide a global assessment of alternative policy packages aimed at lowering carbon emissions. Their findings for the euro area are broadly in line with ours when the carbon tax revenues are redistributed to households, with GDP falling and inflation increasing by comparable magnitudes.

Our analysis is also related to recent studies which use smaller-scale E-DSGE models to investigate the consequences of the carbon transition. For example, Airaudo et al. (2022) use a small-open-economy model with endogenous energy efficiency, calibrated to Chile. In their setting, an increase in carbon taxes lowers the use of brown energy and improves the efficiency of green energy use, leading to an increase in firms' marginal costs with overall inflationary effects. Using a smaller-scale two-sector model of green and brown production without a role for distinct energy usage, Ferrari and Nispi Landi (2022) focus instead on a framework with abatement technology. Their model predicts that an increase in carbon taxes raises the (costly) abatement effort of brown firms and places downward pressure on aggregate demand and hence inflation. Priftis and Schoenle (2023) use a model with disaggregated energy and financial intermediaries to show how carbon transfers (the inverse of carbon taxes) can plausibly mitigate energy price increases such as the ones witnessed in recent quarters. This suggests that, in their model, carbon taxes also lead to inflationary effects, as predicted in this paper.

The remainder of the paper is structured as follows. Section 2 describes the specification of the disaggregated energy sector, which is incorporated into the original version of the NAWM, and discusses the calibration and validation of the augmented model, with a focus on its energy-related aspects. Section 3 sets out the central scenario of carbon tax policy aimed at reducing carbon emissions, reports the main quantitative simulation results and explores their sensitivity to different implementation assumptions. Section 4 extends the model by introducing emission abatement efforts on the part of intermediate-good firms. Finally, Section 5 concludes the paper.

2 The model

In this section we describe the specification of our model and discuss the model calibration and validation strategy. The model extends the original two-country version of the NAWM with a disaggregated energy sector, along with a small third country extracting and exporting fossil resources. Since it otherwise retains the original structure, we just provide a non-technical sketch of the original model and present subsequently the new elements, as well as the new equations, that are most relevant for understanding the enhanced role of the energy sector in the extended model. Similarly, as regards calibration and validation, we focus on the energy-related aspects of the model. In support of the model description, Figure 1 provides a simple representation of the input and output flows across the different sectors of energy and non-energy production in the model.

2.1 A sketch of the original model

The original version of the NAWM consists of two symmetric countries of different size: the euro area and the United States, the latter representing the rest of the industrialised world. International linkages arise from the trade of goods and international assets, allowing for gradual exchange-rate pass-through and imperfect risk sharing.

In each country, there are four types of economic agents: households, firms, a fiscal and a monetary authority. The NAWM features two distinct types of households which differ with respect to their ability to participate in asset markets, with one type of households only holding money as opposed to also trading bonds and accumulating physical capital. Thus, also households with limited access to asset markets can smooth consumption by adjusting their holdings of money. Nevertheless, due to the existence of these two types of households, fiscal policies other than government spending—notably transfers—have real effects even though both types of households are optimising subject to intertemporal budget constraints. Further, it is assumed that both types of households supply differentiated labour services and act as wage setters in monopolistically competitive markets by charging a markup over their marginal rate of substitution. Wage setting is characterised by sticky nominal wages and indexation, resulting in two separate wage Phillips curves.

Regarding firms, the NAWM distinguishes between producers of tradable differentiated intermediate goods and producers of three non-tradable final goods: a private consumption good, a private investment good, and a public consumption good. The intermediate-good producers sell their differentiated outputs in both domestic and foreign markets under monopolistic competition, while the final-good producers operate under perfect competition and take prices as given. It is assumed that the intermediate-good producers set different prices in domestic and foreign markets, by charging a markup over marginal cost but pricing in local currency. In both markets, there is sluggish price adjustment due to staggered price contracts and indexation, yielding two separate price Phillips curves.

The fiscal authority purchases units of the public consumption good and makes transfer payments to the two types of households in unevenly distributed amounts. These expenses are financed by different types of distortionary taxes, including taxes on consumption purchases, labour and capital income, as well as profits. A simple feedback rule is assumed to stabilise the government debt-to-output ratio by adjusting lump-sum taxes to be paid by the two types of households.

Finally, the monetary authority is assumed to follow an inertial Taylor-type interest-rate rule featuring interest-rate smoothing, which is specified in terms of annual consumer-price inflation and quarterly output growth.

2.2 Demand side with energy consumption

Compared to the original model, the demand side has been extended by accounting for energy consumption by households. The assumptions are the following:

- Households consume a composite final consumption good, which is composed of energy and a consumption good excluding energy.
- The consumption good excluding energy, and the investment and public consumption goods are composites of domestic and imported intermediate goods.

Specifically, the two types of households in the model consume a composite final good Q_t^C, which is produced by a competitive firm that bundles an energy good, E_t^C, and a consumption good excluding energy, Q_t^{CX}:[6]

$$Q_t^C = \left[\nu_C^{\frac{1}{\mu_C}} \left((1 - \Gamma_{E^C,t}) E_t^C \right)^{\frac{\mu_C - 1}{\mu_C}} + (1 - \nu_C)^{\frac{1}{\mu_C}} \left(Q_t^{CX} \right)^{\frac{\mu_C - 1}{\mu_C}} \right]^{\frac{\mu_C}{\mu_C - 1}}, \tag{1}$$

where μ_C is the long-run elasticity of substitution between the two goods, ν_C determines their shares in the bundle, and $\Gamma_{E^C,t} = \Gamma_{E^C}(E_t^C / Q_t^C; \gamma_{E^C})$ represents quadratic adjustment costs related to the change in the quantity of the energy good in the production of the final consumption good. Because it is costly to adjust the quantity of the energy good, the short-run elasticity of substitution between energy and the consumption good excluding energy can be significantly below μ_C.

The demand equations for energy and for the consumption good excluding energy are:

$$E_t^C = \nu_c \left(\frac{P_{E,t}}{\Gamma_{E^C,t}^{\dagger} P_{C,t}} \right)^{-\mu_C} \frac{Q^C}{1 - \Gamma_{E^C,t}}, \tag{2}$$

$$Q_t^{CX} = (1 - \nu_c) \left(\frac{P_{CX,t}}{P_{C,t}} \right)^{-\mu_C} Q_t^C, \tag{3}$$

where $P_{C,t}$ is the price of the final consumption good, $P_{E,t}$ and $P_{CX,t}$ are the prices of energy and the consumption good excluding energy, respectively, and $\Gamma_{E^C,t}^{\dagger}$ denotes an analytical expression derived from the energy adjustment cost function.

[6] The two main countries in the extended model are symmetric and, therefore, the exposition does not use country-specific notation, except for the exposition in the subsection where the third fossil resource-exporting country is introduced.

The consumption good excluding energy is a bundle of a domestic intermediate good, H_t^C, and an imported intermediate good, IM_t^C:

$$Q_t^{CX} = \left[\nu_{CX}^{\frac{1}{\mu_{CX}}} \left(H_t^C\right)^{\frac{\mu_{CX}-1}{\mu_{CX}}} + (1-\nu_{CX})^{\frac{1}{\mu_{CX}}} \left((1-\Gamma_{IM^C,t})IM_t^C\right)^{\frac{\mu_{CX}-1}{\mu_{CX}}}\right]^{\frac{\mu_{CX}}{\mu_{CX}-1}}, \tag{4}$$

where μ_{CX} is the long-run elasticity of substitution between the two goods, ν_{CX} determines their shares in the bundle, and $\Gamma_{IM^C,t} = \Gamma_{IM^C}(IM_t^C/Q_t^{CX};\gamma_{IM^C})$ represents quadratic adjustment costs related to the change in the quantity of the imported intermediate good. Because of the adjustment costs, the short-term elasticity of substitution can be significantly below μ_{CX}.

The demand equations for domestic and imported intermediate goods are:

$$H_t^C = \nu_{CX}\left(\frac{P_{H,t}}{P_{CX,t}}\right)^{-\mu_{CX}} Q_t^{CX}, \tag{5}$$

$$IM_t^C = (1-\nu_{CX})\left(\frac{P_{IM,t}}{\Gamma_{IM^C,t}^{\dagger} P_{CX,t}}\right)^{-\mu_{CX}} \frac{Q_t^{CX}}{1-\Gamma_{IM^C,t}}, \tag{6}$$

where $P_{H,t}$ and $P_{IM,t}$ are the prices of the domestic and imported intermediate goods, respectively, and $\Gamma_{IM^C,t}^{\dagger}$ denotes an analytical expression derived from the import adjustment cost function.

The price indices corresponding to the consumption bundles Q_t^C and Q_t^{CX} are:[7]

$$P_{C,t} = \left[\nu_C\left(\frac{P_{E,t}}{\Gamma_{E^C,t}^{\dagger}}\right)^{1-\mu_C} + (1-\nu_C)\left(P_{CX,t}\right)^{1-\mu_C}\right]^{\frac{1}{1-\mu_C}}, \tag{7}$$

$$P_{CX,t} = \left[\nu_{CX}\left(P_{H,t}\right)^{1-\mu_{CX}} + (1-\nu_{CX})\left(\frac{P_{IM,t}}{\Gamma_{IM^C,t}^{\dagger}}\right)^{1-\mu_{CX}}\right]^{\frac{1}{1-\mu_{CX}}}. \tag{8}$$

The production technologies for private investment and public consumption goods, Q_t^I and Q_t^G, as well as the corresponding intermediate-good demand equations and price indices are analogous to equations (4), (5), (6) and (8) for the consumption good excluding energy. That is, we make the simplifying assumption that these goods do not include an explicit energy component.

[7]Note that we will normalise the price of the composite consumption good to one when solving and simulating the model. That is, the consumption good will serve as the numéraire.

Finally, we note that we have modified the preference specification of households following Galí, Smets and Wouters (2012). Specifically, the modified preferences include an endogenous shifter affecting households' marginal disutility of labour which allows to make the *short-term* wealth effect on labour supply arbitrarily small.[8] This feature is especially important for obtaining economically plausible adjustments of labour in response to permanent shocks which give rise to sizeable wealth effects.

2.3 Supply side with disaggregated energy sector

The supply side of the original model, with its focus on domestic value added and intermediate-good production, has been extended to a three-sector setup, accounting for a disaggregated energy sector. The assumptions are the following:

- Domestic intermediate goods are composites of energy and value added and produced by monopolistically competitive firms.
- Energy is a composite good made of dirty and clean energy and produced by a competitive firm.
- Dirty and clean energy are composites of either fossil or green resources and value added and produced by monopolistically competitive firms.
- The monopolistically competitive producers of dirty and clean energy set prices in a staggered Calvo-style fashion.

2.3.1 Intermediate-good production with energy input

The domestic intermediate good used for private consumption purposes, H_t^C, as well as the domestic intermediate goods for private investment and public consumption, H_t^I and H_t^G, are themselves composites of differentiated intermediate-good varieties, $Y_{f,t}$, which are produced by monopolistically competitive firms indexed by f. These firms combine energy, $E_{f,t}^Y$, and the value added, $KN_{f,t}^Y$, from employing capital and labour services:

$$Y_{f,t} = z_t^Y \left[\nu_Y^{\frac{1}{\mu_Y}} \left(E_{f,t}^Y \right)^{\frac{\mu_Y - 1}{\mu_Y}} + (1 - \nu_Y)^{\frac{1}{\mu_Y}} \left(KN_{f,t}^Y \right)^{\frac{\mu_Y - 1}{\mu_Y}} \right]^{\frac{\mu_Y}{\mu_Y - 1}} - \psi^Y, \tag{9}$$

[8] Details on the inclusion of the preference shifter in our model, which results in a modification of the households' wage-setting decisions and hence labour supply, are available upon request.

where μ_Y denotes the long-run elasticity of substitution between energy and value added, while ν_Y determines the share of energy in the production of the intermediate good. z_t^Y represents the level of sectoral productivity, and, because of fixed costs, ψ^Y, production is subject to increasing returns to scale.[9]

Capital and labour services, $K_{f,t}^Y$ and $N_{f,t}^Y$, are combined using a constant-returns-to-scale technology with unit elasticity,

$$KN_{f,t}^Y = \left(K_{f,t}^Y\right)^{\alpha_Y} \left(N_{f,t}^Y\right)^{1-\alpha_Y}, \tag{10}$$

where α_Y determines the capital share in the value added from capital and labour.

Cost minimisation on the part of the intermediate-good producers yields the following system of demand equations:[10]

$$E_{f,t}^Y = \nu_Y \left(\frac{P_{E,t}}{z_t^Y MC_t^Y}\right)^{-\mu_Y} \frac{Y_{f,t} + \psi^Y}{z_t^Y}, \tag{11}$$

$$K_{f,t}^Y = (1-\nu_Y)\,\alpha_Y \left(\frac{R_{K,t}}{MC_t^{KN^Y}}\right)^{-1} \left(\frac{MC_t^{KN^Y}}{z_t^Y MC_t^Y}\right)^{-\mu_Y} \frac{Y_{f,t} + \psi^Y}{z_t^Y}, \tag{12}$$

$$N_{f,t}^Y = (1-\nu_Y)(1-\alpha_Y) \left(\frac{(1+\tau_t^{W_f})W_t}{MC_t^{KN^Y}}\right)^{-1} \left(\frac{MC_t^{KN^Y}}{z_t^Y MC_t^Y}\right)^{-\mu_Y} \frac{Y_{f,t} + \psi^Y}{z_t^Y}, \tag{13}$$

where

$$MC_t^Y = \left(z_t^Y\right)^{-1} \left[\nu_Y \left(P_{E,t}\right)^{1-\mu_Y} + (1-\nu_Y)\left(MC_t^{KN^Y}\right)^{1-\mu_Y}\right]^{\frac{1}{1-\mu_Y}}, \tag{14}$$

$$MC_t^{KN^Y} = \left(\alpha_Y^{\alpha_Y}(1-\alpha_Y)^{1-\alpha_Y}\right)^{-1} \left(R_{K,t}\right)^{\alpha_Y} \left((1+\tau_t^{W_f})W_t\right)^{1-\alpha_Y} \tag{15}$$

denote the marginal costs of producing a unit of the intermediate good and a unit of value added, respectively. Here, we have made use of the fact that marginal costs are identical across intermediate-good producers, $MC_t^Y = MC_{f,t}^Y$ and $MC_t^{KN^Y} = MC_{f,t}^{KN^Y}$, since all producers face the same input prices, $P_{E,t}$, $R_{K,t}$ and $(1+\tau_t^{W_f})W_t$, and since they all have access to the same production technology.

Operating under monopolistic competition, the intermediate-good producers set the prices of the goods sold domestically or abroad in a Calvo (1983)-style staggered fashion as a mark-up over marginal costs; see Coenen et al. (2007) for details.

[9] Note that the fixed costs of production will be calibrated so as to ensure zero profits of intermediate-good producers in the steady state. This in turn guarantees that there is no incentive for other producers to enter the market in the long run.

[10] For details on the derivation of the intermediate-good producers' demand for household-specific varieties of labour services and ensuing aggregation issues, see Coenen et al. (2007). Capital is homogenous and, hence, demand for capital services across intermediate-good producers is additive.

Finally, aggregating across the continuum of intermediate-good producers, we obtain the total sectoral demand for energy, $E_t^Y = \int_0^1 E_{f,t}^Y \, df$.

2.3.2 Energy production and energy prices

The energy bundle

A competitive firm bundles "dirty" and "clean" energy, $\mathcal{D}_t$ and $\mathcal{C}_t$, into the energy good E_t,

$$E_t = z_t^E \left[\nu_E^{\frac{1}{\mu_E}} \left((1-\Gamma_{\mathcal{D},t})\mathcal{D}_t \right)^{\frac{\mu_E-1}{\mu_E}} + (1-\nu_E)^{\frac{1}{\mu_E}} \left(\mathcal{C}_t \right)^{\frac{\mu_E-1}{\mu_E}} \right]^{\frac{\mu_E}{\mu_E-1}}, \tag{16}$$

where μ_E is the long-run elasticity of substitution between dirty and clean energy goods, ν_E determines their shares in the bundle, and $\Gamma_{\mathcal{D},t} = \Gamma_{\mathcal{D}}(\mathcal{D}_t/E_t; \gamma_{\mathcal{D}})$ represents quadratic adjustment costs related to the change in the quantity of the dirty energy input. Because of the adjustment costs, the short-term elasticity of substitution can be significantly below μ_E. z_t^E represents the level of productivity of aggregate energy production.

The energy-bundling firm faces a tax, $\tau_t^{M_{\mathcal{D}}}$, which is levied as a surcharge on the price of the dirty energy input. This tax is proportional to the carbon emission content of dirty energy, $M^{\mathcal{D}}$, and represents the central policy instrument in our model setting to foster the transition from dirty to clean energy.

The respective demand equations for dirty and clean energy are:

$$\mathcal{D}_t = \nu_E \left(\frac{(1+\tau_t^{M_{\mathcal{D}}})\, P_{\mathcal{D},t}}{\Gamma_{\mathcal{D},t}^{\dagger}\, z_t^E \, P_{E,t}} \right)^{-\mu_E} \frac{E_t}{(1-\Gamma_{\mathcal{D},t})\, z_t^E}, \qquad \mathcal{C}_t = (1-\nu_E) \left(\frac{P_{\mathcal{C},t}}{z_t^E \, P_{E,t}} \right)^{-\mu_E} \frac{E_t}{z_t^E}, \tag{17}$$

where $P_{\mathcal{D},t}$ and $P_{\mathcal{C},t}$ are the prices of dirty and clean energy, respectively, and $\Gamma_{\mathcal{D},t}^{\dagger}$ denotes an analytical expression derived from the dirty energy adjustment cost function.

For given prices of dirty and clean energy, the price index of the composite energy good is given by:

$$P_{E,t} = \left(z_t^E \right)^{-1} \left[\nu_E \left(\frac{(1+\tau_t^{M_{\mathcal{D}}})\, P_{\mathcal{D},t}}{\Gamma_{\mathcal{D},t}^{\dagger}} \right)^{1-\mu_E} + (1-\nu_E) \left(P_{\mathcal{C},t} \right)^{1-\mu_E} \right]^{\frac{1}{1-\mu_E}}. \tag{18}$$

In equilibrium, market clearing requires that the supply of the composite energy good equals the energy demand for producing the final consumption good and for producing the non-energy intermediate goods: $E_t = E_t^C + E_t^Y$.

The dirty and clean energy goods themselves are bundles of differentiated energy varieties that are produced by a continuum of monopolistically competitive firms indexed by d and c, respectively:

$$\mathcal{D}_t = \left[\int_0^1 (\mathcal{D}_{d,t})^{\frac{\theta_\mathcal{D}-1}{\theta_\mathcal{D}}} \, dd \right]^{\frac{\theta_\mathcal{D}}{\theta_\mathcal{D}-1}}, \qquad \mathcal{C}_t = \left[\int_0^1 (\mathcal{C}_{c,t})^{\frac{\theta_\mathcal{C}-1}{\theta_\mathcal{C}}} \, dc \right]^{\frac{\theta_\mathcal{C}}{\theta_\mathcal{C}-1}}, \tag{19}$$

where $\theta_\mathcal{D}$ and $\theta_\mathcal{C}$ are the elasticities of substitution between the varieties of dirty and the varieties of clean energy, respectively.

With the prices for the dirty and clean energy varieties, $P_{\mathcal{D},d,t}$ and $P_{\mathcal{C},c,t}$, being set in monopolistically competitive markets (see below), the energy producer takes these prices as given and chooses the optimal input of the dirty and clean energy varieties by minimising the expenditure for the bundles of these varieties subject to the aggregation constraints (19). This yields the following demand equations:

$$\mathcal{D}_{d,t} = \left(\frac{P_{\mathcal{D},d,t}}{P_{\mathcal{D},t}} \right)^{-\theta_\mathcal{D}} \mathcal{D}_t, \qquad \mathcal{C}_{c,t} = \left(\frac{P_{\mathcal{C},c,t}}{P_{\mathcal{C},t}} \right)^{-\theta_\mathcal{C}} \mathcal{C}_t, \tag{20}$$

where

$$P_{\mathcal{D},t} = \left[\int_0^1 (P_{\mathcal{D},d,t})^{1-\theta_\mathcal{D}} \, dd \right]^{\frac{1}{1-\theta_\mathcal{D}}}, \qquad P_{\mathcal{C},t} = \left[\int_0^1 (P_{\mathcal{C},c,t})^{1-\theta_\mathcal{C}} \, dc \right]^{\frac{1}{1-\theta_\mathcal{C}}} \tag{21}$$

are the aggregate price indices for the bundles of dirty and clean energy, respectively.

