ENERGY AND CLIMATE POLICY IN A DSGE MODEL OF THE UNITED KINGDOM

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Abstract

We build an open economy Dynamic Stochastic General Equilibrium model with energy and use it to simulate the impact of different climate policies – specifically the introduction of a carbon tax and bans on petrol or gas usage by households – on macroeconomic variables. We show how the introduction of a carbon tax leads to falls in both households' consumption of energy and firms' use of energy in production, while also having the effect of shifting the production of electricity from fossil fuels to renewable sources. The effects of a ban on household consumption of petrol or gas depend crucially on the elasticity of substitution between different energy sources in consumption. For very low elasticities of substitution, a ban on petrol or gas usage also led households to cut down on their use of electricity, whereas for larger elasticities of substitution, households switched into electricity. Regardless of the elasticity of substitution, aggregate consumption fell on impact in response to the bans before rising over time. GDP and the gross output of non-energy fall in response to both a carbon tax and a ban on petrol or gas consumption by households. Finally, both policies result in a temporary increase in inflation and a tightening in monetary policy.

Classification: Q28, Q38, Q43, Q48, Q58, E32

Keywords: Climate Change, Dynamic Stochastic General Equilibrium, Carbon Tax, Climate policy, Energy, Energy policy, Renewable energy, Macroeconomics, UK economy

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1 Introduction and motivation

With the Paris agreement, signed in December 2015, governments around the world committed to reducing anthropogenic greenhouse gas (GHG) emissions in order to limit temperature increases to 2º C, and as close as possible to 1.5º C, relative to the pre-industrial average. Several countries and jurisdictions, including the United States, United Kingdom, European Union, and Japan, have also set ambitious 'net zero' targets for all GHG by 2050.[1] Such ambitious climate policies could have significant effects on the macroeconomy, and could therefore have implications for monetary policy. More specifically, the introduction of a carbon tax designed to discourage the use of fossil fuel could result in a period of higher energy costs for households and businesses, and change their consumption and production behaviour, affecting both aggregate demand and aggregate supply in the economy. Similarly, regulation to promote renewable fuels will affect the relative price of different energy sources and could stimulate investment in green energy and technology, increasing aggregate demand and possibly boosting aggregate supply through an increase in the capital stock and innovation.[2]

This paper contributes to the emerging literature that quantifies the impact of climate change policy on the macroeconomy in the contest of a Dynamic Stochastic General Equilibrium (DSGE) model. We build a DSGE model of a small open economy and calibrate it on UK data to investigate the potential impact of two policies that the UK government could introduce, to aid the transition to net zero emissions, on the UK macroeconomy. The model includes a comprehensive treatment of energy markets that accounts for energy services both in households' consumption and in firms' production in different ways. We believe our framework to be a realistic set up for modelling the effects of energy and other climate policies that seek to bring about a transition to net zero emissions through several different channels: (1) petrol being replaced by electricity in transport services for household consumption; (2) natural gas for domestic heating purposes being replaced by electricity in households' consumption; and (3) natural gas being replaced by renewable sources in the production of electricity.

Two additional features characterise our modelling approach. First, we do not explicitly model the climate externality included in standard climate-economy models that originates from fossil fuel combustion and the resulting concentration of GHG in the atmosphere. Our model represents a small economy, with a negligible share of global emissions, and therefore any domestic climate policy would have a very small impact on the stock of global emissions. Moreover, the time horizon we consider corresponds to business cycle frequencies, over which climate policy is unlikely to affect global GHG concentrations and the resulting damage from climate change. In our model, climate policy is exogenously determined based on scientific principles that align with the Paris Agreement. More specifically, a net zero target by 2050 is informed by the need to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" stipulated by Article 4.1 of the Paris Agreement (UNFCCC 2015). Second, our

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[1] At the time of writing, 97 parties, representing 101 countries and 80.7 per cent of global GHG emissions, had communicated a net-zero target Net-zero Target Status | Net-Zero Targets | Climate Watch (climatewatchdata.org).