Dirty and clean energy producers

The monopolistically competitive producers of dirty energy combine imported "fossil" resources, $\mathcal{F}_{d,t}$, with capital and labour services, $K^\mathcal{D}_{d,t}$ and $N^\mathcal{D}_{d,t}$:

$$Y^\mathcal{D}_{d,t} = z^\mathcal{D}_t \left[\nu_\mathcal{D}^{\frac{1}{\mu_\mathcal{D}}} (\mathcal{F}_{d,t})^{\frac{\mu_\mathcal{D}-1}{\mu_\mathcal{D}}} + (1-\nu_\mathcal{D})^{\frac{1}{\mu_\mathcal{D}}} \left(KN^\mathcal{D}_{d,t} \right)^{\frac{\mu_\mathcal{D}-1}{\mu_\mathcal{D}}} \right]^{\frac{\mu_\mathcal{D}}{\mu_\mathcal{D}-1}} - \psi^\mathcal{D}, \tag{22}$$

$$KN^\mathcal{D}_{d,t} = \left(K^\mathcal{D}_{d,t} \right)^{\alpha_\mathcal{D}} \left(N^\mathcal{D}_{d,t} \right)^{1-\alpha_\mathcal{D}}, \tag{23}$$

where $\mu_\mathcal{D}$ is the elasticity of substitution between fossil resources and the value added from using capital and labour, and $\nu_\mathcal{D}$ and $\alpha_\mathcal{D}$ determine the shares of the factors of production in the respective technologies. $z^\mathcal{D}_t$ and $\psi^\mathcal{D}$ represent, respectively, the productivity level and fixed costs of production in the dirty energy sector.

The producers' demand equation for the fossil resources used in the production of dirty energy is:[11]

$$\mathcal{F}_{d,t} = \nu_{\mathcal{D}} \left(\frac{S_t P_{\mathcal{F},t}}{z_t^{\mathcal{D}} \, MC_t^{Y^{\mathcal{D}}}} \right)^{-\mu_{\mathcal{D}}} \frac{Y_{d,t}^{\mathcal{D}} + \psi^{\mathcal{D}}}{z_t^{\mathcal{D}}}, \tag{24}$$

where $P_{\mathcal{F},t}$ is the global price of fossil resources and S_t denotes the exchange rate that converts it into the domestic currency price, while the marginal costs of producing dirty energy and the non-fossil-resource component are given by:

$$MC_t^{Y^{\mathcal{D}}} = \left(z_t^{\mathcal{D}}\right)^{-1} \left[\nu_{\mathcal{D}} (S_t P_{\mathcal{F}_t})^{1-\mu_{\mathcal{D}}} + (1-\nu_{\mathcal{D}})(MC_t^{KN^{\mathcal{D}}})^{1-\mu_{\mathcal{D}}}\right]^{\frac{1}{1-\mu_{\mathcal{D}}}}, \tag{25}$$

$$MC_t^{KN^{\mathcal{D}}} = \left(\alpha_{\mathcal{D}}^{\alpha_{\mathcal{D}}} (1-\alpha_{\mathcal{D}})^{1-\alpha_{\mathcal{D}}}\right)^{-1} (R_{K,t})^{\alpha_{\mathcal{D}}} \left((1+\tau_t^{W_f}) W_t\right)^{1-\alpha_{\mathcal{D}}}. \tag{26}$$

Here, we have made again use of the fact that marginal costs are identical across producers, $MC_t^{Y^{\mathcal{D}}} = MC_{d,t}^{Y^{\mathcal{D}}}$ and $MC_t^{KN^{\mathcal{D}}} = MC_{d,t}^{KN^{\mathcal{D}}}$, since all producers face the same input prices and since they all have access to the same production technology.

Aggregating across the continuum of dirty energy producers, we obtain the total demand for fossil resources, $\mathcal{F}_t = \int_0^1 \mathcal{F}_{d,t} \, dd$. The global supply of fossil resources and the clearing of the global market for fossil resources is discussed below.

In contrast, the monopolistically competitive producers of clean energy combine domestic "green" resources, $\mathcal{G}_{c,t}$, with capital and labour services, $K_{c,t}^{\mathcal{C}}$ and $N_{c,t}^{\mathcal{C}}$:

$$Y_{c,t}^{\mathcal{C}} = z_t^{\mathcal{C}} \left[\nu_{\mathcal{C}}^{\frac{1}{\mu_{\mathcal{C}}}} (\mathcal{G}_{c,t})^{\frac{\mu_{\mathcal{C}}-1}{\mu_{\mathcal{C}}}} + (1-\nu_{\mathcal{C}})^{\frac{1}{\mu_{\mathcal{C}}}} \left(KN_{c,t}^{\mathcal{C}}\right)^{\frac{\mu_{\mathcal{C}}-1}{\mu_{\mathcal{C}}}}\right]^{\frac{\mu_{\mathcal{C}}}{\mu_{\mathcal{C}}-1}} - \psi^{\mathcal{C}}, \tag{27}$$

$$KN_{c,t}^{\mathcal{C}} = \left(K_{c,t}^{\mathcal{C}}\right)^{\alpha_{\mathcal{C}}} \left(N_{c,t}^{\mathcal{C}}\right)^{1-\alpha_{\mathcal{C}}}, \tag{28}$$

where $\mu_{\mathcal{C}}$ is the elasticity of substitution between green resources and the value added from using capital and labour, and $\nu_{\mathcal{C}}$ and $\alpha_{\mathcal{C}}$ determine the shares of the factors of production in the respective technologies. $z_t^{\mathcal{C}}$ and $\psi^{\mathcal{C}}$ represent, respectively, the productivity level and fixed costs of production in the clean energy sector.

The producers' demand equation for green resources in the production of clean energy is:

$$\mathcal{G}_{c,t} = \nu_{\mathcal{C}} \left(\frac{P_{\mathcal{G},t}}{z_t^{\mathcal{C}} \, MC_t^{Y^{\mathcal{C}}}} \right)^{-\mu_{\mathcal{C}}} \frac{Y_{c,t}^{\mathcal{C}} + \psi^{\mathcal{C}}}{z_t^{\mathcal{C}}}, \tag{29}$$

[11] For the sake of brevity, the demand equations for capital and labour services, $K_{d,t}^{\mathcal{D}}$ and $N_{d,t}^{\mathcal{D}}$, are not reported here. They are obtained in analogy to the demand equations (12) and (13) for the intermediate-good producers, with obvious differences in notation.

where $P_{\mathcal{G},t}$ is the price of green resources.[12]

The marginal costs of producing clean energy and the non-green-resource component, $MC_t^{Y^{\mathcal{C}}}$ and $MC_t^{KN^{\mathcal{C}}}$, are obtained in analogy to the marginal cost expressions (25) and (26) for dirty energy production, with obvious differences in notation.

Aggregating across the continuum of clean energy producers, we obtain the total demand for green resources, $\mathcal{G}_t = \int_0^1 \mathcal{G}_{c,t}\, dc$. As regards supply, it is assumed that green resources are a fixed endowment in each period of time, $\bar{\mathcal{G}}_t$, which can be thought of as the production factor "land" available for the generation of renewable energy. Furthermore, it is assumed that the price of the green resources, $P_{\mathcal{G},t}$, adjusts instantaneously to balance supply and aggregate demand: $\bar{\mathcal{G}}_t = \mathcal{G}_t$.

Like in the intermediate-good sector, price setting in the energy-producing sectors is subject to Calvo-style staggered price-adjustment frictions. This implies that changes in the cost of producing the energy goods, notably the prices of fossil and green resources, will only be passed gradually into intermediate-good prices, as well as into the price of the final consumption good.

Producers of dirty energy that can reset their price with probability $(1 - \xi_{\mathcal{D}})$ maximise the discounted sum of their current and expected future nominal profits:

$$\mathrm{E}_t \left[\sum_{k=0}^{\infty} \Lambda_{I,t,t+k}\, \xi_{\mathcal{D}}^k\, D_{d,t+k}^{\mathcal{D}} \right], \tag{30}$$

where $\Lambda_{I,t,t+k} = \beta^k \Lambda_{I,t+k}/\Lambda_{I,t}$ represents the stochastic discount factor of the members of the financially unconstrained household, denoted by I, that are assumed to own the dirty energy producing firms, and $D_{d,t}^{\mathcal{D}} = P_{\mathcal{D},d,t}\mathcal{D}_{d,t} - MC_t^{Y^{\mathcal{D}}}\mathcal{D}_{d,t}$ are current-period nominal profits (net of fixed costs) which are to be paid as dividends to household I.

The optimal reset price is identical across producers, $\widetilde{P}_{\mathcal{D},t} = \widetilde{P}_{\mathcal{D},d,t}$, and given by:

$$\frac{\widetilde{P}_{\mathcal{D},t}}{P_{\mathcal{D},t}} = \frac{\theta_{\mathcal{D}}}{\theta_{\mathcal{D}} - 1} \frac{F_{\mathcal{D},t}}{G_{\mathcal{D},t}}, \tag{31}$$

where the auxiliary variables $F_{\mathcal{D},t}$ and $G_{\mathcal{D},t}$ are defined recursively as:

$$F_{\mathcal{D},t} = MC_t^{Y^{\mathcal{D}}}\mathcal{D}_t + \xi_{\mathcal{D}}\beta\, \mathrm{E}_t \left[\frac{\Lambda_{I,t+1}}{\Lambda_{I,t}} \left(\frac{\pi_{\mathcal{D},t+1}}{\left(\pi_{\mathcal{D},t}^{\chi_{\mathcal{D}}}\, \pi_{\mathcal{D}}^{1-\chi_{\mathcal{D}}}\right)} \right)^{\theta_{\mathcal{D}}} F_{\mathcal{D},t+1} \right], \tag{32}$$

[12] As for the dirty-energy producing firms, the demand equations for capital and labour services, $K_{c,t}^{\mathcal{C}}$ and $N_{c,t}^{\mathcal{C}}$, are not reported.

$$G_{\mathcal{D},t} = P_{\mathcal{D},t}\mathcal{D}_t + \xi_{\mathcal{D}}\beta \,\mathrm{E}_t \left[\frac{\Lambda_{I,t+1}}{\Lambda_{I,t}} \left(\frac{\pi_{\mathcal{D},t+1}}{\left(\pi_{\mathcal{D},t}^{\chi_{\mathcal{D}}}\, \pi_{\mathcal{D}}^{1-\chi_{\mathcal{D}}}\right)} \right)^{\theta_{\mathcal{D}}-1} G_{\mathcal{D},t+1} \right]. \tag{33}$$

These recursive expressions also account for the possibility that producers which cannot optimally reset their price in the current period are allowed to index the price prevailing in the previous period, $P_{\mathcal{D},d,t-1}$, to a weighted average of past inflation, $\pi_{\mathcal{D},t-1} = P_{\mathcal{D},t-1}/P_{\mathcal{D},t-2}$, and steady-state inflation, $\pi_{\mathcal{D}}$.

The aggregate dirty energy price index is obtained as the weighted average of the optimal reset price and the past price (indexed to past and steady-state inflation):

$$P_{\mathcal{D},t} = \left[(1-\xi_{\mathcal{D}}) \left(\widetilde{P}_{\mathcal{D},t}\right)^{1-\theta_{\mathcal{D}}} + \xi_{\mathcal{D}} \left(P_{\mathcal{D},t-1} \pi_{\mathcal{D},t-1}^{\chi_{\mathcal{D}}} \pi_{\mathcal{D}}^{1-\chi_{\mathcal{D}}} \right)^{1-\theta_{\mathcal{D}}} \right]^{\frac{1}{1-\theta_{\mathcal{D}}}}. \tag{34}$$

As regards the producers of clean energy, we assume that they eventually receive a fraction $s^{\mathcal{C}}_{M_{\mathcal{D}}}$ of the government's carbon tax revenues $\tau_t^{M_{\mathcal{D}}} P_{\mathcal{D},t}\, \mathcal{D}_t$ in the form of a subsidy with a view to stimulating clean energy production:

$$s^{\mathcal{C}}_{M_{\mathcal{D}}}\, \tau_t^{M_{\mathcal{D}}}\, P_{\mathcal{D},t}\, \mathcal{D}_t \;=\; \tau_t^{\mathcal{C}} \int_0^1 P_{\mathcal{C},c,t}\, \mathcal{C}_{c,t}\; dc, \tag{35}$$

where $\tau_t^{\mathcal{C}}$ is the subsidy rate and $\int_0^1 P_{\mathcal{C},c,t}\, \mathcal{C}_{c,t}\; dc$ represents the aggregate revenues of clean energy producers net of subsidies.

Like the producers of dirty energy, the clean energy producers reset their price with probability $(1-\xi_{\mathcal{C}})$ with the objective of maximising the discounted sum of their current and expected future nominal profits:

$$\mathrm{E}_t \left[\sum_{k=0}^{\infty} \Lambda_{I,t,t+k}\, \xi_{\mathcal{C}}^k\, D^{\mathcal{C}}_{c,t+k} \right], \tag{36}$$

where $\Lambda_{I,t,t+k} = \beta^k \Lambda_{I,t+k}/\Lambda_{I,t}$ again is the stochastic discount factor of the members of household I that are assumed to also own the clean energy producing firms and

$$\begin{aligned} D^{\mathcal{C}}_{c,t} &= P_{\mathcal{C},c,t}\, \mathcal{C}_{c,t} - MC_t^{Y^{\mathcal{C}}} \mathcal{C}_{c,t} + \tau_t^{\mathcal{C}}\, P_{\mathcal{C},c,t}\, \mathcal{C}_{c,t} \\ &= (1+\tau_t^{\mathcal{C}})\, P_{\mathcal{C},c,t}\, \mathcal{C}_{c,t} - MC_t^{Y^{\mathcal{C}}} \mathcal{C}_{c,t} \end{aligned} \tag{37}$$

are current period nominal profits net of fixed costs but including subsidies, which are to be paid as dividends to household I.

The optimal reset price is identical across producers, $\widetilde{P}_{\mathcal{C},t} = \widetilde{P}_{\mathcal{C},c,t}$, and given by:

$$\frac{\widetilde{P}_{\mathcal{C},t}}{P_{\mathcal{C},t}} = \frac{\theta_{\mathcal{C}}}{\theta_{\mathcal{C}}-1} \frac{F_{\mathcal{C},t}}{G_{\mathcal{C},t}}, \tag{38}$$

where the auxiliary variables $F_{\mathcal{C},t}$ and $G_{\mathcal{C},t}$ are defined recursively as:

$$F_{\mathcal{C},t} = MC_t^{Y^{\mathcal{C}}} \mathcal{C}_t + \xi_{\mathcal{C}} \beta \, \mathrm{E}_t \left[\frac{\Lambda_{I,t+1}}{\Lambda_{I,t}} \left(\frac{\pi_{\mathcal{C},t+1}}{\left(\pi_{\mathcal{C},t}^{\chi_{\mathcal{C}}} \, \pi_{\mathcal{C}}^{1-\chi_{\mathcal{C}}} \right)} \right)^{\theta_{\mathcal{C}}} F_{\mathcal{C},t+1} \right], \tag{39}$$

$$G_{\mathcal{C},t} = (1 + \tau_t^{\mathcal{C}}) \, P_{\mathcal{C},t} \mathcal{C}_t + \xi_{\mathcal{C}} \beta \, \mathrm{E}_t \left[\frac{\Lambda_{I,t+1}}{\Lambda_{I,t}} \left(\frac{\pi_{\mathcal{C},t+1}}{\left(\pi_{\mathcal{C},t}^{\chi_{\mathcal{C}}} \, \pi_{\mathcal{C}}^{1-\chi_{\mathcal{C}}} \right)} \right)^{\theta_{\mathcal{C}}-1} G_{\mathcal{C},t+1} \right]. \tag{40}$$

Again, the recursive expressions account for the possibility that producers which cannot optimally reset their price in the current period are allowed to index the price prevailing in the previous period, $P_{\mathcal{C},c,t-1}$, to a weighted average of past inflation, $\pi_{\mathcal{C},t-1} = P_{\mathcal{C},t-1}/P_{\mathcal{C},t-2}$, and steady-state inflation, $\pi_{\mathcal{C}}$. The expressions differ from those for the dirty energy producers by the presence of the subsidy rate $\tau_t^{\mathcal{C}}$.

In equilibrium, clearing of the markets for the dirty and the clean energy goods requires that aggregate supply equals aggregate demand, with $Y_t^{\mathcal{D}} = s_{\mathcal{D},t} \, \mathcal{D}_t$ and $Y_t^{\mathcal{C}} = s_{\mathcal{C},t} \, \mathcal{C}_t$, where $s_{\mathcal{D},t}$ and $s_{\mathcal{C},t}$ are wedges which reflect the price dispersion across energy varieties owing to staggered price setting by the energy producers. Aggregate (gross) profits of dirty and clean energy producers are given by $D_t^{\mathcal{D}} = P_{\mathcal{D},t} \, \mathcal{D}_t - MC_t^{Y^{\mathcal{D}}} (s_{\mathcal{D},t} \, \mathcal{D}_t + \psi^{\mathcal{D}})$ and $D_t^{\mathcal{C}} = (1 + \tau_t^{\mathcal{C}}) \, P_{\mathcal{C},t} \, \mathcal{C}_t - MC_t^{Y^{\mathcal{C}}} (s_{\mathcal{C},t} \, \mathcal{C}_t + \psi^{\mathcal{C}})$, respectively.

2.4 Measuring aggregate output

To obtain a measure of aggregate output, we calculate the total net value of the goods produced in the intermediate-good and energy sectors. This is akin to measuring gross domestic product (GDP) using the production approach. Accordingly, we subtract the expenses on intermediate inputs from the value of production in the respective sector.

For the intermediate-good sector, the aggregated net value of production is given by:

$$V_t^Y \;=\; P_{Y,t} \, Y_t \;-\; P_{E,t} \, E_t^Y, \tag{41}$$

where $P_{Y,t}$ is the implicit price of the continuum of differentiated intermediate goods, with

$$\begin{aligned} P_{Y,t} \, Y_t \;&\equiv\; \int_0^1 P_{H,f,t} \, H_{f,t} \, df + \int_0^1 S_t \, P_{X,f,t} \, X_{f,t} \, df \\ &=\; P_{H,t} \, H_t + S_t \, P_{X,t} \, X_t, \end{aligned} \tag{42}$$

taking into account that the differentiated intermediate goods, $Y_{f,t}$, with $Y_{f,t} = H_{f,t} + X_{f,t}$ and $H_{f,t} = H^C_{f,t} + H^I_{f,t} + H^G_{f,t}$, are sold domestically and abroad at local market prices $P_{H,f,t}$ and $P_{X,f,t}$.

Similarly, for the consolidated energy sector, we obtain:

$$V^E_t \;=\; P_{E,t}\, E_t \,-\, S_t\, P_{\mathcal{F},t}\, \mathcal{F}_t, \tag{43}$$

with

$$\begin{aligned} P_{E,t}\, E_t &= \int_0^1 P_{\mathcal{D},d,t}\, \mathcal{D}_{d,t}\, dd + \int_0^1 P_{\mathcal{C},c,t}\, \mathcal{C}_{c,t}\, dc \\ &= P_{\mathcal{D},t}\, \mathcal{D}_t + P_{\mathcal{C},t}\, \mathcal{C}_t. \end{aligned} \tag{44}$$

Adding up the net value of production of the intermediate-good and of the consolidated energy sector, (41) and (43), and using that $E_t = E^C_t + E^Y_t$, yields a measure of total nominal output, which we will refer to as "nominal GDP":

$$GDP^n_t \equiv P_{H,t}\, H_t + S_t\, P_{X,t}\, X_t + P_{E,t}\, E^C_t \,-\, S_t\, P_{\mathcal{F},t}\, \mathcal{F}_t. \tag{45}$$

Recalling that $H_t = H^C_t + H^I_t + H^G_t$, using the following expressions resulting from the cost-minimisation problems of the producers of the final consumption good and of the consumption good excluding energy,

$$P_{C,t}\, Q^C_t = P_{CX,t}\, Q^{CX}_t + \frac{P_{E,t}}{\Gamma^\dagger_{E^C,t}}(1 - \Gamma_{E^C,t})\, E^C_t, \tag{46}$$

$$P_{CX,t}\, Q^{CX}_t = P_{H,t}\, H^C_t + \frac{P_{IM,t}}{\Gamma^\dagger_{IM^C,t}}(1 - \Gamma_{IM^C,t})\, IM^C_t, \tag{47}$$

as well as a corresponding expression for the private investment good,

$$P_{I,t}\, Q^I_t = P_{H,t}\, H^I_t + \frac{P_{IM,t}}{\Gamma^\dagger_{IM^I,t}}(1 - \Gamma_{IM^I,t})\, IM^I_t, \tag{48}$$

and invoking the following market-clearing conditions for the final goods,[13]

$$Q^C_t = C_t + \Gamma_{v,t}, \qquad Q^I_t = I_t + \Gamma_{u,t}\, K_t, \qquad Q^G_t = G_t, \tag{49}$$

[13] Note that the expressions $\Gamma_{v,t}$ and $\Gamma_{u,t}$ refer to consumption transaction costs and capital utilisation costs, respectively. The public consumption good is composed only of domestic intermediate goods and, hence, $Q^G_t = H^G_t$ and $P_{G,t} = P_{H,t}$.

we obtain after some algebra an expression for nominal GDP which is also tantamount to measuring GDP based on the expenditure approach:

$$
\begin{aligned}
GDP_t^n &= P_{C,t}\,(C_t+\Gamma_{v,t}) + P_{I,t}\,(I_t+\Gamma_{u,t}\,K_t) + P_{G,t}\,G_t - P_{E,t}\,\frac{1-\Gamma_{E^C,t}-\Gamma^{\dagger}_{E^C,t}}{\Gamma^{\dagger}_{E^C,t}}\,E_t^C \\
&\quad + S_t\,P_{X,t}\,X_t - P_{IM,t}\left(\frac{1-\Gamma_{IM^C,t}}{\Gamma^{\dagger}_{IM^C,t}}\,IM_t^C + \frac{1-\Gamma_{IM^I,t}}{\Gamma^{\dagger}_{IM^I,t}}\,IM_t^I\right) - \; S_t\,P_{\mathcal{F},t}\,\mathcal{F}_t, \qquad (50)
\end{aligned}
$$

except for the terms related to the various adjustment costs in the model which eat up resources.

Finally, we split nominal GDP into its price and real components, $P_{GDP,t}$ and GDP_t, by calculating real GDP from the preceding expression at steady-state relative prices and by inferring the GDP price for a given value of real GDP. As the model does not predict a smooth endogenous transition path for changes in steady-state relative prices in response to a permanent shock, we make the auxiliary assumption that steady-state relative prices adjust from their initial towards their new steady-state values along a geometrically converging path. Similarly, we define a smooth measure of trend real GDP, which we will denote by $\overline{GDP}_t$, as a geometrically converging path from the initial towards the new steady-state value of real GDP.

2.5 Monetary and fiscal policy

The monetary authority is assumed to stabilise annual consumer price inflation excluding energy around target and quarterly real GDP growth relative to trend real GDP growth by setting the annualised short-term (gross) nominal interest rate, R_t^4, according to the following rule:

$$
\begin{aligned}
R_t^4 &= 0.9\cdot R_{t-1}^4 + (1-0.9)\cdot\left[R^4 + 1.5\cdot\left(\frac{P_{CX,t}}{P_{CX,t-4}} - \Pi\right)\right] \\
&\qquad + 0.1\cdot\left(\frac{GDP_t}{GDP_{t-1}} - \frac{\overline{GDP}_t}{\overline{GDP}_{t-1}}\right), \qquad (51)
\end{aligned}
$$

where $R^4=\beta^{-4}\Pi$ is the annualised (gross) equilibrium nominal interest rate, and Π denotes the monetary authority's (gross) inflation target.

The fiscal authority stabilises nominal government debt, B_t, relative to nominal GDP by adjusting lump-sum taxes, T_t, according to the following rule,

$$\frac{T_t}{GDP_t^n} \;=\; 0.1 \cdot \left(\frac{B_t}{GDP_t^n} - B_{GDP} \right), \tag{52}$$

where B_{GDP} denotes the fiscal authority's target for the government debt-to-GDP ratio.

Details on the specification of the fiscal authority's budget constraint are provided in Coenen et al. (2007). For the energy extension of the NAWM, the only modification of the budget constraint concerns the receipt of additional revenues from the carbon tax levied on the use dirty energy , $\tau_t^{M_{\mathcal{D}}} P_{\mathcal{D},t}\, \mathcal{D}_t$, and their possible disbursement in the form of transfers to households or as subsidies to firms, as will be discussed below.

2.6 Supply of fossil resources

The original two-country setting of the NAWM, which covers the euro area and the rest of the industrialised world, as represented by the US, is augmented with a third country which extracts and exports fossil resources. It is assumed that this country is an endowment economy with a given amount of fossil resources in every period of time, which are exported to the euro area and the rest of the world. There is no local production of goods except for the extraction of fossil resources and, hence, all goods for consumption purposes need to be imported from the euro area and the rest of the world.

Specifically, using the superscript 'X' to indicate variables of the country exporting fossil resources, and letting 'EA' and 'RoW' indicate variables of the euro area and the rest of the world, respectively, the aggregate resource constraint of the fossil resource-exporting country is given by:[14]

$$\begin{aligned} GDP_t^{n,X} \;&=\; P_{C,t}^{X}\, C_t^{X} + P_{\mathcal{F},t}^{EA}\, \mathcal{F}_t^{EA} + P_{\mathcal{F},t}^{RoW}\, \mathcal{F}_t^{RoW} \\ &\quad - \left(P_{IM,t}^{EA}\, IM_t^{X,RoW} / S_t^{EA,RoW} + P_{IM,t}^{RoW}\, IM_t^{X,EA} \right), \end{aligned} \tag{53}$$

where $IM_t^{X,RoW}$ and $IM_t^{X,EA}$ are the goods imported by the fossil resource-exporting country from the rest of the world and the euro area, $P_{IM,t}^{EA}$ and $P_{IM,t}^{RoW}$ are the local market prices which are paid by importers of foreign goods in the euro area and in the rest of the world, and $S_t^{EA,RoW}$ denotes the bilateral nominal exchange rate of the euro area vis-à-vis the rest

[14] To balance the specification of the augmented three-country set-up of the model, we shall normalise, without loss of generality, consumer prices of the fossil resource-exporting country to one; that is, $P_{C,t}^{X} = 1$.

of the world. That is, we assume that the respective import prices also apply for the fossil resource-exporting country and that the currency of the rest of the world serves as its domestic currency.

As regards the bilateral trade flows between the fossil resource-exporting country and its two trading partners, we account for a low propensity to import out of revenues from exporting fossil resources in the shorter term. Specifically, we assume that the imports of the fossil resource-reporting country from its trading partners adjust gradually towards achieving balanced bilateral trade within roughly a year according to a simple equilibrium-correction mechanism:

$$IM_t^{X,EA} = IM_{t-1}^{X,EA} - 0.2 \cdot \left(IM_{t-1}^{X,EA} - P_{\mathcal{F},t-1}^{EA} \, \mathcal{F}_{t-1}^{EA} / P_{IM,t-1}^{RoW} \right), \tag{54}$$

$$IM_t^{X,RoW} = IM_{t-1}^{X,RoW} - 0.2 \cdot \left(IM_{t-1}^{X,RoW} - P_{\mathcal{F},t-1}^{RoW} \, \mathcal{F}_{t-1}^{RoW} / \left(P_{IM,t-1}^{EA} / S_{t-1}^{EA,RoW} \right) \right). \tag{55}$$

In addition, we assume that the temporary trade surpluses/deficits that occur during the adjustment process are balanced through income transfers. This is tantamount to assuming that the trading partners of the fossil resource-exporting country have state-contingent claims on the excess revenues from the export of fossil resources.[15]

Finally, to ensure the clearing of the global market for fossil resources, it is assumed that the law of one price holds, $P_{\mathcal{F},t}^{EA} = P_{\mathcal{F},t}^{RoW}$, and that the market price of fossil resources adjusts instantaneously to balance the supply of and demand for fossil resources: $\bar{\mathcal{F}}_t^X = \mathcal{F}_t^{EA} + \mathcal{F}_t^{RoW}$, where $\bar{\mathcal{F}}_t^X$ is the given endowment of fossil resources.

2.7 Calibration and validation

We calibrate the steady-state shares and the structural parameters related to the use and production of energy in our model using a variety of data sources, drawing on the available evidence in the literature and with a view to obtaining plausible adjustment paths in response to a supply-driven increase in the price of fossil resources. Like for the original NAWM, we assume that the United States (US) are representing the rest of the industrialised world.

[15] It should be noted that, while our specification of a gradual re-balancing of trade flows is more compelling than the assumption of balanced bilateral trade in every period, it neglects the possibility of an accumulation of foreign assets by fossil resource-exporting countries following a large increase in the price of fossil resources and, therefore, the potential emergence of global saving imbalances weighing on global demand.

Energy-related steady-state shares

The energy-related steady-state shares are reported in Table 1. Regarding the shares of energy used in final private consumption and as inputs into intermediate-good production, we make use of input-output tables from the 2018 edition of the OECD TiVA database. The sectoral classification provided is in line with Eurostat's NACE Revision 2. We consider energy-producing sectors as the sum of inputs from: i) mining and quarrying of energy products (B.05, B.06), ii) manufacturing of coke and refined petroleum products (C.19), and iii) electricity, steam, gas, and air conditioning supply (D). The share of energy in private final consumption is directly observable (5.5% for the euro area; 3.3% for the US), whereas we calculate the share of energy in intermediate-good production as the share of intermediate inputs into value added (7.2% for the euro area; 7.1% for the US).[16]

We calibrate the shares of clean and dirty energy in the production of energy by using 2019 data on gross energy balances from Eurostat. This database reports the contribution of different primary energy sources in the production and imports of total energy in the euro area, in terms of tonnes of oil equivalent. Dirty energy is taken as being the sum of production and imports from: solid fossil fuels, peat and peat products, oil shale and oil sands, natural gas, oil and petroleum products (excl. biofuels), and non-renewable waste. In turn, clean energy is taken as being the sum of production from: renewables and biofuels, and nuclear heat.[17] The resulting dirty and clean energy shares are 71.7% and 28.3%, respectively. Notably, the Eurostat database does not report information for the US, so we assume that the respective US shares are identical to those in the euro area.

Finally, the shares of fossil and green resources in the production of dirty and clean energy, respectively, are obtained from the 2018 KLEMS database. Given that the KLEMS database does not distinguish between sources of primary energy production, we assume that the share of value added in each of the dirty and clean energy sectors is identical and corresponds to value added from all energy-producing sectors. We hence calculate

[16]Note that the OECD TiVA database also allows us to identify whether the energy inputs used in consumption and intermediate-good production are domestically produced or imported from abroad. Regarding intermediate-good production, the foreign component corresponds to roughly 1/3 and is hence broadly consistent with our modelling assumption that fossil resources are imported from abroad.

[17]We calculate the total primary production and imports of energy by removing the contributions from heat, and 'other sources', as these combine both clean and dirty energy sources (heat), which are inconsistent with our modelling framework, or their source is unknown ('other sources').

the contribution of value added as a share of intermediate consumption from the following three NACE Revision 2 sectors: i) mining and quarrying (B), ii) manufacturing of coke and refined petroleum products (C.19), iii) electricity, steam, gas, and air conditioning supply (D).[18] The corresponding share of fossil (green) resources in dirty (clean) energy is 73.0% in the euro area, and 52.8% in the US.

Energy-related structural parameters

The energy-related structural parameters are reported in Table 2. Regarding the use of energy in final consumption, the (quasi-)share parameter ν_C is implicitly calibrated by matching the actual energy-consumption ratio reported in Table 1. The resulting parameter value is 0.061 for the euro area and 0.037 for the US. The long-run substitution elasticity between energy and the consumption good excluding energy, μ_C, is set to 0.4, both for the euro area and the US. In doing so, we follow approaches in the model-based literature, in which energy sources (namely oil) are combined with consumption goods using CES aggregators (see, e.g., Bodenstein, Erceg and Guerrieri (2011), Bodenstein, Guerrieri and Gust (2013) for a calibrated model, or Bodenstein, Guerrieri and Killian (2012) and Balke and Brown (2018) for an estimated model of the US economy). The elasticity of energy adjustment costs, γ_{E^C}, is set to 5, which is a value large enough to prevent implausibly large energy substitution in response to energy price changes in the short term.

As regards the use of energy in intermediate-good production, the (quasi-)share parameter ν_Y is again implicitly calibrated by matching the actual share and approximately equals 0.072 for the euro area and 0.071 for the US. We set the long-run substitution elasticity between energy and the capital-labour bundle, μ_Y, uniformly to 0.4, following again Bodenstein, Guerrieri and Gust (2013) amongst others. Accordingly, the long-run substitution elasticity is symmetric on the production and the consumption side.

Concerning the calibration of the disaggregated energy sector, we normalise several relative prices by appropriately adjusting the level of productivity in the energy production functions, which enables us to bring the quasi-share of primary resources in the production

[18] Note that, related to mining and quarrying, the KLEMS database does not distinguish between energy- and non-energy products. In addition, for the US, the electricity, steam, gas, and air conditioning supply energy sector also includes value added from activities related to: water supply, sewerage, and waste management.

of dirty and clean energy and the quasi-share of dirty energy in aggregate energy production close to the actual shares. First, we set the initial price of the fossil resources in the US as well as the initial prices of the green resources in both the euro area and the US equal to marginal costs in the dirty and clean energy sectors by adjusting the respective endowments. And second, we set the initial after-tax prices of dirty energy in the euro area and in the US equal to the prices of clean energy by adjusting the productivity levels in the dirty energy sectors, while the initial prices of the energy bundles are set to equal non-energy marginal costs in the intermediate-good sectors by adjusting the productivity of aggregate energy production. Following this indirect approach, the implied share of dirty energy in the production of the energy bundle, ν_E, equals 0.717 for both the euro area and the US. The implied shares of fossil resources in the production of dirty energy, $\nu_{\mathcal{D}}$, are 0.732 for the euro area and 0.528 for the US, while the implied shares of green resources in the production of clean energy, $\nu_{\mathcal{C}}$, are 0.730 for the euro area and 0.528 for the US.

Turning to the substitution elasticity between dirty and clean energy in aggregate energy production, the evidence from the literature is relatively scarce. We follow Papageorgiou et al. (2017), who estimate CES production functions for a panel of 26 countries using sectoral data and find that this elasticity lies between 1.8 and 3. A value of μ_E greater than unity implies that clean and dirty energy bundles are (imperfect) substitutes rather than complements. We opt for a value towards the lower end of this range and set $\mu_E = 1.8$. This calibration is in line with the choices in Acemoglu et al. (2012), who aggregate clean and dirty energy inputs in a model of endogenous and directed technical change, but also with the calibration of the E-QUEST model of Varga et al. (2021), who aggregate clean and dirty capital-energy composites, noting that both of these works assume values on the higher end of the spectrum. Next, we set the elasticity of dirty energy adjustment costs, $\gamma_{\mathcal{D}}$, to 5 so as to obtain an economically plausible pass-through of fossil price changes to nominal and real variables (see the following section for details). The price elasticities of demand for dirty and clean energy varieties, $\theta_{\mathcal{D}}$ and $\theta_{\mathcal{C}}$, are calibrated in a consistent fashion to the price elasticity of demand for the intermediate goods, θ_Y, that is to a value of 6. This delivers a gross markup equal to 1.2 in the steady state for all sectors.

Regarding the production of dirty and clean energy varieties, our strategy for calibrating the substitution elasticity between resources and the capital-labour bundle ($\mu_{\mathcal{D}}$ for the fossil resources and $\mu_{\mathcal{C}}$ for the green resources) is to explore values in a close range to the values employed for the substitution elasticity between the energy aggregate and the capital-labour bundle, μ_Y, and between the energy aggregate and the consumption good excluding energy, μ_C. We opted for this approach in an attempt to ensure symmetry across energy-related substitution elasticities in the model, but also because evidence for $\mu_{\mathcal{D}}$ and $\mu_{\mathcal{C}}$ is unavailable from the literature. Taking into account the interaction with $\gamma_{\mathcal{D}}$, we conclude from our experiments that $\mu_{\mathcal{D}} = \mu_{\mathcal{C}} = 0.25$ generates a plausible adjustment of consumer price inflation following fossil price changes, with annual inflation increasing by 0.375 percentage point after a 20% increase in the fossil price (see the following section for details). The calibration of $\gamma_{\mathcal{D}}$ also interacts (non-linearly) with the fraction of producers not setting prices optimally in the dirty and clean energy production sectors, $\xi_{\mathcal{D}}$ and $\xi_{\mathcal{C}}$, which we set to 0.25, implying an average price contract duration of 1.33 quarters.[19] This is shorter than the contract durations in the intermediate-good production sector, especially for the intermediate goods sold domestically.

Next, to calibrate the share of capital in the capital-labour bundle used for the production of clean and dirty energy, $\alpha_{\mathcal{D}}$ and $\alpha_{\mathcal{C}}$, we again make use of the 2018 KLEMS database. To this end we note that the capital (labour) shares correspond to the factor income shares attributable to capital (labour) in the production of dirty and clean energy. Consistent with the definitions in the National Accounts, capital income is defined as: gross operating surplus and other income, whereas labour income is defined as: compensation of employees. In line with the assumption we make in calculating the actual shares of fossil/green resources in the production of dirty/clean energy, we again do not distinguish between sources of primary energy production and assume that the capital (and labour) shares are identical in the clean and dirty energy sectors. The corresponding capital shares are $\alpha_{\mathcal{D}} = \alpha_{\mathcal{C}} = 0.707$ for the euro area and $\alpha_{\mathcal{D}} = \alpha_{\mathcal{C}} = 0.716$ for the US.[20]

Finally, the fixed costs in the production of dirty and clean energy are implicitly calibrated so that the profits of the firms in each sector are zero in the steady state. This

[19]We assume that dirty and clean energy producers do not index prices, so $\chi_{\mathcal{D}} = \chi_{\mathcal{C}} = 0$ for both the euro area and the US.

[20]For the US, the electricity, steam, gas, and air conditioning supply energy sector also includes value added from activities related to: water supply, sewerage, and waste management.

results in values of $\psi_{\mathcal{D}} = 0.249$ and $\psi_{\mathcal{C}} = 0.098$ for the euro area, and $\psi_{\mathcal{D}} = 0.232$ and $\psi_{\mathcal{C}} = 0.092$ for the US.

A shock to the supply of fossil resources

We validate the calibration of our model by simulating a shock to the supply of fossil resources that gives rise to a permanent increase in the price of fossil resources. Specifically, we assume that the supply of resources from the fossil-exporting country is gradually reduced such that the global fossil resource price (in US dollars, and expressed relative to US consumer prices) increases by 20% within roughly 10 quarters. The results of the simulation are shown in Figure 2.

As the increase in the fossil resource price feeds directly through to the price of the final consumption good, consumer price inflation surges over the year following the shock to the supply of fossil resources. Specifically, annual consumer price inflation reaches a peak of around 0.375 percentage point above target inflation after about 6 quarters and gradually returns to target thereafter. At the same time, the increase in the fossil resource price also gives rise to a very marked increase in the costs of energy producers. This cost increase is passed through from energy producers to intermediate-good producers and thereafter to the final-good producers.[21] Accordingly, the increase in the fossil resource price puts upward pressure on annual consumer price inflation excluding energy, with a peak at about 0.1 percentage point.

The adjustment on the real side of the economy follows from the implied fall in current and expected future real income of households, which causes them to cut back on consumption. The reduction in investment is stronger because of the decline in firm's profitability and the need to lower the economy-wide capital stock, but also due to the unconstrained households' desire to smooth consumption over time. The fall in real income reflects the fact that the reduction in fossil resource supply and the ensuing increase in the fossil resource price leads to a deterioration of the euro area terms of trade. This brings about a temporary increase in nominal imports from the fossil-exporting country along with a decrease in nominal exports, resulting in a deterioration of the euro area trade balance. In

[21] It is worth noting that the prices of both dirty and of clean energy rise, as the fall in the supply of fossil resources and the ensuing price increase leads to a shift in demand away from dirty to clean energy. The implied rise in the price of clean energy is, however, considerably weaker.

real terms, both imports and exports decline. Overall, the fall in GDP is lasting, with a decline by about 1.3% below its initial steady-state value in the medium to long run.

Regarding the response of monetary policy, the monetary authority in the model follows an interest rate rule that disregards the direct effects of the adverse fossil resource shock via energy prices on consumer price inflation. As a result, the nominal interest rate is raised only very moderately, but persistently, also reflecing the fact that the increase in consumer price inflation is accompanied by a shortfall in GDP growth.

We compare our model-based predictions of the effects of an increase in the price of fossil resources with empirical estimates of Peersman and Van Robays (2009, 2012) for the euro area, according to which a permanent 10% increase in the price of oil raises the level of consumer prices by about 0.4% and lowers GDP by about 0.3% in the long run. Once we re-scale the shock to the supply of fossil resources in our model so as to obtain a similarly sized increase in the price of fossil resources, we obtain a 0.4% increase in the level of consumer prices and a 0.65% decrease in GDP, broadly in line with the estimates of Peersman and Van Robays when taking into account estimation uncertainty.[22] All in all, this suggests that our model delivers also empirically plausible predictions of the effects of a change in the price of fossil resources.

3 A model-based assessment of carbon transition policies

In this section we first set out our central carbon transition scenario. Using our model, we then quantify the implications of the scenario for key macroeconomic variables, including inflation, GDP, energy prices and carbon emissions. Subsequently, we explore the sensitivity of our quantitative findings by analysing the role of monetary and fiscal policies in addressing the adjustment costs associated with the carbon transition scenario, the consequences of following alternative tax paths in implementing the scenario and the impact of an imperfectly credible implementation of the scenario. We finally illustrate the importance of enhancing the supply of clean energy as a means to accelerate the carbon transition. Additional sensitivity analyses are provided in the Appendix.

[22] Note that Peersman and Van Robays specify the oil price shock in nominal terms, whereas we consider a real price increase. The difference, however, is small due to the rather small change in consumer prices.