[2] Previous work by Batten (2018), Batten *et al.* (2016, 2018 and 2020) and Angeli *et al.* (2022) describes the transmission channels of climate policy to the different components of aggregate demand and supply, as well as emerging evidence of these impacts and their possible implications for monetary policy.

modelling strategy reflects the geographical separation between climate objective and climate policy: while the Paris Agreement sets a global objective, action to achieve that objective occurs at the national level: each individual country is responsible for setting its own climate policies to achieve this goal, and the delivery of these policies takes place at the local level. While the physical impacts of climate change occur on a global scale over a long time horizon, and therefore modelling them at a global level is appropriate, the design, implementation and impact of climate change policies occur predominantly at the national level, and their impact is best modelled at the level of a single economy.[3] In this paper, we focus on a specific country – the United Kingdom – with a well-developed climate policy framework.[4] To our knowledge, this is the first paper that models the macroeconomic effects of climate policies that could be implemented to meet the UK net zero target, through the lens of a New Keynesian (NK) DSGE model.[5]

We consider two climate policies that seek to move the economy to net zero. First, we model the introduction of a carbon tax on the two fossil fuels, petrol and gas, included in our model. We then look at the effects of outright bans on their use by households, where the bans are assumed to be unanticipated and immediate. In the model, the introduction of a carbon tax leads to falls in both households' consumption of energy and firms' use of energy in production, while also having the effect of shifting the production of electricity from fossil fuels to renewable sources. The effects of a ban on household consumption of petrol or gas, on the other hand, depend crucially on the elasticity of substitution between different energy sources in consumption. For very low elasticities of substitution, a ban on petrol or gas usage also led households to cut down on their use of electricity, whereas for larger elasticities of substitution, households switched into electricity. Regardless of the elasticity of substitution, aggregate consumption fell on impact in response to the bans before rising over time. GDP and the gross output of non-energy fall in response to both a carbon tax and a ban on petrol or gas consumption by households. Finally, both policies result in a temporary increase in inflation and a tightening in monetary policy.

The rest of the paper is organised as follows. In section 2 we discuss the related literature. We describe the model in section 3 and discuss the data we use to calibrate it in section 4. Section 5 discusses our results and section 6 presents our conclusions and next steps.

2 Related literature

This paper contributes to the growing literature that assesses the impact of climate policy on the macroeconomy in a general equilibrium setting. The impact of climate policies can be studied through simulations in climate-economy models such as the Integrated Assessment Models (IAMs), in particular those including a dynamic computable general equilibrium (CGE) economic module, such as Hassler and Krusell (2018) and McKibbin *et al.* (2009), and those that include frictions typical

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[3] Annicchiarico and Dilusio (2019) investigate the international transmission of economic shocks in a two-country DSGE model under different environmental policy regimes.

[4] In the Appendix, we discuss climate policy in detail, including net zero targets in the UK and across the world.

[5] Few studies focus on the impact of the Paris Agreement on a single country. Examples include McFarland *et al.* (2018) for the US and Weng *et al.* (2018) for China. See Liu *et al.* (2020) for a review.

of DSGE models, such as Golosov *et al.* (2014) and van der Ploeg and Rezai (2021).[6] Results from these models vary greatly and are strongly dependent on the model's assumptions.

Using the macroeconomic model NiGEM extended to include climate change, Holland and Whyte (2021) find that an unexpected increase in the carbon tax raises the average price of primary fuel inputs, permanently reducing output unless fully offset by energy efficiency gains. The introduction of a carbon tax also drives inflation temporarily higher. McKibbin *et al.* (2009) examine how climate policy affects the transmission of macroeconomic shocks – specifically, a shock to productivity growth in less-developed countries and a 'financial crisis shock' – through the economy using G-Cubed, a multicounty, multisector hybrid DSGE/CGE model (McKibbin and Wilcoxen, 1999, 2013). The authors find that a global 'cap and trade' regime significantly changes the way growth shocks are transmitted between regions, while price-based systems – such as a global carbon tax – do not. This is because the rigid quantity-based system (i.e., 'cap-and-trade') leads to large variations in the price of carbon, which then leads to large variations in other macroeconomic variables. McKibbin *et al.* (2020) observe that the short-run effects of climate policies on macroeconomic variables depend on the response of monetary policy. Using the E3 climate model, Goulder *et al.* (2019) find that a $40 per ton carbon tax increasing at 2 per cent annually leads to GDP costs of less than one-third of a percent.