3.1 The carbon transition scenario

The calibration of our central carbon transition scenario is empirically grounded in the concept of Effective Carbon Rates (ECRs) developed by the OECD. ECRs reflect the price of carbon emissions resulting from three different sources: fuel excise taxes, carbon taxes and tradeable emission permit prices. They are calculated at the country level for six sectors, covering almost the entire economy: industry, electricity, agriculture and fisheries, residential and commercial services, off-road transport and road transport (see OECD, 2021, for details). The sectoral ECRs can be aggregated according to their contributions to the total carbon emissions released. For the euro area, the *average* ECR stands at 84.7 euro per tonne of CO2 (€/tCO2) in 2021.[23] The fiscal revenues from the three sources underlying the calculations of the euro area average ECR amount to 1.83% of GDP.

To reach the European Union's net-zero emission target by 2050, as set out in the European Green Deal, the price of carbon emissions in the euro area needs to be raised significantly and in a timely manner. To this end, and given our primary focus on short to medium-term macroeconomic dynamics, our central carbon transition scenario assumes a steady and linear increase in the euro area average ECR to a target rate of €140/tCO2 over the period from 2022 to 2030.[24] The assumed target rate is broadly consistent with estimates of the International Energy Agency, according to which advanced economies need to raise the price of carbon emissions to 140 US dollars per tonne of CO2 ($/tCO2) until 2030 in order to meet their longer-term net-zero pledges, provided that the prospective effects from additional non-price policy measures in their overall decarbonisation strategy as well as technological advancements are achieved (see IEA, 2022).[25]

For the rest of the industrialised world, the average ECR is assumed to increase by the same amount as for the euro area but in *relative* terms; that is, by 65.3%. The resulting absolute increase is considerably smaller though, because of the lower initial level of the

[23] The sectoral ECRs in the euro area differ substantially: for the first five sectors the ECRs range from €36/tCO2 to €70/tCO2, whereas the ECR for the road transport sector is €171/tCO2.

[24] The target rate of €140/tCO2 for the euro area reflects a target rate of €120/tCO2 for all sectors except road transportation, for which an increase to €200/tCO2 is assumed. A higher target rate for the road transportation sector is considered, because the current rate is already above €120/tCO2 and existing policy proposals imply further increases.

[25] Note that, according to the International Energy Agency, the price of carbon emissions would need to be raised progressively further to $250/tCO2 to achieve full decarbonisation by 2050.

ECR, which is around \$28.5/tCO2 in 2021. This assumption reflects the fact that some other industrialised countries, notably the United States and Japan, have opted for an overall decarbonisation strategy that focuses on subsidising clean energy production, including nuclear power generation, rather than taxing carbon emissions.

As regards the design of our central scenario, two remarks are in order. First, the size of the increase in carbon emission prices by 2030 which is needed to eventually meet the net-zero emission goal in 2050 is subject to considerable uncertainty. For example, recent IMF calculations suggest that carbon prices will need to reach values between \$140/tCO2 and \$200/tCO2 globally by 2030 to achieve a 25% reduction in CO2 emissions by 2030 relative to 2021 (IMF, 2022). The NGFS estimates that a global carbon price between \$120/tCO2 and \$250/tCO2 is required to reach net-zero emissions by 2050 (NGFS, 2022), while the Quinet Commission recommends a carbon price of €250/tCO2 by 2030 (Quinet et al., 2019). Accordingly, our assumed ECR targets for the euro area and especially for the rest of the industrialised world are conservative.

And second, our scenario does not capture the interaction between climate policies and climate change. Specifically, the macroeconomic effects of the scenario are compared to a baseline where carbon prices do not change, assuming that the resulting physical damages from failing to implement effective climate policies are economically not costly. While such a no-policy-change baseline is not realistic, designing a baseline scenario that accounts for physical damages is beyond our analysis and, given that we focus on a limited time horizon until 2030, arguably not yet relevant. Likewise, our scenario does not capture the benefits of avoiding the adverse macroeconomic effects from climate incidents that an effective carbon tax policy would help to mitigate.

3.2 The effects of the carbon transition scenario

We implement the carbon transition scenario for the euro area by choosing the initial value of the carbon tax rate in our model such that the implied carbon tax-related revenues are equal 1.83% of GDP, in accordance with the actual fiscal revenues for the average ECR of €84.7/tCO2 in 2021.[26] The scenario experiment is then to linearly increase the model-

[26] The implementation strategy for the rest of the industrialised world is similar but accounts for differences in the initial value of the carbon tax and in the emission intensity of production compared to the euro area.

consistent carbon tax rat by 65.3% over the 9-year period from 2022 to 2030 to match the target ECR of €140/tCO2. Thereafter the carbon tax rate is kept unchanged. The accruing additional carbon tax-related revenues are assumed to be evenly distributed to households in the form of lump-sum transfers. From the perspective of our model, this is arguably the most neutral assumption concerning the conduct of fiscal policy. In addition, we assume that the fossil resource-exporting country in the model gradually reduces the global supply of fossil resources over the scenario period so as to stabilise the real fossil-resource price in US dollar terms. Without this assumption the amount of carbon emissions resulting from the use of fossil resources would remain unchanged despite the carbon tax increase because global demand needs to meet global supply in equilibrium.

The aggregate and sectoral effects of the carbon tax scenario are shown in Figures 3 and 4, respectively. At the aggregate level, the carbon tax increase is inflationary and leads to a lasting decline in GDP: Consumer price inflation rises as higher energy prices due to the increase in the carbon tax feed directly into the price of the final consumption good. The increase in inflation is gradual and hump-shaped, reaching a peak of around 0.2 percentage point in the course of 2023 and receding slowly by the end of 2030.[27] On average, inflation increases by about 8.5 basis points over the period from 2022 to 2030. Inflation excluding energy rises as intermediate-good producers gradually pass through the increase in their marginal cost due to higher energy prices to the producers of the final goods used for consumption and investment purposes. Overall, the increase in energy prices puts only very moderate upward pressure on inflation excluding energy, with a peak effect that remains below 5 basis points and peters out slowly thereafter.

As regards the adjustment on the real side of the economy, households cut back on consumption because of the fall in current and expected future real income following the increase in the carbon tax rate. However, to the extent that the fiscal authority's carbon tax revenues are distributed to households via lump-sum transfers, the adverse impact on real income and thus consumption is largely mitigated, with consumption falling only moderately

[27] As shown in Appendix A.1, the peak inflation effect would be close to 0.35 percentage point if the calibration of the energy share in the final consumption good of our model were to be based on the larger energy expenditure share in the consumption bundle used in the calculation of the Harmonised Index of Consumer Prices (HICP) for the euro area.

by about 0.7% in the medium to longer term.[28] The fall in investment is markedly stronger, with a decline of close to 2.75% at the trough in 2026, reflecting the decline in firms' profitability and the need to reduce the economy-wide capital stock. With the impact on net trade being overall muted, the fall in domestic demand translates into a gradual but lasting fall in GDP by roughly 1.2% in the medium to longer term, closely matching the decline in trend GDP.[29] Given the overall decline in aggregate demand, aggregate hours worked and capital services fall. Likewise, wages and the return on capital decline, which dampens the effect of the increase in energy prices on inflation.

In response to the carbon tax-induced increase in inflation and the implied decline in GDP, the monetary authority raises the short-term nominal interest rate modestly over the medium term, reflecting the fact that it stabilises inflation excluding energy relative to GDP growth. Overall, this policy response is sufficient to keep the inflationary effects of the carbon tax increase contained, while limiting the fall in GDP below its trend.

At the sectoral level, the increase in carbon taxes operates by affecting relative energy prices: As carbon taxes are levied as a surcharge on the price of dirty energy, aggregate energy producers substitute away from utilising more costly dirty energy and into utilising clean energy for producing the energy bundle that enters final consumption and intermediate-good production. The degree to which this occurs is driven by the elasticity of substitution between clean and dirty energy. In line with empirical evidence, this elasticity is assumed to be moderate in the long run, but markedly lower in the short run because of temporary adjustment costs. The shift of demand from dirty to clean energy puts downward pressure on the pre-tax price of dirty energy, but upward pressure on the price of clean energy, with the latter contributing to the increase in the aggregate price of energy over and above the increase in the after-tax price of dirty energy.[30] Aggregate energy production

[28] The moderate decline in consumption in response to the carbon tax increase represents a major difference compared to the sizeable decline in consumption following an adverse shock to the supply of fossil resources; see Figure 2. The reason is that, in response to this shock, the terms of trade deteriorate, resulting in a transfer of real income to the fossil resource-exporting country.

[29] As discussed in Section 2.4, trend GDP in our model captures the smooth transition of aggregate output from its initial to its new steady-state level following a permanent shock. For the carbon tax scenario this implies that no more than 85% of the change in steady-state output is absorbed into trend GDP by the end of the implementation period of the scenario.

[30] Note that the downward pressure on the pre-tax price of dirty energy is offset to the extent that the fossil resource-exporting country reduces the supply of fossil resources over the medium to longer term so as to stabilise the real price of the fossil resources in US dollar terms.

falls, masking that, because of a reallocation of capital and labour inputs, the production of clean energy rises, albeit modestly.

Due to the lower use of dirty energy in aggregate energy production and the fall in the production of intermediate goods, total carbon emissions are reduced by roughly 7% in the medium to longer term.[31] The by far largest contribution to the reduction in carbon emissions comes from lower dirty energy utilisation, whereas the contribution of lower non-energy carbon emissions from lower intermediate-good production is rather limited. While the reduction in total carbon emissions is sizeable, it falls clearly short of the 25% reduction needed by 2030 according to IMF calculations.[32] If this benchmark were to be met by exclusively raising the price of carbon emissions, the carbon tax in the scenario experiment would need to be increased by about 340%, from the current value of €84.7/tCO2 to roughly €375/tCO2. In this hypothetical case, the peak inflation effect of the carbon tax increase would amount to 0.9 percentage point, while GDP would decline by about 5.5% over the medium to longer term.

3.3 Monetary policy and the inflation-output trade-off

The monetary authority in our model aims to stabilise consumer price inflation excluding energy around its inflation target, while keeping GDP growth close to trend GDP growth. As shown in Figure 3, a modest, albeit persistent interest-rate increase is sufficient to contain the inflationary effects of the carbon tax-induced increase in energy prices, while limiting the fall in GDP below its trend.

To further examine the influence of monetary policy on the outcomes of the carbon transition scenario, we revisit the scenario by assuming that the monetary authority follows, alternatively, two versions of the Taylor (1993) interest-rate rule:

$$R_t^4 \quad = \quad 0.9 \cdot R_{t-1}^4 + (1-0.9) \cdot \left[R^4 + 1.5 \cdot \left(\tilde{\pi}_t^{(4)} - \Pi \right) + 0.5 \cdot ygap \right], \tag{56}$$

[31] We find a similar percentage reduction in carbon emissions for the rest of the industrialised world despite the smaller absolute increase in the carbon tax rate. This finding follows from the considerably higher carbon intensity of production in the rest of the industrialised world.

[32] As shown in Appendix A.2, carbon emissions would be reduced by additional 3.75 percentage points if the long-run substitution elasticity between dirty and clean energy were to be increased to a value of 3, which is at the upper end of the range of estimates considered in the calibration, provided that the supply of green resources adjusts so as to stabilise the real green-resource price in the long run, as in the case of the fossil resources. Otherwise, mainly the price of green resources and, thus, the price of clean energy would adjust, and the reduction in carbon emissions would be little affected.

which features an interest-rate reaction to the output gap, $ygap_t = GDP_t/\overline{GDP}_t - 1$, instead of the GDP growth gap, $GDP_t/GDP_{t-1} - \overline{GDP}_t/\overline{GDP}_{t-1}$ and where $\tilde{\pi}_t^{(4)}$ denotes the monetary authority's preferred measure of annual inflation. Otherwise, the Taylor rule is congruent with the model's default interest-rate rule (see equation (51) in Section 2.5).[33] Under the first version of the Taylor rule, the monetary authority continues to stabilise consumer price inflation excluding energy, $\tilde{\pi}_t^{(4)} = P_{CX,t}/P_{CX,t-4}$, whereas it stabilises overall consumer price inflation, $\tilde{\pi}_t^{(4)} = P_{C,t}/P_{C,t-4}$ under the second version.

The outcomes of the carbon transition scenario under the alternative Taylor rules are shown in Figure 5, compared to the outcomes under the model's default interest-rate rule, which serves as a benchmark. Under the version of the Taylor rule with an interest-rate reaction to inflation excluding energy, both overall inflation and inflation excluding energy rise more strongly and more persistently, while the output gap, measuring the shortfall of GDP below trend GDP, is visibly mitigated during the first few years. This is due to the fact that the monetary authority is concerned with the output gap rather than the GDP growth gap. Accordingly, it provides more stimulus to aggregate demand in order to limit the size of the emerging output gap. This is reflected in the outcome that, even though the nominal interest rate rises by a larger amount because of the stronger increase in inflation, the implied decline in the ex ante real interest rate is about twice as large.

By contrast, under the Taylor-rule version with an interest-rate reaction to overall inflation, the inflation effects over the scenario period are markedly below those under the Taylor rule with a reaction to overall inflation. This is due to the fact that the monetary authority is also reacting to the direct inflation impact of the tax-induced increase in energy prices. Accordingly, monetary policy is considerably tighter, as reflected in the smaller decline in the real interest rate. As a result, the GDP shortfall is mitigated less.

All in all, the outcomes of the carbon transition scenario under the alternative Taylor rules suggest that the implied monetary policy trade-off between stabilising inflation and GDP is manageable. However, a policy-maker who has a strong preference to mitigate the GDP shortfall would want to "look through" the carbon tax-induced direct effect of

[33] We prefer the growth-gap specification of the interest-rate rule because it largely insulates the conduct of monetary policy within the model from the auxiliary assumption we have made regarding the determination of trend GDP; see Section 2.4. Moreover, there is empirical evidence that the growth gap is more important than the output gap in estimated interest-rate rules for the euro area; see, e.g., Coenen et al. (2018).

higher energy prices on inflation and stabilise inflation excluding energy at the expense of tolerating higher overall inflation.

3.4 Distributional implications of transfers and subsidies

One of the advantages of a carbon tax compared to other climate policies is that it generates additional fiscal revenues, which can be used to mitigate adverse side effects of the carbon tax or to stimulate economic behaviour that enhances overall policy effectiveness. Here we investigate two such uses, one where the disproportionate carbon tax burden of low-income households is alleviated by means of targeted transfers, and one where the production of clean energy is subsidised.

Targeted transfers

A side effect of the increase in the carbon tax is that it disproportionately affects the real disposable income of financially constrained households in our model, who only earn labour income and, moreover, are unable to smooth consumption by adjusting holdings of government bonds, or physical capital. The fiscal authority can address this side effect by distributing a larger share of the additional revenues raised by the increase in the carbon tax to these households. Specifically, while we have assumed in our central scenario that all additional revenues are distributed evenly among households in per-capita terms, we now consider an alternative targeted transfer scheme, according to which the revenues are redistributed in favour of the constrained households such that they can maintain their relative consumption position, at least in the long run.

The scenario results obtained under the targeted transfer scheme are shown in Figure 6. For the aggregate variables, notably for inflation and GDP, they are very similar to the results under the benchmark scheme with evenly distributed transfers, suggesting that the aggregate effects of the redistribution of revenues under the targeted transfer scheme are minor. However, the redistribution of revenues has important effects on inequality, measured here as the dispersion of consumption across households. Specifically, under the benchmark transfer scheme, consumption of both constrained and unconstrained households falls permanently, yet with the decline in consumption of the constrained households being considerably stronger. By contrast, under the targeted transfer scheme, the decline in consumption of the constrained households is noticeably dampened, whereas the decline in consumption of the unconstrained household is intensified.

To show the implications of the alternative transfer schemes for consumption inequality more clearly, Figure 6 also depicts the evolution of the *ratio* of the consumption levels of both types of households. Under the benchmark scheme, the consumption ratio falls and thus the gap between the consumption levels of constrained and unconstrained households widens.[34] This suggests that a carbon tax increase with an even distribution of revenues amongst households has a regressive effect. This regressive effect is eventually overcome under the targeted transfer scheme, with a reduction in the consumption gap over the medium term, as can be inferred from the stabilisation of the consumption ratio over the scenario period, and a closing of the gap in the long run.

Green subsidies

The fiscal authority can also use revenues resulting from an increase in the carbon tax as a "green" subsidy to foster clean energy production. Importantly, since we assume in our central scenario that all additional carbon-tax-related revenues are evenly transferred to households, granting such a subsidy comes along with a corresponding reduction in transfers and will hence have distributional implications as well.

To illustrate the relevant mechanisms, Figure 7 shows the effects of redirecting 50% of the additional revenues that accrue from the carbon tax increase to subsidise the sales price of the clean energy-producing firms in our model. In terms of aggregate effects, and compared to the benchmark scenario without subsidy, the green subsidy scheme leads to a modestly smaller decrease in GDP. This in turn translates into a slightly stronger increase in inflation. The overall very muted effect on aggregate consumption masks the impact of two countervailing forces. First, granting the green subsidy results in a sustained increase in firms' revenues from clean energy production, despite the fact that the production volume is actually expanded only very little, while the sales price excluding subsidy marginally falls.[35] The higher profits associated with the increase in revenues are paid as dividends

[34] Based on evidence from the ECB's Household Finance and Consumption Survey, the initial value of the consumption ratio has been calibrated such that the consumption level of constrained households equals 80% of the consumption level of unconstrained households.

[35] The limited expansion of the production volume follows from the fact that the production technology and the supply of green resources used in the production of clean energy are not favourably affected by the subsidy scheme. At the same time, the substitutability of capital and labour with primary resources is low and prevents a material shift of these factors towards clean energy production. See Section 3.7 for illustrative simulations of the effects of expanding the supply of clean energy.

to the unconstrained households who own the clean energy-producing firms and lead them to expand consumption on account of higher current and expected future income. And second, the fact that granting the subsidy comes along with a corresponding reduction in carbon tax-related transfers to households results in an off-setting fall in income and, hence, consumption, especially on the part of the unconstrained households. In the aggregate, consumption falls by slightly less in the short term but remains close to the benchmark scenario outcome over the medium to long term.

3.5 Implications of alternative carbon tax paths

In our central carbon transition scenario we assume that the carbon tax rate increases linearly over a 9-year period from 2022 to 2030. Here, we investigate the implications of bringing the tax increase forward or of postponing it. Specifically, we consider two alternative paths for the carbon tax increase: The first path assumes a front-loaded increase, while the second path assumes a back-loaded and delayed increase, with the length of the scenario period being extended by 50% to mid 2035. All paths ultimately yield the same tax increase and hence have the same long-run effects. However, as shown in Figure 8, the short and medium-run effects of the different tax paths can vary considerably.

Compared to the results obtained for the linear carbon tax path, the front-loaded tax increase brings about a larger fall in GDP over the short and medium term, driven by a stronger decline in consumption and investment. The ensuing stronger decline in wages and in the return on capital dampens the rise in marginal costs of intermediate-good producers following from the faster rise in after-tax energy prices owing to the front-loaded tax increase. This explains why overall inflation peaks at a somewhat higher level and a bit earlier, before returning to target more quickly. The faster increase in the price of dirty energy, together with the stronger decrease in aggregate energy demand, leads to a somewhat faster reduction in dirty energy production and carbon emissions.

The back-loaded and delayed tax increase implies that households and firms anticipate the slower but eventually accelerating increase in the carbon tax. Accordingly, they expand their consumptive and productive uses of energy in the short term to benefit from still lower energy prices early on. In equilibrium, the more limited fall in energy demand holds up energy prices and implies that they increase initially almost as strongly as under the linear tax path. As a result, inflation reaches a peak level which is only slightly lower, but remains persistently higher after 2025 because of the continued increase in the carbon tax. The upward inflation pressure only ceases once the carbon tax reaches its final level. On the real side, GDP is more resilient, reflecting the more gradual decline in consumption and investment due to the weaker but more drawn-out impact of the tax increases on the income of households and on firms' profitability. As energy demand is sustained for longer, dirty energy production and carbon emissions decrease with a delay.

3.6 Imperfect credibility of the transition scenario

So far we have examined the effects of the carbon transition scenario under the assumption of full credibility of the carbon tax path. This assumption implies that households and firms fully anticipate the future carbon tax increases, understand that they are permanent, and take them into account in their current forward-looking decisions. To gauge the importance of the assumption of full credibility, we revisit the effects of the scenario under the alternative assumption of imperfect credibility where households and firms do not believe in the future carbon tax increases until they are actually observed. Accordingly, households and firms only incrementally update their perceptions of the path of tax rates over time.[36]

The effects of the carbon transition scenario under imperfect credibility are shown in Figure 9, compared to the effects of the scenario under perfect credibility. As households and firms do not anticipate the actual path of carbon tax increases correctly, they are surprised in every period by a partial and small carbon tax increase. The intertemporal forward-looking element of decision-making in response to the correctly anticipated carbon tax path is therefore missing and, as a consequence, there are no visible effects of front-loading. On the nominal side, the observed small carbon tax increases feed only gradually into the price-setting decisions of dirty and aggregate energy producers, and from there, directly and indirectly, into consumer prices. The implied increase in inflation is sluggish and very contained, but also much more persistent, than in the benchmark scenario with

[36] Our approach of introducing imperfect credibility in the implementation of the carbon tax scenario is similar to the approach followed in a recent IMF study (see IMF, 2022). Other approaches in the literature may instead consider that, after the entire sequence of tax increases has materialised, the tax rate returns to its initial level (see, e.g., Ferrari and Nispi Landi, 2020).

perfect credibility. Similarly, GDP decreases more slowly than in the benchmark scenario, which is again due to the lack of the forward-looking element in decision-making, especially regarding households' consumption and investment spending.