The NK e-DSGE modelling approach represents a promising alternative tool for environmental policy analysis.[7] Annicchiarico and Di Dio (2015) build a closed economy NK model that includes emissions, abatement technology and environmental damage, as well as frictions, to explore the role of nominal rigidities in shaping the macroeconomic performances of different environmental policy regimes, whereas Annicchiarico and Di Dio (2017) study the optimal environmental and monetary policy mix in the presence of economic frictions. Xiao *et al.* (2018) employ a NK e-DSGE framework embodying nominal price rigidities, environmental policies, emissions, as well as real uncertainties and energy efficiency, to compare the impacts of different environmental policies on macroeconomic fluctuations. Argentiero *et al.* (2018) compare the effectiveness of two policies promoting renewable energy investment: an R&D subsidy (technology push) and a price subsidy (demand pull). Chen *et al.* (2021) extend the standard NK e-DSGE model by adding concealed emissions and the stringency of climate policy enforcement. [8]

Our model includes a fuller treatment of energy markets compared with most e-DSGE models, since it includes energy in household's consumption, as well as input in final goods production. It also includes a more detailed treatment of financial markets by adding bonds, money and inflation. In this sense, it is close to the recent literature on the impact of energy shocks and energy transition policies in a DSGE setting. Punzi (2019), for example, examines the impact of increases in energy prices and their volatility on GDP and the business cycle in a small open economy DSGE model, and find that energy shocks exacerbate macroeconomic fluctuations. Zhang *et al.* (2021) build a DSGE model of the Chinese economy to investigate the effect of a policy aimed at reducing Chinese coal capacity. Diluiso *et al.* (2021) estimate a DSGE model for the Euro Area which features the production of low

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[6] This section discusses the modelling of general climate policy. Studies that assess the impact of the Paris agreement specifically are summarised in Liu *et al.* (2020).

[7] Early e-DSGE models, such as Fischer and Springborn (2011), Heutel (2012) and Angelopoulos *et al.* (2013), were based on a Real Business Cycle framework with flexible prices. Fischer and Heutel (2013) offer a comprehensive review of these models.

[8] See Annicchiarico *et al.* 2022 for an extensive literature review of DSGE models, including their NK extensions.

carbon and fossil fuel energy and their use as input in businesses' production function. The authors assess the impact of two different carbon transition paths on macroeconomic and price stability.

Our paper builds on previous work that models energy shocks in a DSGE model of the UK economy. Harrison *et al.* (2011) look at the effects of permanent energy price shocks on the UK economy and show that such shocks have important implications for monetary policy. Millard (2011) considers the implications of an estimated version of that model for the responses of various macroeconomic variables to different economic shocks and decomposes movements of energy and non-energy output and inflation into the proportions caused by each of the shocks.

In this paper, we enrich the treatment of energy services in the model.[9] More specifically, we separate the electricity and gas services used in consumption and as inputs in production. We also allow for electricity to be produced using either fossil fuels (natural gas) or renewable sources. This enables us to examine the effects of imposing a tax on the carbon emissions resulting from the use, in consumption and production, of the two types of fossil fuels in our model – oil (petrol) and natural gas – as well as the effects of imposing an outright ban on their use. The model we develop is designed to simulate the impact of different climate policies on the UK economy. We start by modelling the effects of a carbon tax on the economy and monetary policy. We then consider the effects of a surprise announcement permanently banning the use of fossil fuel by households.

A small but expanding set of empirical studies on the impact of past climate policies on the macroeconomy also informs and motivates our work. Metcalf and Stock (2020, 2023) analyse the effects of carbon taxes across 31 European countries and find no evidence that carbon taxes have had a negative effect on GDP growth or employment. Känzig (2022) finds that higher carbon prices in the EU Emission Trading Scheme (ETS) led to a temporary but substantial fall in economic activity while Känzig and Konradt (2023) find that the economic cost of the EU ETS are larger than those of carbon taxes. Calel and Dechezleprêtre (2016) conclude that the EU ETS increased low-carbon innovation among regulated firms by as much as 10 per cent.

Evidence on the impact of Canada's carbon tax, mostly based on the experience of British Columbia (BC) also suggests the lack of statistically significant impacts of the tax on GDP. Elgie and McClay (2013) and Elgie (2014) use a difference-in-differences approach to analyse the impact of BC's carbon tax on GDP and find that BC's GDP per capita outperformed the rest of Canada's over the period 2008 – 2013. Metcalf (2019) finds no adverse GDP impacts of BC's carbon tax based on a difference-in-differences analysis of a panel of Canadian provinces over the period 1990 – 2016. Bernard *et al.* (2018) estimate a VAR model using monthly data for BC from January 1987 to December 2016, and find no impact of the carbon tax on GDP.

The BC experiment was also found to have labour market effects. Yamazaki (2017) distinguished two channels through which a carbon tax can affect employment: (1) the *output effect* increases costs and discourages employment, and (2) the *redistribution effect* stimulates demand when carbon tax revenues are returned to businesses and households. In this study, based on a panel of industries across Canadian provinces, the author finds that the output effect reduced employment, while the redistribution effect increased it, leading to a small positive and statistically significant increase in

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[9] See e.g. the WITCH model of Bosetti *et al.* (2007, 2008, 2009) for a full bottom-up treatment of different types of fuels in IAMs.

employment. The introduction of the carbon tax also reduced average hourly and weekly wages by 1.8 and 1.6 per cent respectively per C$10/t CO2 equivalent. Moreover, jobs shifted from carbon-intensive sectors to non-carbon-intensive sectors. Using individual data from the Canadian monthly labour force survey, Yip (2018) finds that BC's carbon tax added 1.2 to 1.3 percentage points to the unemployment rate. The author also finds no impact on working hours or on the labour force participation rate. Overall, while the estimated empirical effects of carbon policies on macroeconomic variables might be small, the historical carbon prices on which these studies are based tend to be below the level required for a meaningful transition to net zero.

3 The model

In this section, we develop a model of a small open economy with four sectors: households, firms, the government and a monetary authority. The model extends that of Harrison *et al.* (2011) in ways that enable us to examine the effects on the economy of a carbon tax and carbon regulation. Households maximise their utility subject to their budget constraint. They consume petrol, gas, electricity and a 'non-energy good' and supply labour to firms. Non-energy goods producers combine labour, capital, imported intermediates, electricity, gas and petrol to produce their output, which they sell in a monopolistically-competitive market.

Electricity producers combine labour, capital and gas to produce their output. The households are endowed with gas and petrol; we think of this as capturing reserves of North Sea oil and gas, though we do not model the extraction process.[10] Any gas and petrol required by firms over and above this endowment is imported. The government finances its (exogenous) spending needs by taxing carbon emissions and by imposing lump-sum taxes on households. The central bank operates a Taylor rule. In what follows, we describe the problems faced by each of the agents in our model.