Finally, under imperfect credibility the carbon tax scenario has much more gradual effects in terms of reducing dirty energy production and thus carbon emissions. This has lasting detrimental climate consequences as the sluggishness in the reduction of carbon emissions implies a markedly larger increase in the stock of emissions.

3.7 Enhancing the supply of clean energy

Our central carbon tax scenario so far has assumed that the supply of green resources as well as the efficiency of clean energy production have remained invariant during the carbon transition. Yet, it would be natural to expect that both of these dimensions change over time, either as the result of additional government policies, or due to technological innovation. For example, an increase in green resource supply can result from a government policy that allows issuance of additional production permits for the use of larger natural territories (e.g., increased land or sea surface use), while efficiency improvements in clean energy production should arise from the adoption of new technologies. In a similar vein, favourable supply effects can be achieved by expanding the capacity of clean energy production (e.g., by undertaking "green" investments).

We revisit our central carbon tax scenario, allowing this time for a 10% increase in either the productivity of clean energy production or the endowment of green resources, with the increase being gradually phased in. The results of the scenario with the alternative specifications of clean energy supply are shown in Figure 10. Compared to the benchmark case, the carbon tax increase is somewhat less inflationary in the shorter term, while the decline in GDP is diminished over all horizons. These effects can be explained by the different adjustment paths for the prices and the production volumes of the energy components. As the supply of green resources grows, or as the technology of clean energy production improves, the upward pressure on the price of clean energy, which results from the desire of the aggregate energy producer to switch from dirty to clean energy inputs, is basically offset, while clean energy production increases very strongly. This translates into a smaller increase in the aggregate price of energy and a weaker decline in aggregate energy production. As household income and firm profitability benefit from lower increases in energy prices, both consumption and investment demand rise, which in turn results in an increase in GDP. A consequence of enhancing the supply of clean energy is that the resulting reduction in carbon emissions is greater, reaching approximately 8.5%. This reflects the fact that enhancing the supply of clean energy enables the shift towards the use of clean energy inputs in the production of aggregate energy.

4 Extension: Non-energy emissions and abatement

We introduce into our model an additional policy instrument aimed at mitigating carbon emissions, namely a tax on non-energy carbon emissions of intermediate-good firms. This instrument can be interpreted as a shadow price of environmental regulation, aimed at lowering the amount of emissions per unit of output produced. In practice, firms are incentivised to engage in costly abatement through, e.g., the installation of new pollution filters, in an effort to reduce their non-energy emission tax burden.

4.1 Intermediate-good production with optimal abatement

If the release of emissions unrelated to energy inputs is costly to intermediate-good firms and subject to abatement effort, the marginal cost of an additional unit of output has two components: the cost associated with the extra capital, labour and energy inputs needed to produce the additional unit, and the cost associated with non-energy emissions and their abatement. The first component is determined by the intermediate-good firms' production technology and input prices, while the second depends on the price which intermediate-good firms are charged for releasing emissions and on the available abatement technology.

Specifically, allowing intermediate-good firm f to abate a fraction of its non-energy emissions, $A^Y_{f,t}$, the emissions actually released at firm level, $M^Y_{f,t}$, are given by:

$$M^Y_{f,t} \quad = \quad \left(1 - A^Y_{f,t}\right) s^Y_M \, Y_{f,t}, \tag{57}$$

where $s^Y_M \geq 0$ measures the emissions per unit of output in the absence of the firm's abatement effort; see, e.g., Heutel (2012).

The cost of abating emissions in terms of forgone output, $CA^Y_{f,t}$, is, in turn, a function of the abatement effort and proportional to the level of output produced:

$$CA^Y_{f,t} \;=\; \varphi_1 \left(A^Y_{f,t}\right)^{\varphi_2} Y_{f,t}, \tag{58}$$

where $\varphi_1, \varphi_2 > 0$ are technology parameters; see, e.g., Nordhaus (2008). The parameter φ_1 is a scaling coefficient per unit of output, while the parameter φ_2 determines the convexity of the cost function.

Taking the unit price of emissions, $P_{M,t}$, as given, it follows from the firm's static cost minimisation problem that the optimal abatement effort equates the marginal value product of abatement to its marginal cost:[37]

$$\frac{P_{M,t}}{P_{Y,f,t}}\, s^Y_M \;=\; \varphi_1\, \varphi_2 \left(A^Y_{f,t}\right)^{\varphi_2 - 1}, \tag{59}$$

where $P_{Y,f,t}$ denotes the price of the intermediate good produced by firm f.[38]

Assuming that the unit emission price is administered by government and levied as a surcharge on the firm's sales price, with $P_{M,t} = \tau^{M_Y}_t P_{Y,f,t}$,[39] all firms choose the same *optimal* abatement effort, $A^Y_t = A^Y_{f,t}$ with $A^Y_t = (\tau^{M_Y}_t\, s^Y_M\, (\varphi_1\, \varphi_2)^{-1})^{1/(\varphi_2 - 1)}$, which increases with the emission-related price surcharge, $\tau^{M_Y}_t$, and the emission intensity, s^Y_M.

It follows that, with optimal abatement effort, the individual firm's current-period nominal profits (net of fixed cost) are given by:

$$\begin{aligned}
D^Y_{f,t} &= P_{Y,f,t}\, Y^d_{f,t} - MC^Y_t\, Y^d_{f,t} - \tau^{M_Y}_t P_{Y,f,t} \left(1 - A^Y_t\right) s^Y_M\, Y^d_{f,t} - P_{Y,f,t}\, \varphi_1 \left(A^Y_t\right)^{\varphi_2} Y^d_{f,t} \\
&= \left(1 - \tau^{M_Y}_t \left(1 - A^Y_t\right) s^Y_M - \varphi_1 \left(A^Y_t\right)^{\varphi_2}\right) P_{Y,f,t}\, Y^d_{f,t} - MC^Y_t\, Y^d_{f,t} \\
&= \Xi(\tau^{M_Y}_t, s^Y_M)\, P_{Y,f,t}\, Y^d_{f,t} - MC^Y_t\, Y^d_{f,t},
\end{aligned} \tag{60}$$

with

$$\begin{aligned}
\Xi(\tau^{M_Y}_t, s^Y_M) \;=\; & 1 - \tau^{M_Y}_t \left(1 - (\tau^{M_Y}_t\, s^Y_M\, (\varphi_1\, \varphi_2)^{-1})^{1/(\varphi_2 - 1)}\right) s^Y_M \\
& - \varphi_1 \left((\tau^{M_Y}_t\, s^Y_M\, (\varphi_1\, \varphi_2)^{-1})^{1/(\varphi_2 - 1)}\right)^{\varphi_2}.
\end{aligned} \tag{61}$$

[37] Note that the optimality condition implies zero abatement effort on the part of the firm in the absence of a price for emissions or in the case of a zero emission intensity of production.

[38] To simplify the exposition, we abstract from the fact that the intermediate good is sold in domestic and foreign markets at differentiated local prices.

[39] Since the intermediate-good firms' staggered price-setting behaviour introduces a source of heterogeneity, this assumption allows us to continue solving the resulting aggregation problem by ensuring symmetry of firms' optimal price-setting decisions.

Here, $Y^d_{f,t}$ denotes the aggregate demand for the intermediate good produced by firm f, and MC^Y_t is the component of the firm's overall marginal cost associated with the extra capital, labour and energy inputs needed to produce an additional unit of output.

The optimal price contract for intermediate goods is chosen symmetrically by those firms f that have received permission to reset their price with probability $(1 - \xi_Y)$, with $\widetilde{P}_{Y,t} = \widetilde{P}_{Y,f,t}$. Using the re-formulated expression for nominal profits (60), it is given by:

$$\frac{\widetilde{P}_{Y,t}}{P_{Y,t}} \quad = \quad \frac{\theta_Y}{\theta_Y - 1} \frac{F_{Y,t}}{G_{Y,t}}, \tag{62}$$

where the auxiliary variables $F_{Y,t}$ and $G_{Y,t}$ are defined recursively as:

$$F_{Y,t} \quad = \quad MC^Y_t Y^d_t + \xi_Y \beta \, \mathrm{E}_t \left[\frac{\Lambda_{I,t+1}}{\Lambda_{I,t}} \left(\frac{\pi_{Y,t+1}}{\pi^{\chi_Y}_{Y,t} \, \pi^{1-\chi_Y}_Y} \right)^{\theta_Y} F_{Y,t+1} \right], \tag{63}$$

$$G_{Y,t} \quad = \quad \Xi(\tau^{M_Y}_t, s^Y_M) \, P_{Y,t} Y^d_t + \xi_Y \beta \, \mathrm{E}_t \left[\frac{\Lambda_{I,t+1}}{\Lambda_{I,t}} \left(\frac{\pi_{Y,t+1}}{\pi^{\chi_Y}_{Y,t} \, \pi^{1-\chi_Y}_Y} \right)^{\theta_Y - 1} G_{Y,t+1} \right], \tag{64}$$

with Y^d_t denoting the aggregate demand for all intermediate-good varieties.

This expression differs from the expression for the original model set-up without costly emissions and abatement effort (see Coenen et al., 2007) in that aggregate revenues, $P_{Y,t} Y^d_t$, are multiplied by the factor $\Xi(\tau^{M_Y}_t, s^Y_M)$, which summarises the effects of costly emissions and optimal abatement effort on firms' optimal price-setting decision.

The aggregate price index is obtained as the weighted average of the optimal reset price and the past price (indexed to past and steady-state inflation):

$$P_{Y,t} \quad = \quad \left[(1 - \xi_Y) \left(\widetilde{P}_{Y,t} \right)^{1-\theta_Y} + \xi_Y \left(P_{Y,t-1} \pi^{\chi_Y}_{Y,t-1} \pi^{1-\chi_Y}_Y \right)^{1-\theta_Y} \right]^{\frac{1}{1-\theta_Y}}. \tag{65}$$

In equilibrium, clearing of the market for intermediate goods requires that supply equals demand, with $Y_t = s_{Y,t} \, Y^d_t$, where $s_{Y,t}$ is a wedge which reflects the price dispersion across intermediate-good varieties owing to staggered price setting by their producers. Aggregate (gross) profits, which are paid as dividends to the households that own the intermediate-good producers, are given by $D^Y_t = \Xi(\tau^{M_Y}_t, s^Y_M) \, P_{Y,t} \, Y^d_t - MC^Y_t (s_{Y,t} \, Y^d_t + \psi^Y)$.

Taking into account the foregone output due to abatement, the aggregate net value of production for the intermediate-good sector is given by:

$$V^Y_t \quad = \quad P_{Y,t} \, Y_t - \varphi_1 \left(A^Y_t \right)^{\varphi_2} P_{Y,t} \, Y_t \; - \; P_{E,t} \, E^Y_t$$

$$= \breve{\Xi}(\tau_t^{M_Y}, s_M^Y)\, P_{Y,t}\, Y_t \;-\; P_{E,t}\, E_t^Y, \tag{66}$$

with

$$\breve{\Xi}(\tau_t^{M_Y}, s_M^Y) \;=\; 1 - \varphi_1 \left((\tau_t^{M_Y}\, s_M^Y\, (\varphi_1\, \varphi_2)^{-1})^{1/(\varphi_2 - 1)} \right)^{\varphi_2} \tag{67}$$

and where the last term denotes the aggregate expenses for energy inputs.

Adding up the net value of production of the intermediate-good and of the consolidated energy sector, (66) and (43), and using that $P_{Y,t}\, Y_t = P_{H,t}\, H_t + S_t\, P_{X,t}\, X_t$ and $E_t = E_t^C + E_t^Y$, yields a modified model-consistent measure of nominal GDP:

$$GDP_t^n \;=\; \breve{\Xi}(\tau_t^{M_Y}, s_M^Y) \left[P_{H,t}\, H_t + S_t\, P_{X,t}\, X_t + P_{E,t}\, E_t^C \right] \;-\; S_t\, P_{\mathcal{F},t}\, \mathcal{F}_t, \tag{68}$$

$$\begin{aligned} &= \breve{\Xi}(\tau_t^{M_Y}, s_M^Y) \Bigg[P_{C,t}\, (C_t + \Gamma_{v,t}) + P_{I,t}\, (I_t + \Gamma_{u,t}\, K_t) + P_{G,t}\, G_t \\ &\quad + S_t\, P_{X,t}\, X_t - P_{IM,t} \left(\frac{1 - \Gamma_{IM^C,t}}{\Gamma^{\dagger}_{IM^C,t}}\, IM_t^C + \frac{1 - \Gamma_{IM^I,t}}{\Gamma^{\dagger}_{IM^I,t}}\, IM_t^I \right) \Bigg] \\ &\quad - P_{E,t}\, \frac{1 - \Gamma_{E^C,t} - \Gamma^{\dagger}_{E^C,t}}{\Gamma^{\dagger}_{E^C,t}}\, E_t^C \;-\; S_t\, P_{\mathcal{F},t}\, \mathcal{F}_t, \end{aligned} \tag{69}$$

where the last equation is obtained by following the steps outlined in Section 2.4. It accounts for both the abatement costs of intermediate-good production and the various adjustment costs in the model, which all eat up resources.

4.2 The effects of taxing non-energy emissions

The effects of an increase in taxes on non-energy carbon emissions are shown in Figure 11. The tax rate increases linearly by 65.3%. This increase feeds directly into marginal costs of intermediate-good firms. These firms are then called to trade off the additional cost of the non-energy emissions tax against the cost of increased abatement effort. An increase in abatement effort leads intermediate-good firms to demand less capital and labour, and hence investment demand and production of value added declines. This brings down non-energy emissions, which is the goal of the policy. Given (imperfect) complementarity between value-added in the intermediate-good sector and the energy composite, demand for energy also declines. The decline in energy demand then puts downward pressure on the price of energy. Overall intermediate-good production declines. Recall that abatement is costly: market power allows intermediate-goods firms to shift the abatement burden to households by charging a higher markup. This contributes to an increase in core inflation and a decline in consumption. The latter is somewhat sustained in the short run given the accommodative response of monetary policy, which targets the increase in core inflation and the relatively stronger fall in real activity.

What happens within the energy sector? Under the baseline calibration, we observe that both clean and dirty energy demand falls, but clean energy demand falls by more. This is driven by (at least) two considerations: the elasticity of substitution across energy types within the aggregate energy composite, and by the non-identical declines in the fossil and green resource prices.

5 Conclusion

We have carried out model-based scenario analyses of the macroeconomic effects of raising the price of carbon emissions, which forms an essential element of the overall strategy for decarbonising the euro area economy. As the increase in the price of carbon emissions operates through affecting relative energy prices and by providing incentives to substitute away from using dirty energy towards using clean energy, the modelling of a disaggregated energy sector is pivotal for our analysis. Our central scenario results suggest that increasing the euro area carbon price to €140/tCO2 by 2030, which is modelled as an increasing tax surcharge on the price of dirty energy, entails a transient rise in annual inflation, with a peak effect of around 0.2 percentage point, and a lasting, albeit moderate decline in GDP of roughly 1.2% by 2030, with carbon emissions falling by about 7%. Sensitivity analysis around the central scenario shows that the short and medium-term effects on both inflation and GDP depend on the reaction of monetary policy, the path of the increase in the carbon tax and its credibility, while expanding clean energy supply is key for containing the decline in GDP and for accelerating the decarbonisation of the economy. Moreover, it is shown that undesirable distributional effects can be addressed by appropriately redistributing the fiscal revenues from the tax increase across households.

Looking forward, and with the aim of broadening the scope of our analyses of the effects of carbon transition polices, we plan to extend our modelling framework by including additional elements, notably public "green" investment, complementarity of private and public investment, and technological innovation. In pursuing this agenda, accounting for the endogenous nature of technological innovation (see,e.g., Acemoglu et al., 2012) within a large-scale model like ours will be a particular challenge. We also plan to explore the international dimension of carbon transition policies within our two-country model set-up, both in terms of spill-overs and regarding the possible benefits of policy cooperation.

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Appendix: Additional sensitivity analysis

A.1 The share of energy in final consumption

The share of energy in final consumption is a key parameter that determines the strength of the direct pass-through of energy prices into consumer price inflation. To assess the sensitivity of our results with respect to this parameter, Figure A.1 shows the outcomes of our central carbon transition scenario when the benchmark calibration of the energy share parameter, which is based on input-output tables from the OECD TiVA database, is raised from 5.5% to 10%, broadly consistent with the energy share in the Harmonised Index of Consumer Prices (HICP).

A higher share of energy in the final consumption bundle has three main effects. First, on the nominal side of the economy it leads to a stronger impact of higher carbon taxes on consumer price inflation due to the strong direct pass-through of higher energy prices caused by the increase in the carbon tax. This effect is quite substantial in the short run and leads to a rise in inflation by almost 0.3 percentage point at the peak, which compares to 0.2 percentage point for the benchmark calibration. Inflation is also more persistent and takes longer to return to target. This is in large part due to the fact that the monetary authority aims to stabilise inflation excluding energy, which causes a less vigorous interest-rate response. Second, on the real side the implied reduction in the use of energy has somewhat more negative effects over the medium to longer run, because a larger share of household expenditure is affected by higher energy prices. The latter effect, however, is moderate and only marginally lowers aggregate consumption and thus GDP. And third, the price of energy increases by less in real terms because the consumption bundle includes a larger energy share. In equilibrium this implies that the decline in energy production and in carbon emissions is less pronounced.

A.2 The substitutability of dirty and clean energy

The long-run elasticity of substitution between dirty and clean energy can be an important parameter in determining the potency of transition policies aimed at reducing carbon emissions. Given the scarcity of evidence on this parameter, we examine the sensitivity of our central carbon transition scenario for values that range from moderate complementarity, with a value of 0.8, to strong substitutability, with a value of 3 (being at the upper end of the range of estimates considered in the calibration), and compare the scenario outcomes to those for our benchmark value of 1.8. We do so under two assumptions regarding supply-side adjustments. First, we maintain our benchmark assumption and allow the global supply of fossil resources to adjust so as to stabilise the real fossil-resource price in US dollars at its initial value in the long run. Second, we treat fossil and green resources symmetrically, i.e., we also allow the domestic supply of green resources in the euro area and in the rest of the industrialised world to adjust so that the domestic real green-resource prices return to their initial levels in the long run.

The outcomes for the first case, where only the supply of fossil resources adjusts, are shown in Figure A.2. When the substitution elasticity is lower, it is more difficult for aggregate energy producers to shift from dirty to clean energy. This implies that a smaller reduction in the supply of fossil resources is required to stabilise the fossil-resource price and to clear the global market in the long-run. The larger availability of fossil resources somewhat mitigates the decline in dirty and aggregate energy production. The lower decline in energy production in turn leads to a weaker fall in consumption, investment and GDP. The opposite holds for a higher substitution elasticity. A direct implication of the fact that the fossil-resource market has to clear is that the required adjustment in the supply of fossil resources largely determines the reduction in carbon emissions.

Since the quantity of fossil resources adjusts, while the quantity of green resources remains unchanged, it is basically the adjustment in the price of the green resources and, therefore, the price of clean energy that materially differs when the elasticity of substitution is varied. With a higher substitution elasticity, the increase in the price of clean energy closely follows the increase in the after-tax price of dirty energy. This contributes to a slightly stronger increase in inflation despite somewhat less negative effects on GDP. The opposite holds for a lower substitution elasticity, with the price of clean energy still increasing, but by much less than the price of dirty energy.

In the second case, which is shown in Figure A.3, we treat green and fossil resources symmetrically and the quantities of both types of resources adjust. Moreover, to facilitate the comparison, we also allow the quantity of green resources to adjust in the benchmark simulation. Contrary to what is shown Figure A.2, with a higher substitution elasticity and an increase in the quantity of green resources to stabilise the real green-resource price in the long run, production in the clean energy sector is expanded and substitutes for the carbon tax-induced reduction in dirty energy production. This implies that the quantity of fossil resources declines by more, which in turn leads to a noticeably stronger reduction in carbon emissions. The enhanced ability to substitute away from dirty energy not only implies that domestic energy production is larger, but also that the effective distortion caused by the carbon tax is smaller, as demand can shift to the energy sector not affected by the carbon tax. This ultimately mitigates the decline in GDP. The mechanisms are the same when dirty and clean energy are complements, but they work in the opposite direction.