3.1 Households

The representative household consumes four final goods: petrol, gas, electricity and 'non-energy' goods. Aggregate consumption, *c*, is given by:

$$c_t = \left(\psi_e^{\frac{1}{\sigma_{en}}} c_{en,t}^{1-\frac{1}{\sigma_{en}}} + (1-\psi_e)^{\frac{1}{\sigma_{en}}} c_{n,t}^{1-\frac{1}{\sigma_{en}}} \right)^{\frac{\sigma_{en}}{\sigma_{en}-1}} \quad \textbf{(1)}$$

Where c denotes aggregate consumption, c_{en} denotes consumption of 'energy' and c_{n} denotes consumption of 'non-energy'. Consumption of energy itself is an aggregate of consumption of petrol (ie, oil), c_{p}, gas, c_{g}, and electricity, c_{e}:

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[10] We also abstract from resource constraints and assume that fossil fuels are a non-exhaustible resource at the global level, unlike, e.g., Golosov *et al.* (2014) or Smulders *et al.* (2014). This assumption is consistent with the objective of the Paris agreement of reducing emissions from fossil fuels. McGlade and Etkins (2015), for example, estimate that, in order to limit temperature increases to 2º C, around 33 per cent of oil, 49 per cent of gas, and 82 per cent of coal reserves would need to remain in the ground, even under the assumption that Carbon Capture and Storage (CCS) technology becomes widely used from 2025 onwards, if the cost of CCS remains high.

$$c_{en,t} = \left(\psi_p^{\frac{1}{\sigma_p}} c_{p,t}^{1-\frac{1}{\sigma_p}} + \psi_g^{\frac{1}{\sigma_p}} c_{g,t}^{1-\frac{1}{\sigma_p}} + \left(1 - \psi_p - \psi_g\right)^{\frac{1}{\sigma_p}} c_{e,t}^{1-\frac{1}{\sigma_p}} \right)^{\frac{\sigma_p}{\sigma_{p-1}}} \quad \textbf{(2)}$$

We let the 'non-energy' good be the numeraire and we can then define the consumer price index as the minimum level of expenditure required to obtain one unit of the aggregate consumption good. That is, we solve the problem:

Minimise $P_t c_t = c_{n,t} + \left(P_{p,t} + \tau_C \varpi_{p,c}\right) c_{p,t} + \left(P_{g,t} + \tau_C \varpi_{g,c}\right) c_{g,t} + P_{e,t} c_{e,t}$ **(3)**

Subject to equations **(1)** and **(2)**. Here P denotes the aggregate consumer price index, P_{p} denotes the price of petrol, P_{g} denotes the price of gas and P_{e} denotes the price of electricity. Here τ_{c} denotes the carbon tax – denoted in pounds sterling per ton of carbon – which households (and firms) pay on their consumption of petrol and gas; $\varpi_{p,c}$ denotes the amount of carbon emissions associated with households consuming one unit of petrol; and $\varpi_{g,c}$ denotes the amount of carbon emissions associated with households consuming one unit of gas.

The first-order conditions for this problem imply:

$$\frac{1}{(1-\psi_e)^{\frac{1}{\sigma_{en}}}} \left(\frac{c_t}{c_{n,t}}\right)^{-\frac{1}{\sigma_{en}}} = P_t \quad \textbf{(4)}$$

$$\psi_e^{\frac{-1}{\sigma_{en}}} \left(\frac{c_t}{c_{en,t}}\right)^{-\frac{1}{\sigma_{en}}} \psi_p^{\frac{-1}{\sigma_p}} \left(\frac{c_{en,t}}{c_{p,t}}\right)^{-\frac{1}{\sigma_p}} = \frac{P_t}{P_{p,t} + \tau_C \varpi_{p,c}} \quad \textbf{(5)}$$

$$\psi_e^{\frac{-1}{\sigma_{en}}} \left(\frac{c_t}{c_{en,t}}\right)^{-\frac{1}{\sigma_{en}}} \psi_g^{\frac{-1}{\sigma_p}} \left(\frac{c_{en,t}}{c_{g,t}}\right)^{-\frac{1}{\sigma_p}} = \frac{P_t}{P_{g,t} + \tau_C \varpi_{g,c}} \quad \textbf{(6)}$$

$$\psi_e^{\frac{-1}{\sigma_{en}}} \left(\frac{c_t}{c_{en,t}}\right)^{-\frac{1}{\sigma_{en}}} \frac{1}{(1-\psi_p-\psi_g)^{\frac{1}{\sigma_p}}} \left(\frac{c_{en,t}}{c_{e,t}}\right)^{-\frac{1}{\sigma_p}} = \frac{P_t}{P_{e,t}} \quad \textbf{(7)}$$

The household obtains utility from consumption and disutility from the amount of labour that it supplies to the firms. We further assume that the household owns the capital stock and makes decisions about capital accumulation. This assumption, now standard in the business cycle literature, is made to simplify the firms' decision problem. In addition, the household can also accumulate financial assets, specifically domestic and foreign nominal bonds.

We assume that the household is endowed with petrol and gas, where these endowments are given by $\bar{O}$ and $\bar{G}$, respectively. This reflects the presence of 'North Sea' oil and gas in the United Kingdom. As we move towards a 'net zero' world, households will gradually become unable to sell their endowments of petrol and gas. That is, these will then become 'stranded assets.' We can note that this way of modelling oil and gas follows previous work by Harrison *et al.* (2011) and Millard (2011). Bergholt *et al.* (2019) actually model the production of oil under the assumption that the oil producers have access to (effectively 'own') the oil reserves. We can think of our way of modelling oil as an endowment for the economy as being a 'reduced form' representation of oil companies owning the oil and households owning the oil companies. The key difference between our model and theirs is the assumption that no other resources are used up in the production of oil. We discuss this further in the context of our results below.

Finally, we have assumed that 'renewable energy' is not owned by anyone. That is, although the economy clearly has an endowment of wind, sunshine and water, no-one can buy and sell these. However, to convert these endowments into electricity requires capital and this is discussed later.

The representative household's problem is then to maximise their utility subject to their budget constraint. Mathematically:

Maximise $E_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{c_t^{1-\frac{1}{\sigma_c}}}{1-\frac{1}{\sigma_c}} - \kappa_h \frac{h_t^{1+\frac{1}{\sigma_h}}}{1+\frac{1}{\sigma_h}} \right)$ **(8)**

Subject to $B_t + \frac{B_{f,t}}{s_t} = (1+i_{t-1})B_{t-1} + \left(1+i_{f,t-1}\right)\frac{B_{f,t-1}}{s_t} + W_t h_t + r_{k,t}k_{t-1} - P_t c_t$ **(9)**

$$-I_t - \frac{\chi_{bf}B_{f,t}^2}{2s_t} + P_p\bar{O} + P_g\bar{G} + \Pi_t + T_t$$

And $k_t = (1-\delta)k_{t-1} + \left(1 - S\left(\frac{I_t}{I_{t-1}}\right)\right)I_t$ **(10)**

Where h denotes total hours worked, B denotes (end-of-period) holdings of domestic government bonds, B_f denotes (end-of-period) holdings of foreign government bonds, s denotes the nominal exchange rate (units of foreign currency divided by units of domestic currency), i denotes the domestic nominal interest rate, i_f denotes the foreign nominal interest rate, W denotes the nominal wage, k denotes the end-of-period capital stock and I denotes investment (both consisting of non-energy goods and so having a unit price), r_k is the real rental rate paid on capital, Π is total corporate sector profits (returned to the households lump sum) and T is a lump sum transfer from the government to the household sector. $S(\cdot)$ is an 'investment adjustment cost' function. Following the literature, we assume that $S(1) = S'(1) = 0$.