Table 1: Steady-state shares of energy use and energy production

Ratio	Value: Euro area	Value: Rest of the world	Description
$P_E E^C / P_C C$	0.055	0.033	Energy share in consumption
$P_E E^Y / P_Y Y$	0.072	0.071	Energy share in intermediate-good prod.
$P_{\mathcal{D}} \mathcal{D} / P_E E$	0.717	0.717	Dirty energy share in energy production
$S P_{\mathcal{F}} \mathcal{F} / P_{\mathcal{D}} \mathcal{D}$	0.730	0.528	Fossil resource share in dirty energy prod.
$P_{\mathcal{G}} \mathcal{G} / P_{\mathcal{C}} \mathcal{C}$	0.730	0.528	Green resource share in clean energy prod.
$D^{\mathcal{D}} / P_{\mathcal{D}} \mathcal{D}$	0	0	Profit share in dirty energy sector
$D^{\mathcal{C}} / P_{\mathcal{C}} \mathcal{C}$	0	0	Profit share in clean energy sector

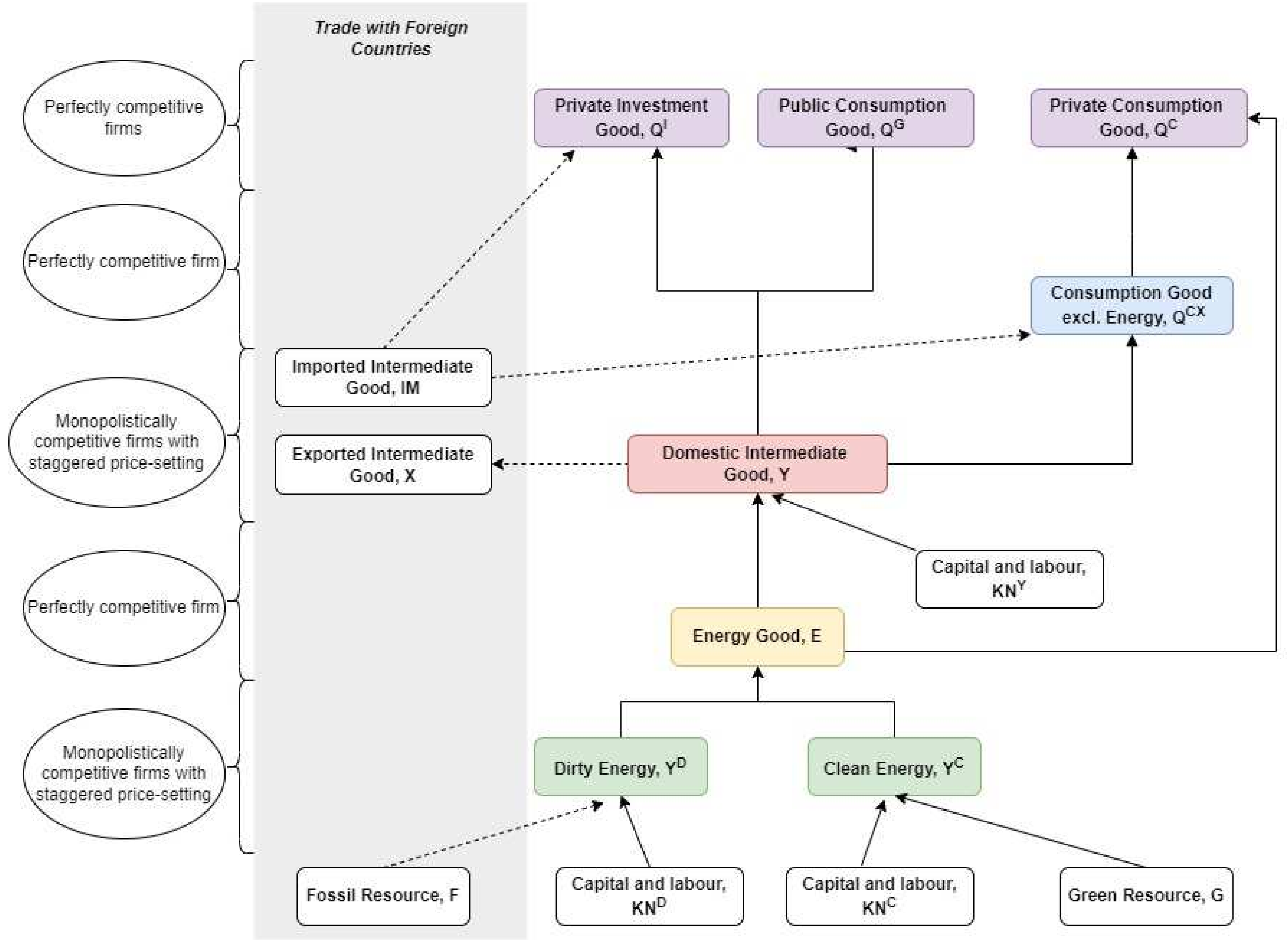
Note: This table reports the calibrated steady-state shares of energy consumption and energy production in the extended version of the NAWM with an energy sector. The calibration of the steady-state shares is based on information from the OECD, Eurostat, and KLEMS.

Table 2: Structural parameters determining the use and production of energy

Parameter	Value: Euro area		Value: Rest of the world		Description
A. Final consumption					
ν_C	0.061⋆		0.037⋆		Share of energy in the production of the final consumption good
μ_C	0.4		0.4		Substitution elasticity between energy and the cons. good excl. energy
γ_{E^C}	5		5		Elasticity of energy adjustment costs
B. Intermediate-good production					
ν_Y	0.072⋆		0.071⋆		Share of energy in the production of intermediate goods
μ_Y	0.4		0.4		Substitution elasticity between energy and the capital-labour bundle
C. Production of energy bundle					
ν_E	0.717⋆		0.717⋆		Share of dirty energy in the production of the energy bundle
μ_E	1.8		1.8		Substitution elasticity between dirty and clean energy
$\gamma_{\mathcal{D}}$	5		5		Elasticity of dirty energy adjustment costs
$\theta_{\mathcal{D}}$, $\theta_{\mathcal{C}}$	6	6	6	6	Price elasticity of demand for dirty and clean energy varieties
D. Production of dirty and clean energy varieties					
$\nu_{\mathcal{D}}$, $\nu_{\mathcal{C}}$	0.732⋆	0.730⋆	0.528⋆	0.528⋆	Share of resources in the production of energy varieties
$\mu_{\mathcal{D}}$, $\mu_{\mathcal{C}}$	0.25	0.25	0.25	0.25	Substitution elasticity between resources and the capital-labour bundle
$\psi_{\mathcal{D}}$, $\psi_{\mathcal{C}}$	0.249⋆	0.098⋆	0.232⋆	0.092⋆	Fixed costs in the production of energy varieties
$\alpha_{\mathcal{D}}$, $\alpha_{\mathcal{C}}$	0.707	0.707	0.716	0.716	Share of capital in the capital-labour bundle
$\xi_{\mathcal{D}}$, $\xi_{\mathcal{C}}$	0.25	0.25	0.25	0.25	Fraction of producers not setting prices optimally
$\chi_{\mathcal{D}}$, $\chi_{\mathcal{C}}$	0	0	0	0	Degree of price indexation

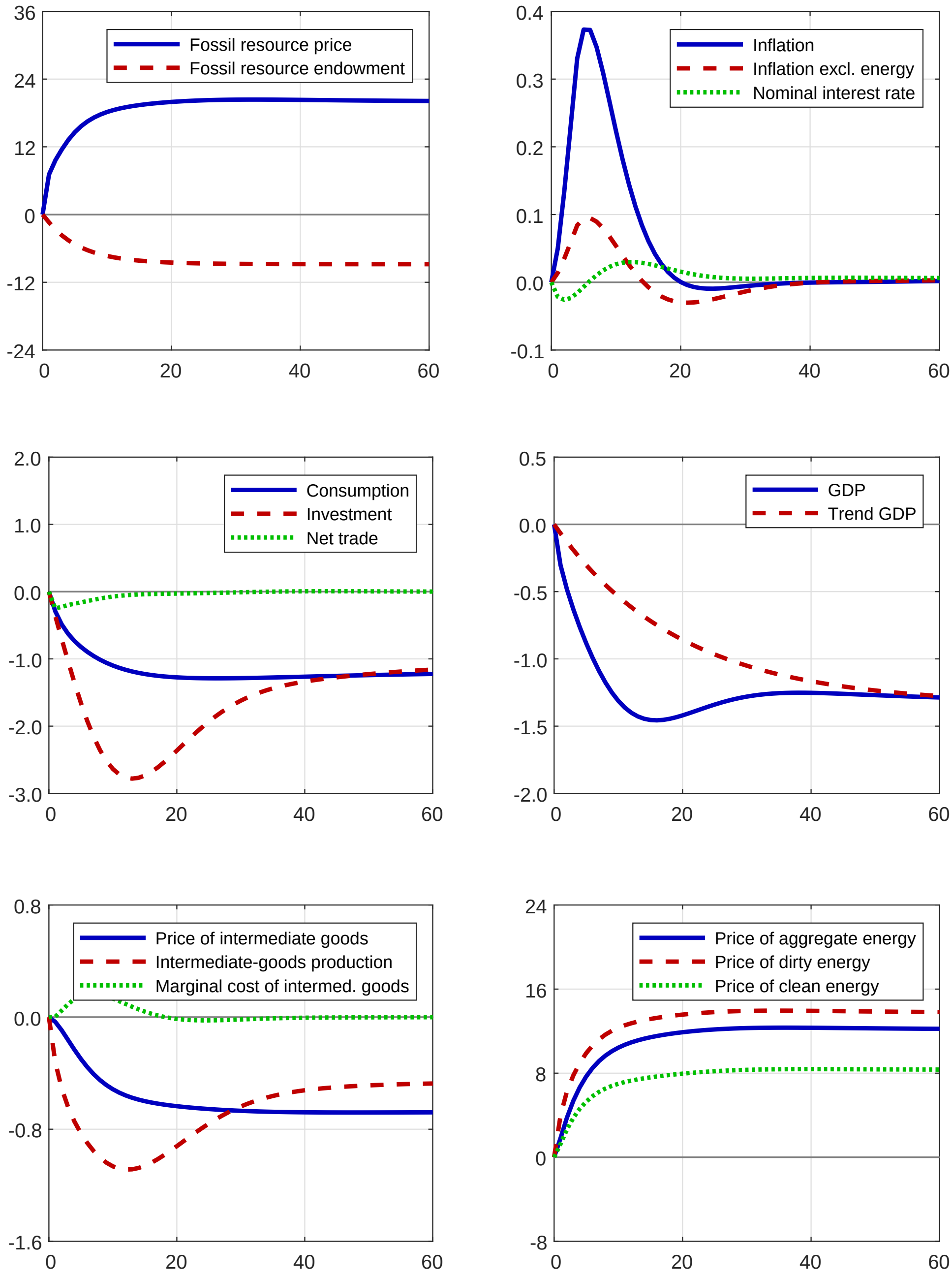
Note: The superscript "⋆" indicates that the parameter value is implicitly calibrated by matching the steady-state ratios reported in Table 1. In the calibration, we normalise several relative prices, with the objective of bringing the quasi-shares in the energy production functions close to the actual shares.

Figure 1: Input and output flows across production sectors



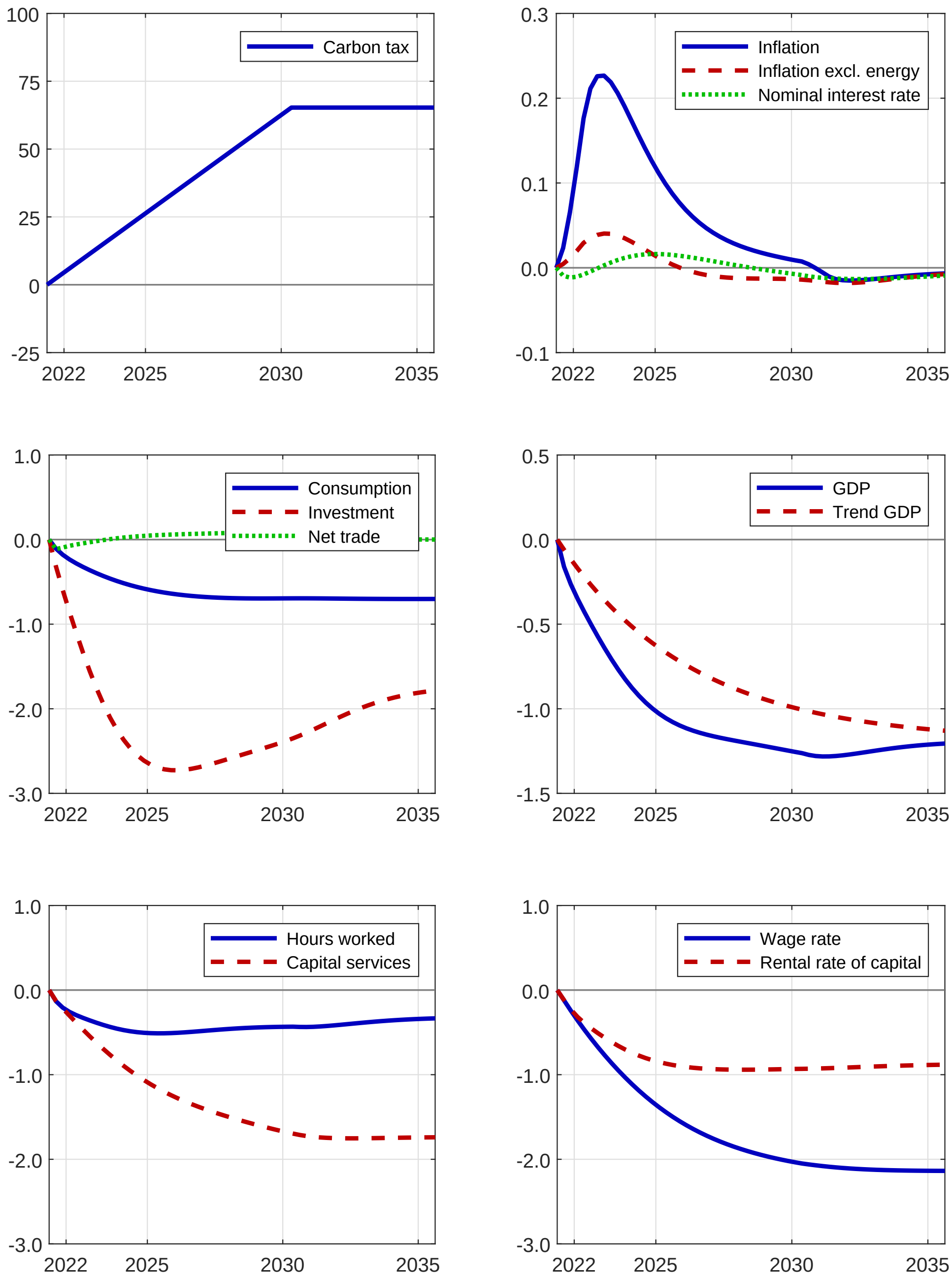
Note: This figure shows a simple chart of the input and output flows across production sectors in the extended version of the NAWM with a disaggregated energy sector.

Figure 2: Effects of a shock to the supply of fossil resources



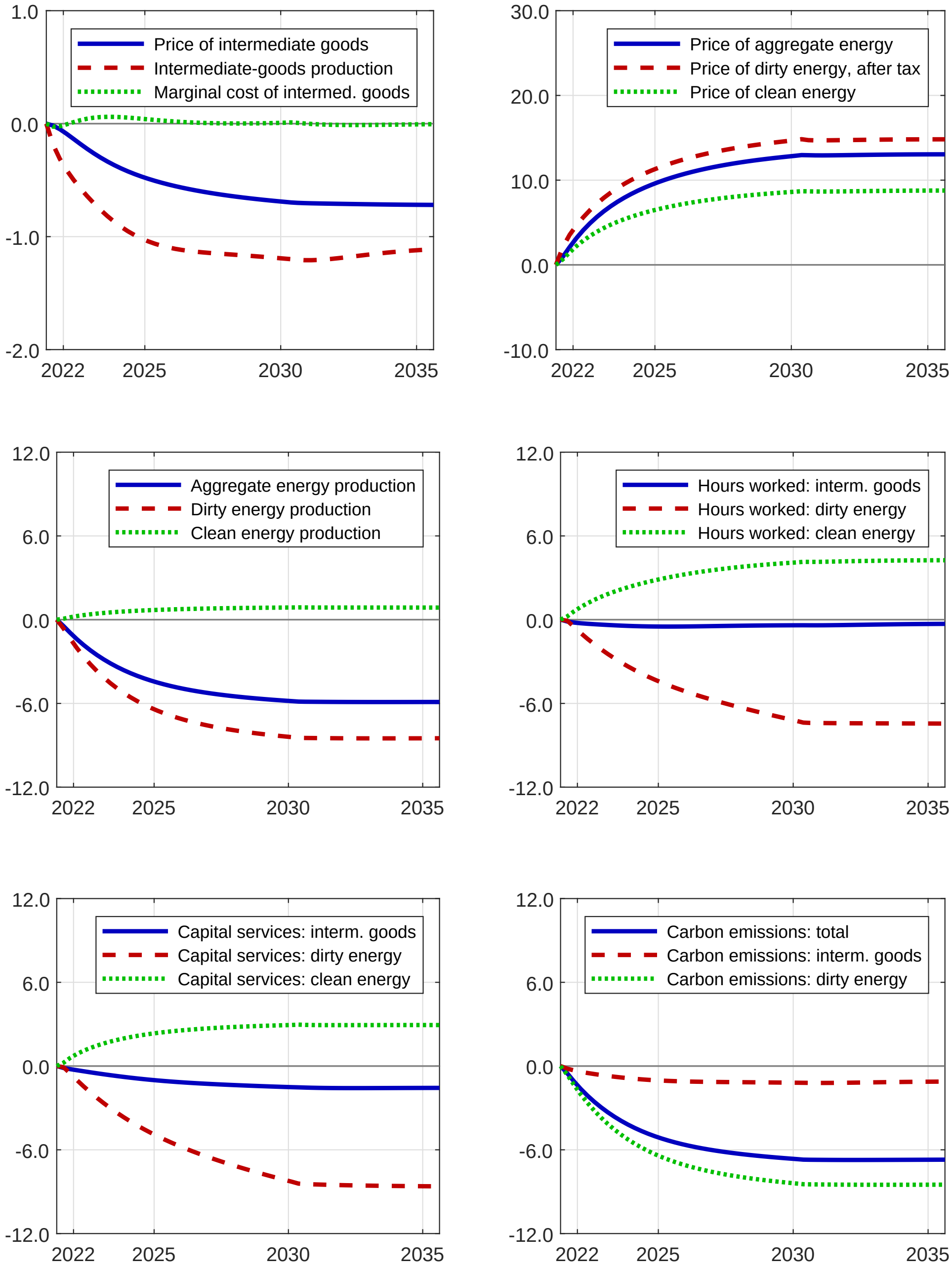
Note: This figure shows the dynamic responses of key aggregate and sectoral variables to an adverse shock to the supply of fossil resources which gives rise to a gradual increase in the fossil resource price (in US dollars) by 20%. Inflation is measured as the annual rate of change in consumer prices, and the nominal interest rate is annualised. Net trade is reported as a share of GDP. Prices are expressed relative to consumer prices, while the marginal cost of intermediate-good production is expressed relative to intermediate-good prices. All dynamic responses are reported as percentage deviations from baseline values, except for the dynamic responses of inflation, the interest rate and net trade, which are reported as percentage-point deviations. The time units on the horizontal axis correspond to quarters.

Figure 3: Aggregate effects of the carbon tax transition scenario



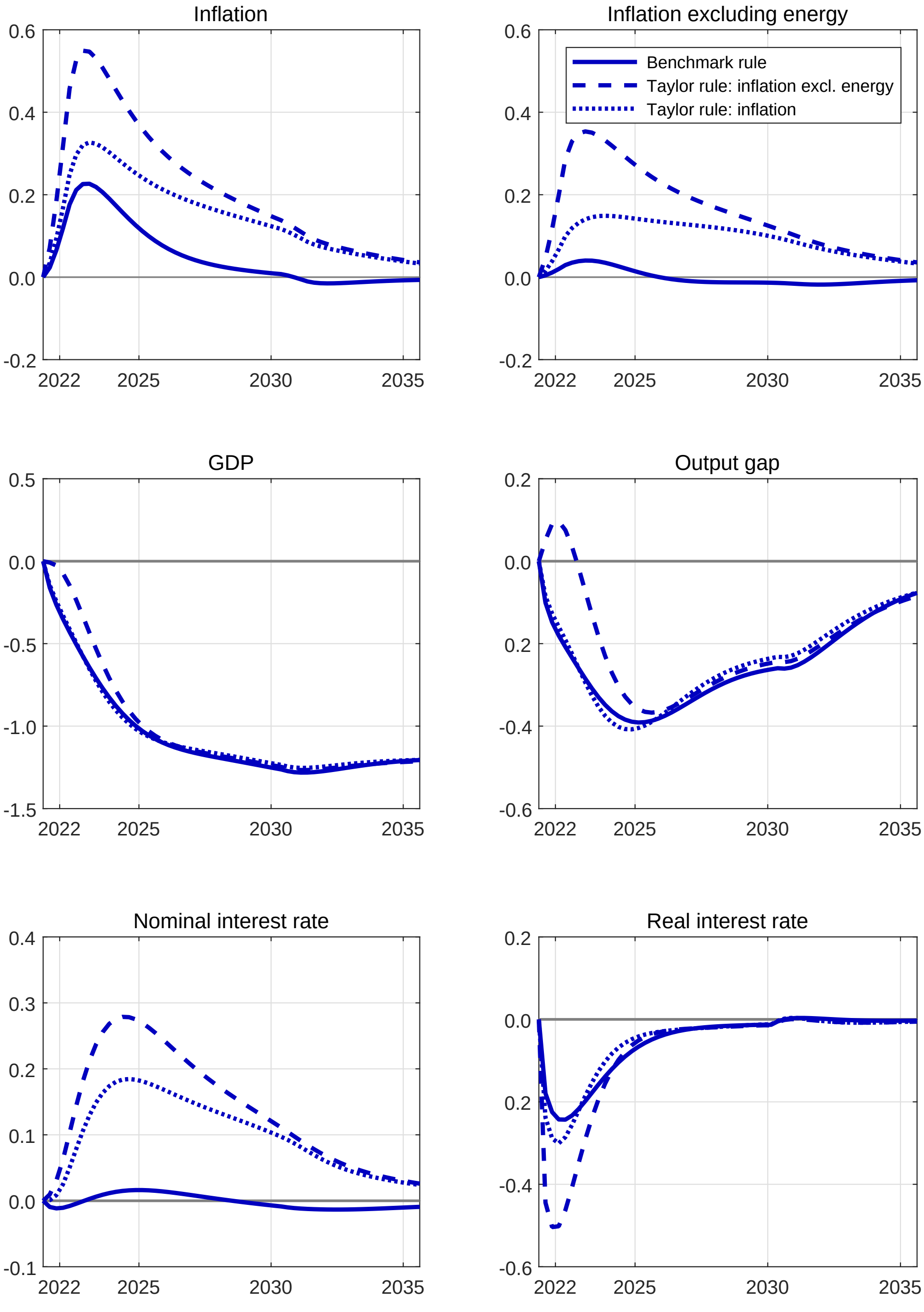
Note: This figure shows the dynamic responses of key aggregate variables to the central carbon tax transition scenario. Inflation is measured as the annual rate of change in consumer prices, and the nominal interest rate is annualised. Net trade is reported as a share of GDP, and the wage rate and the rental rate of capital are expressed relative to consumer prices. All dynamic responses are reported as percentage deviations from baseline values, except for the dynamic responses of inflation, the interest rate and net trade, which are reported as percentage-point deviations.

Figure 4: Sectoral effects of the carbon tax transition scenario



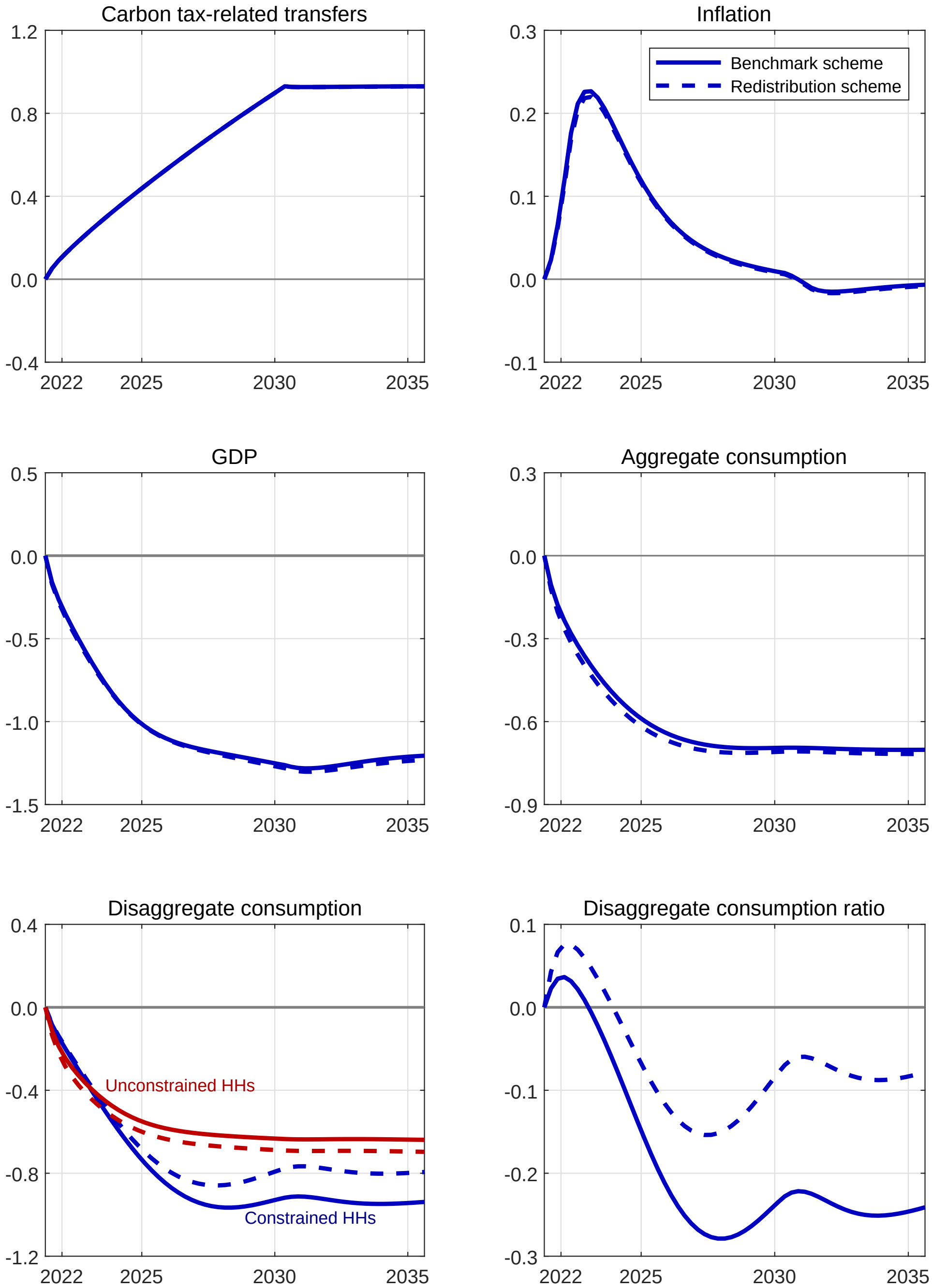
Note: This figure shows the dynamic responses of key sectoral variables to the central carbon tax transition scenario. Prices are expressed relative to consumer prices, while the marginal cost of intermediate-good production is expressed relative to intermediate-good prices. All dynamic responses are reported as percentage deviations from baseline values.

Figure 5: Monetary policy and the inflation-output trade-off



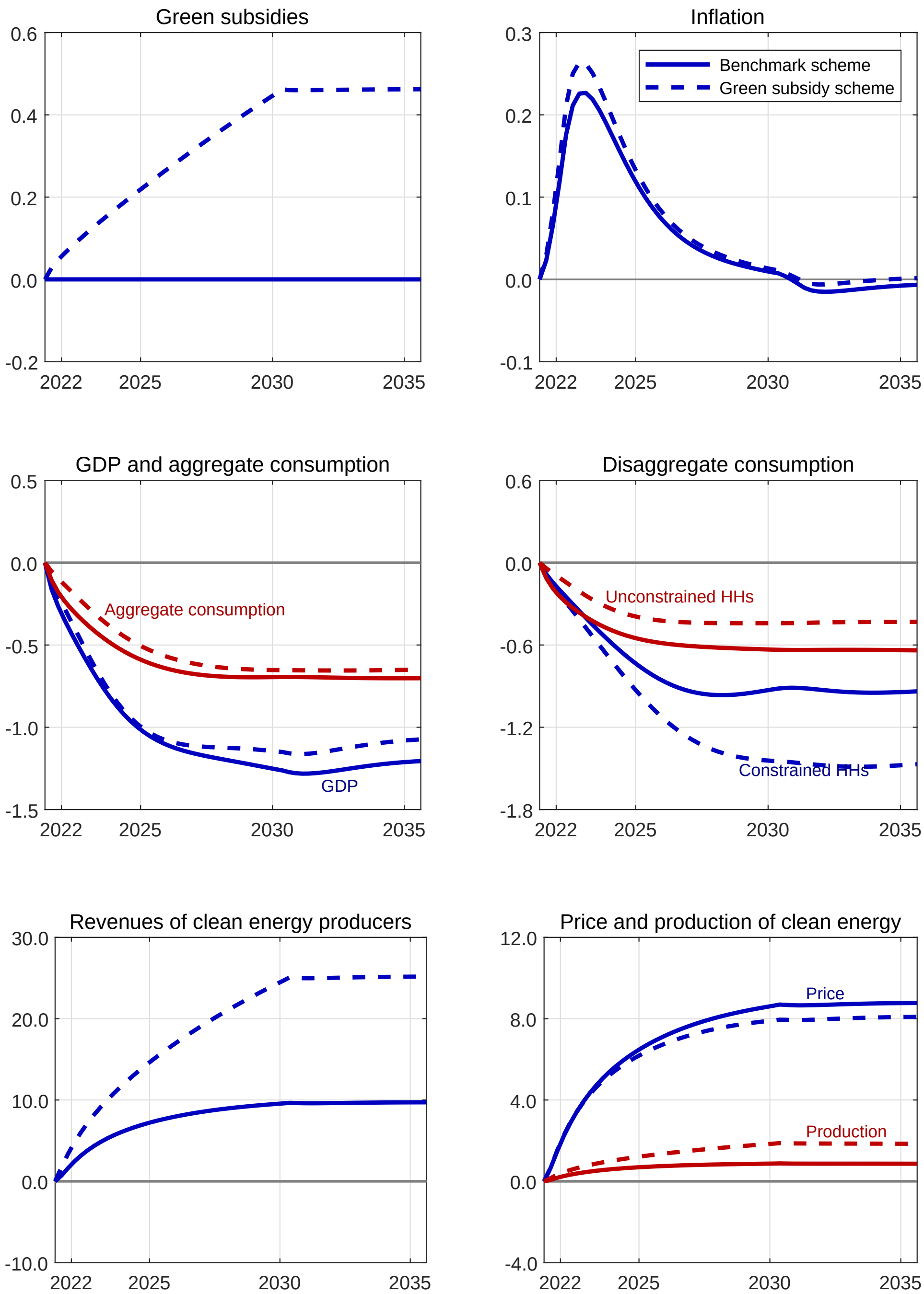
Note: This figure shows the dynamic responses of key aggregate variables to the carbon tax transition scenario for alternative specifications of the monetary policy rule. Inflation is measured as the annual rate of change in consumer prices, and the nominal and real interest rates are annualised. The output gap is measured as the deviation of GDP from trend GDP and expressed as a percentage of trend GDP. All dynamic responses are reported as percentage deviations from baseline values, except for the dynamic responses of inflation and interest rates, which are reported as percentage-point deviations.

Figure 6: Distributional impacts of transfers to households



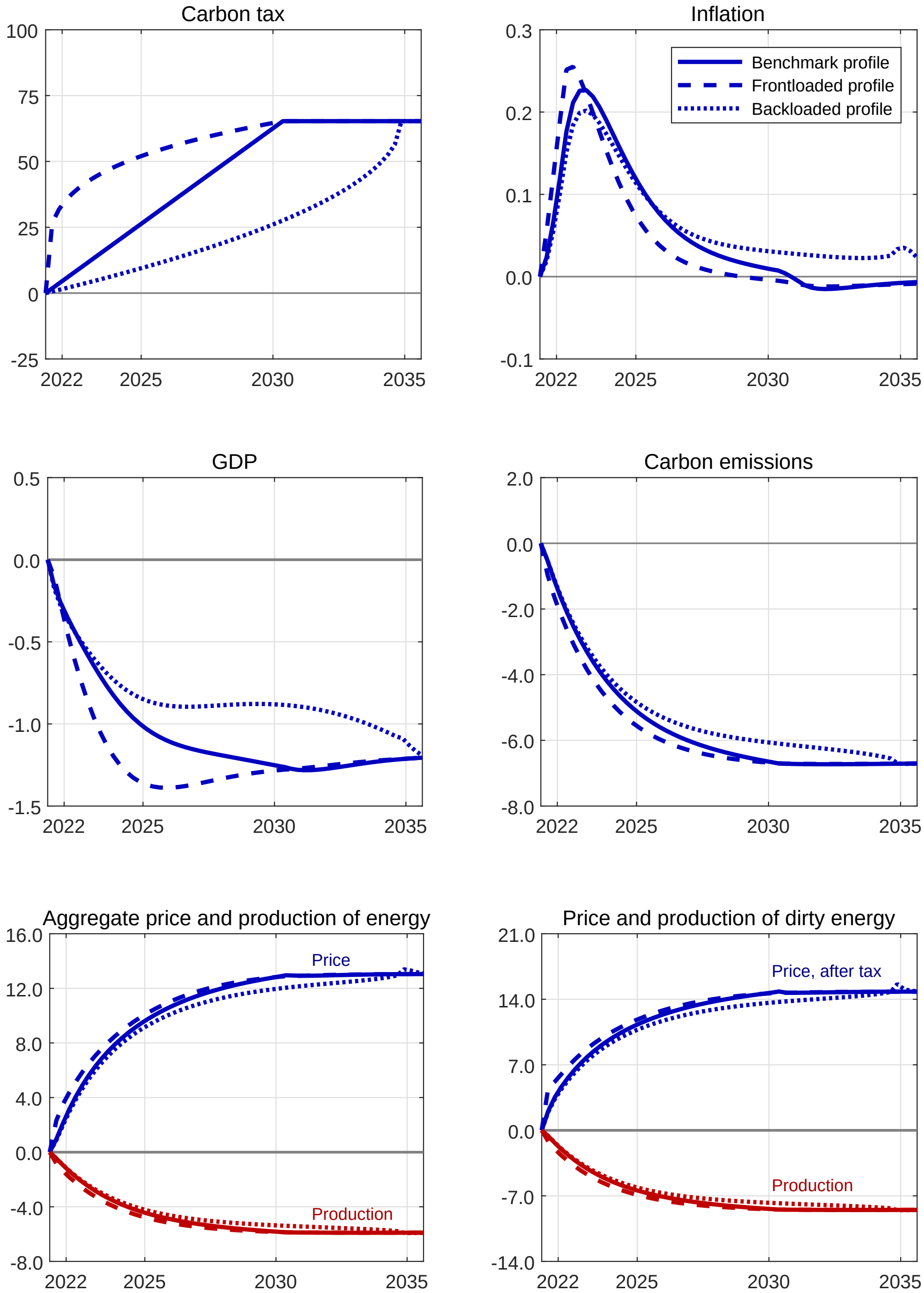
Note: This figure shows the dynamic responses of key aggregate and disaggregate variables to the carbon tax transition scenario for alternative specifications of the carbon tax-related transfer scheme. Inflation is measured as the annual rate of change in consumer prices, and the carbon tax-related transfers are expressed as a share of GDP. The disaggregate consumption ratio is measured as the consumption level of constrained households over the consumption level of unconstrained households. All dynamic responses are reported as percentage deviations from baseline values, except for the dynamic responses of inflation, the transfer-to-GDP ratio and the consumption ratio, which are reported as percentage-point deviations.

Figure 7: Impacts of subsidies to clean energy producers



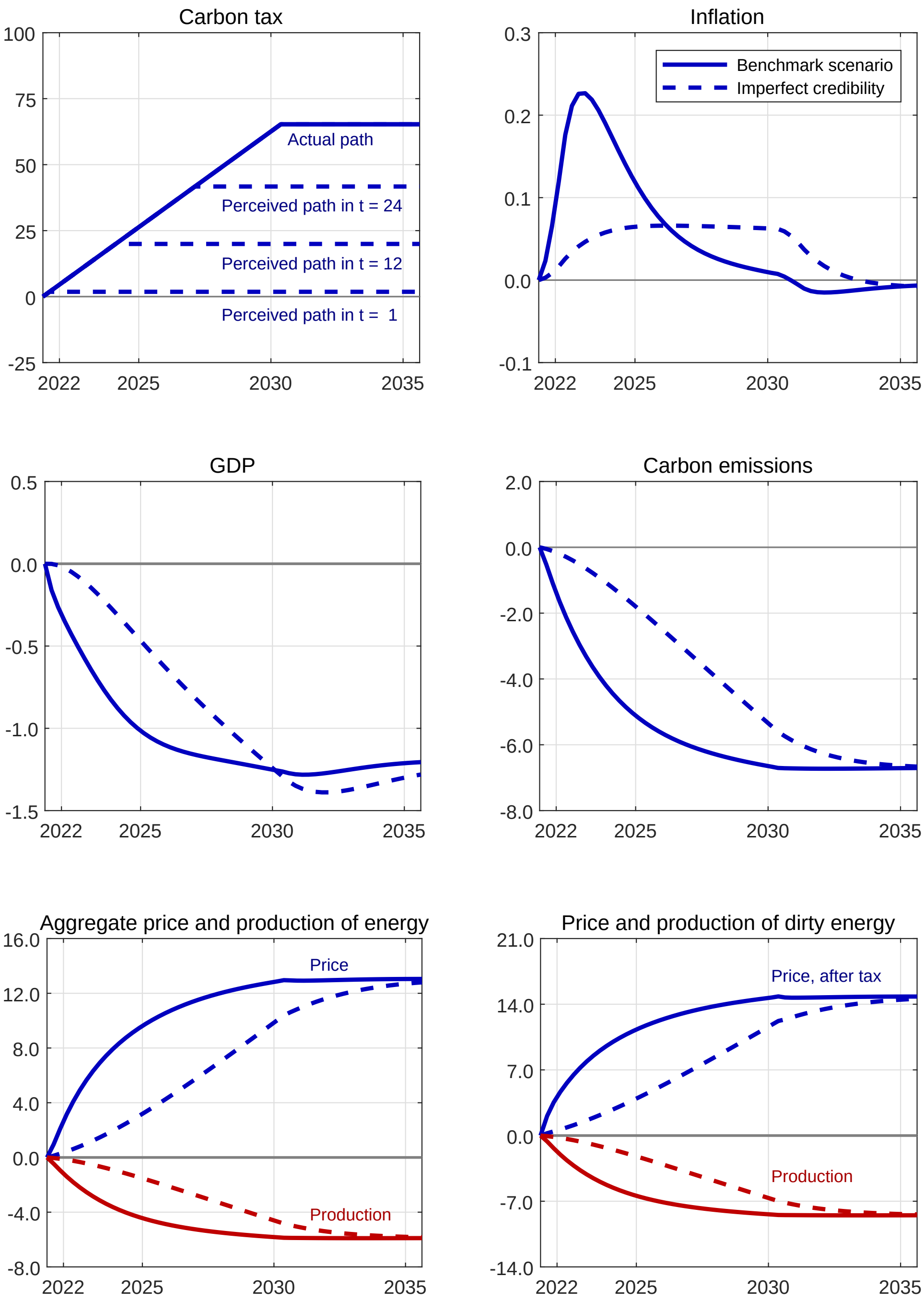
Note: This figure shows the dynamic responses of key aggregate, disaggregate and sectoral variables to the carbon tax transition scenario when half of the carbon tax-related transfers are paid as "green" subsidies to clean energy producers. Inflation is measured as the annual rate of change in consumer prices. The subsidies are expressed as a share of GDP, and the price of clean energy is expressed relative to consumer prices. All dynamic responses are reported as percentage deviations from baseline values, except for the dynamic responses of inflation and the subsidy-to-GDP ratio, which are reported as percentage-point deviations.

Figure 8: Implications of alternative carbon tax paths



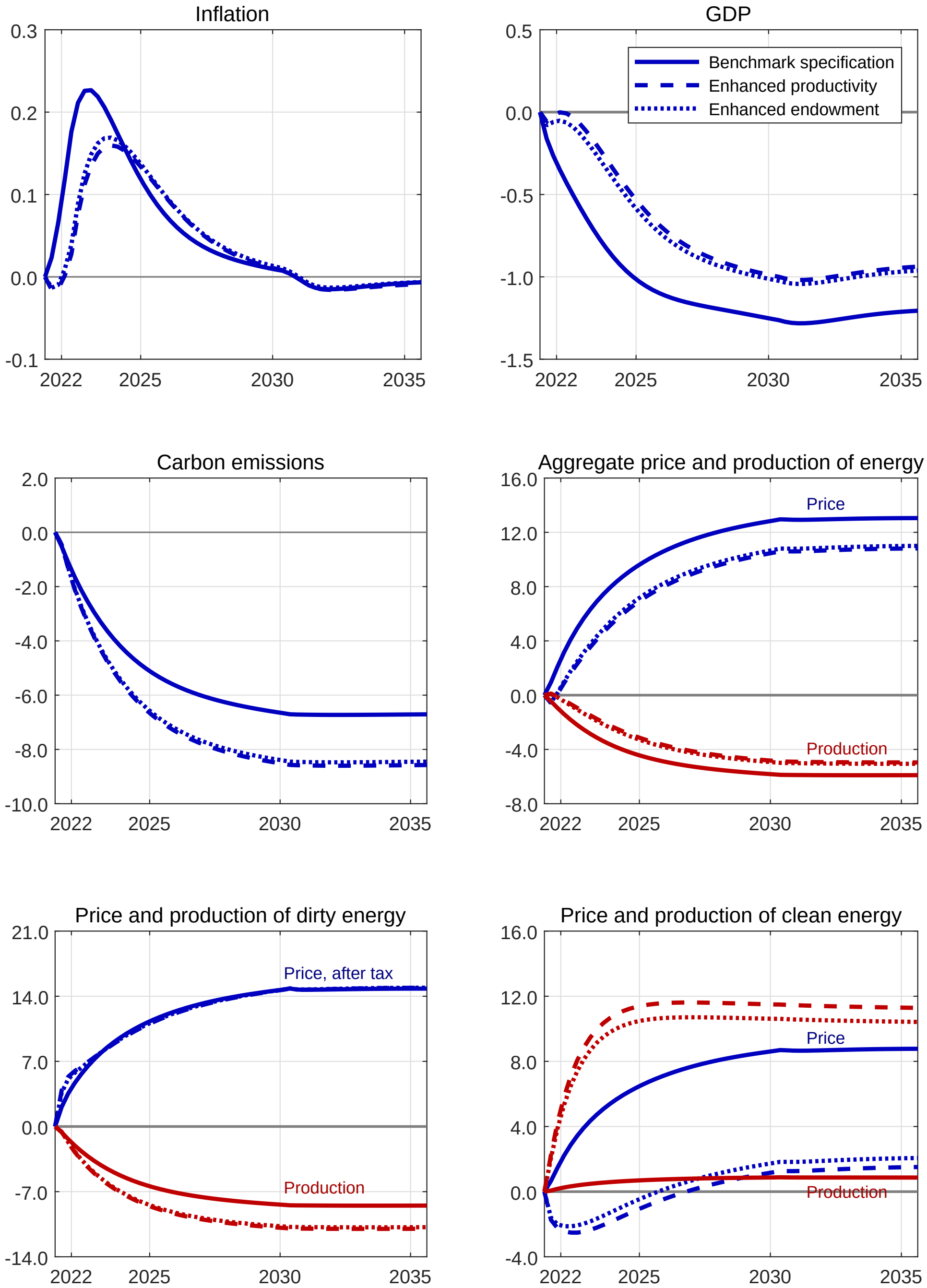
Note: This figure shows the dynamic responses of key aggregate and sectoral variables to the carbon tax transition scenario for alternative profiles of the carbon tax increase. Inflation is measured as the annual rate of change in consumer prices, and aggregate and dirty energy prices are expressed relative to consumer prices. All dynamic responses are reported as percentage deviations from baseline values, except for the dynamic responses of inflation, which are reported as percentage-point deviations.

Figure 9: Implications of imperfect credibility



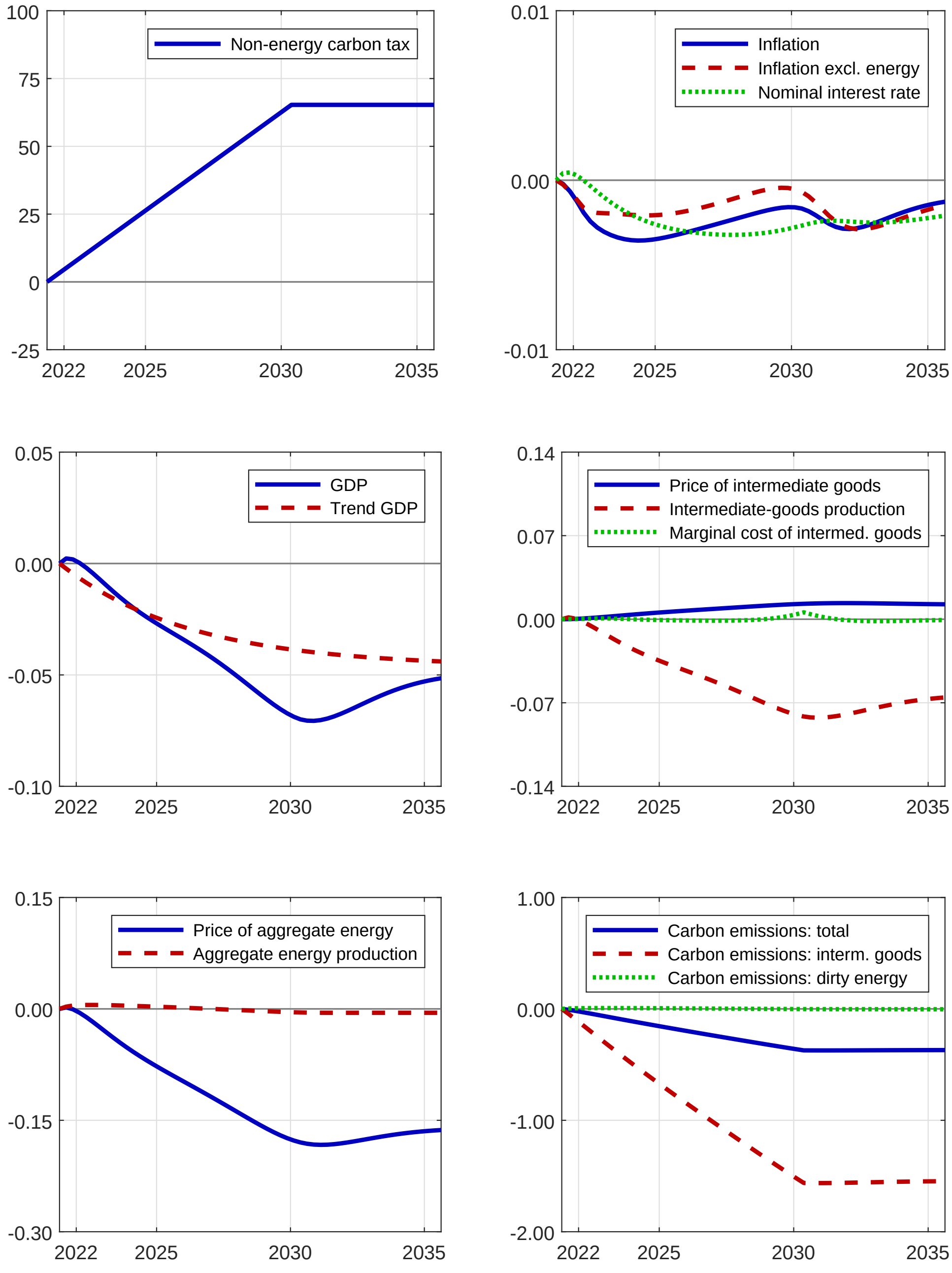
Note: This figure shows the dynamic responses of key aggregate and sectoral variables to the carbon tax transition scenario when the announced path for the carbon tax is imperfectly credible, with agents incrementally adjusting their perception of the expected future tax path period by period. Inflation is measured as the annual rate of change in consumer prices, and aggregate and dirty energy prices are expressed relative to consumer prices. All dynamic responses are reported as percentage deviations from baseline values, except for the dynamic responses of inflation, which are reported as percentage-point deviations.

Figure 10: Enhancing the supply of clean energy



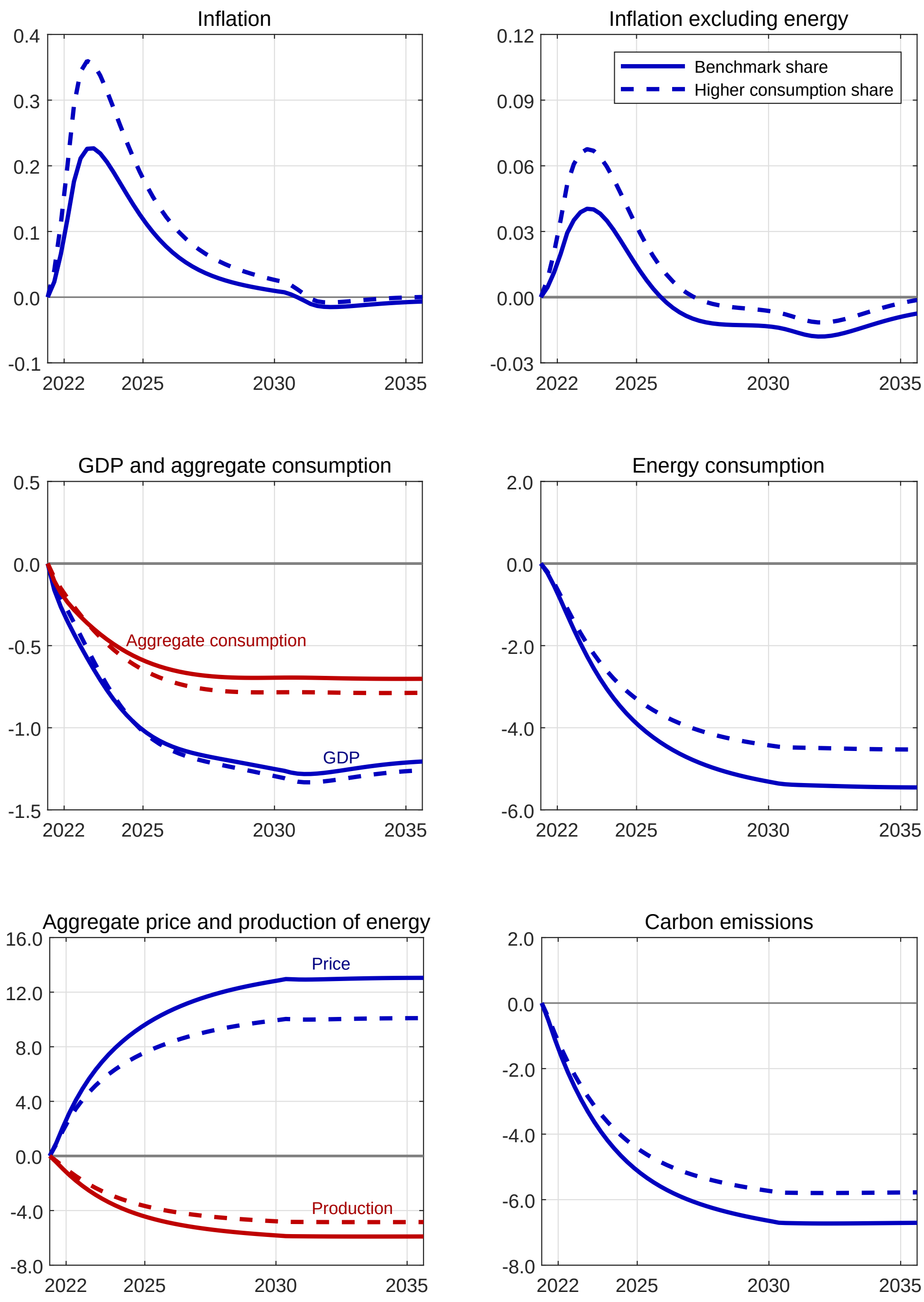
Note: This figure shows the dynamic responses of key aggregate and sectoral variables to the carbon tax transition scenario when the supply of clean energy is enhanced through higher productivity or a larger endowment of green resources, where either productivity or the endowment is raised by 10%. Inflation is measured as the annual rate of change in consumer prices, and all prices are expressed relative to consumer prices. All dynamic responses are reported as percentage deviations from baseline values, except for the dynamic responses of inflation, which are reported as percentage-point deviations.

Figure 11: The role of the abatement channel



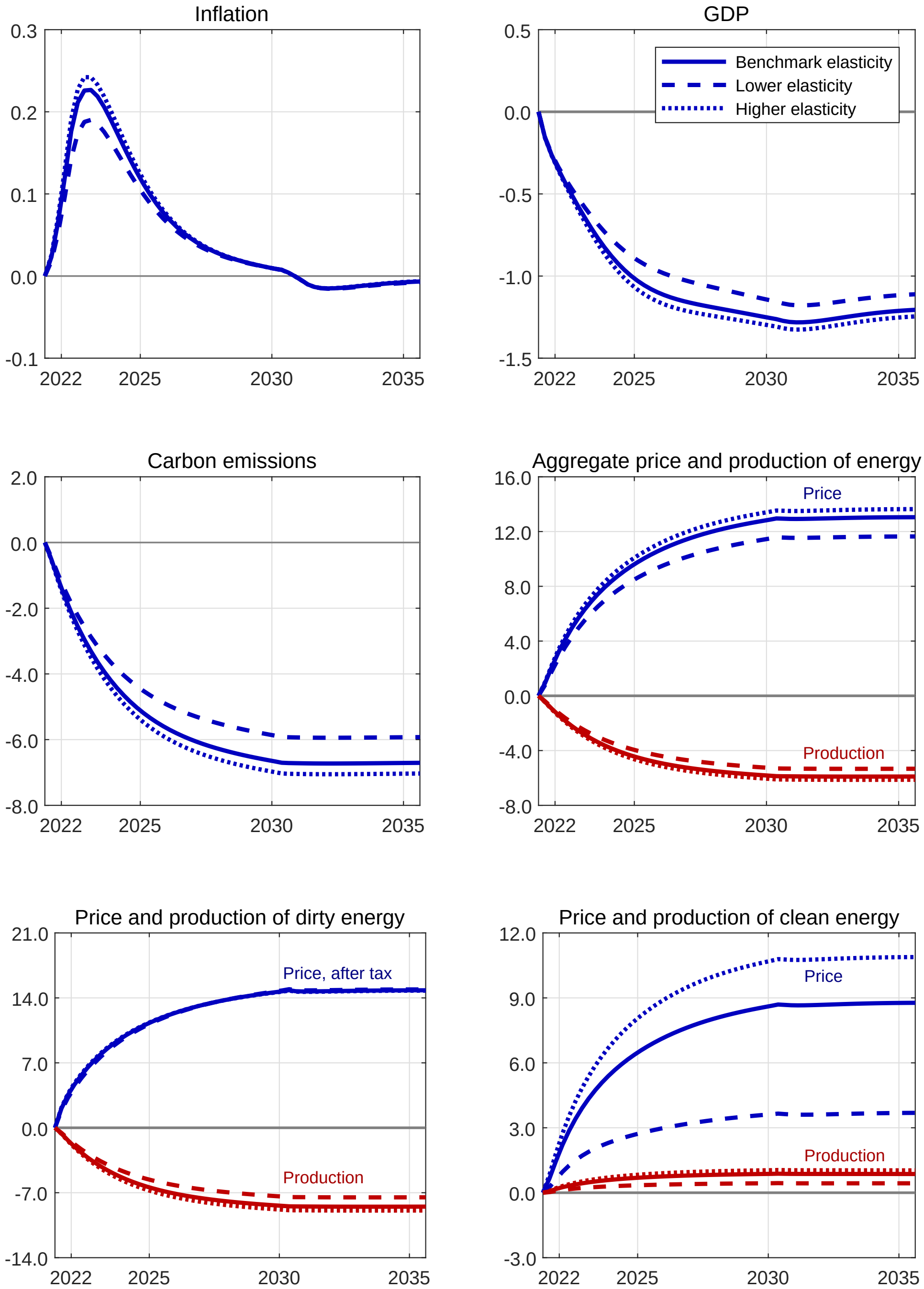
Note: This figure shows the dynamic responses of key aggregate and sectoral variables to an increase in the non-energy carbon tax rate when the abatement channel is active. Inflation is measured as the annual rate of change in consumer prices, and the nominal interest rate is annualised. All prices are expressed relative to consumer prices, while marginal cost is expressed relative to intermediate-goods prices. All dynamic responses are reported as percentage deviations from baseline values, except for the dynamic responses of inflation and the interest rate, which are reported as percentage-point deviations.

Figure A.1: The share of energy in final consumption



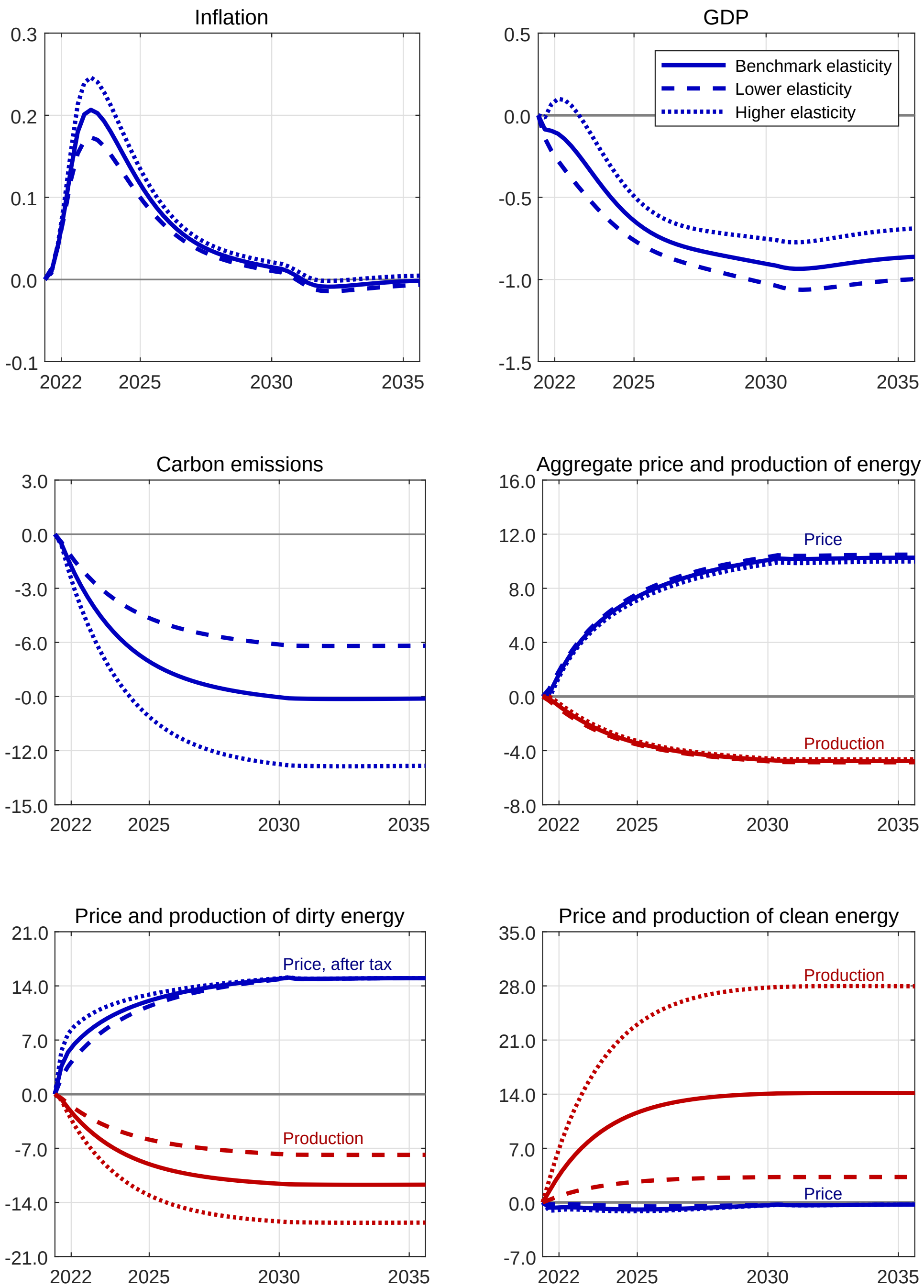
Note: This figure shows the dynamic responses of key aggregate and sectoral variables to the central carbon tax transition scenario for a higher share of energy in the final consumption good. Inflation is measured as the annual rate of change in consumer prices, and the nominal interest rate is annualised. The aggregate energy prices is expressed relative to consumer prices. All dynamic responses are reported as percentage deviations from baseline values, except for the dynamic responses of inflation and the interest rate, which are reported as percentage-point deviations.

Figure A.2: The substitutability of dirty and clean energy with fixed green resources



Note: This figure shows the dynamic responses of key aggregate and sectoral variables to the central carbon tax transition scenario for alternative values of the elasticity of substitution between dirty and clean energy in the production of aggregate energy when the supply of green resources is fixed. Inflation is measured as the annual rate of change in consumer prices, and all prices are expressed relative to consumer prices. All dynamic responses are reported as percentage deviations from baseline values, except for the dynamic responses of inflation, which are reported as percentage-point deviations.

Figure A.3: The substitutability of dirty and clean energy with adjustable green resources



Note: This figure shows the dynamic responses of key aggregate and sectoral variables to the central carbon tax transition scenario for alternative values of the elasticity of substitution between dirty and clean energy in the production of aggregate energy when the supply of green resources adjusts so as to stabilise the relative green-resource price in the longer term. Inflation is measured as the annual rate of change in consumer prices, and all prices are expressed relative to consumer prices. All dynamic responses are reported as percentage deviations from baseline values, except for the dynamic responses of inflation, which are reported as percentage-point deviations.

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