The first order conditions determine the household's choice of aggregate consumption and labour supply:

$$c_t^{-\frac{1}{\sigma_c}} = \beta(1+i_t)E_t \frac{c_{t+1}^{-\frac{1}{\sigma_c}}}{1+\pi_{t+1}} \qquad \textbf{(11)}$$

$$\frac{W_t}{P_t} = \kappa_h c_t^{\frac{1}{\sigma_c}} h_t^{\frac{1}{\sigma_h}} \qquad \textbf{(12)}$$

$$Q_t = \beta E_t \frac{c_{t+1}^{-\frac{1}{\sigma_c}}}{c_t^{-\frac{1}{\sigma_c}}(1+\pi_{t+1})}\left(r_{k,t+1} + Q_{t+1}(1-\delta)\right) \qquad \textbf{(13)}$$

$$1 = Q_t\left(1 - S\left(\frac{I_t}{I_{t-1}}\right) - S'\left(\frac{I_t}{I_{t-1}}\right)\frac{I_t}{I_{t-1}}\right) + \beta E_t \frac{c_{t+1}^{-\frac{1}{\sigma_c}}}{c_t^{-\frac{1}{\sigma_c}}(1+\pi_{t+1})} Q_{t+1} S'\left(\frac{I_{t+1}}{I_t}\right)\left(\frac{I_{t+1}}{I_t}\right)^2 \quad \textbf{(14)}$$

Where Q is the multiplier on the capital accumulation equation and, thus, represents the shadow value of capital and π denotes the rate of consumer price inflation.

Finally, we also obtain the modified uncovered interest parity condition:

$$E_t \frac{s_t}{s_{t+1}} = \frac{1+i_t}{1+i_{f,t}}\left(1 + \chi_{bf} B_{f,t}\right) \quad \textbf{(15)}$$

The portfolio adjustment cost term, $\chi_{bf} B_{f,t}$, ensures that the net foreign asset position of the economy is pinned down in steady state, thus closing the open-economy model by ensuring that the model has a steady-state solution (in this case with zero net foreign assets).

3.2 *Non-energy producers*

We assume a unit continuum of identical non-energy producers. The representative non-energy producer, firm j, say, has the following production function for its output q_j:

$$q_{j,t} = \left((1-\alpha_q)^{\frac{1}{\sigma_q}}\left(B_{j,t}\right)^{\frac{\sigma_q - 1}{\sigma_q}} + \alpha_q^{\frac{1}{\sigma_q}}\left(en_{j,t}\right)^{\frac{\sigma_q - 1}{\sigma_q}}\right)^{\frac{\sigma_q}{\sigma_q - 1}} \quad \textbf{(16)}$$

Where B_j denotes a ‘bundle’ of non-energy inputs and en_j denotes a ‘bundle’ of energy inputs. The non-energy bundle is given by:

$$B_{j,t} = A\left(k_{j,t}\right)^{\alpha_{k,q}} h_{j,t}^{1-\alpha_{k,q}-\alpha_B} M_{j,t}^{\alpha_B} \quad \textbf{(17)}$$

Where k_j denotes capital input, h_j denotes labour, M_j denotes intermediate imported goods.

The energy bundle is given by:

$$en_{j,t} = \left(\psi_{n,p}^{\frac{1}{\sigma_n}} I_{j,p,t}^{1-\frac{1}{\sigma_n}} + \psi_{n,g}^{\frac{1}{\sigma_n}} I_{j,g,t}^{1-\frac{1}{\sigma_n}} + \left(1 - \psi_{n,p} - \psi_{n,g}\right)^{\frac{1}{\sigma_n}} I_{j,e,t}^{1-\frac{1}{\sigma_n}}\right)^{\frac{\sigma_n}{\sigma_n - 1}} \quad \textbf{(18)}$$

where $I_{j,p}$ is the input of petrol, $I_{j,g}$ is input of gas and $I_{j,e}$ is input of electricity.

All firms in this sector face quadratic costs of adjusting prices à la Rotemberg (1982), with adjustment cost parameter χ. The profit maximisation problem for firm j will then be:

Maximise $E_0 \sum_{t=0}^{\infty} \beta^t \Bigg(P_{j,t} q_{j,t} - W_t h_{j,t} - r_{k,t} k_{j,t} - P_{m,t} M_{j,t} - \left(P_{p,t} + \tau_C \varpi_{p,q}\right) I_{j,p,t} -$
$\left(P_{g,t} + \tau_C \varpi_{g,q}\right) I_{j,g,t} - P_{e,t} I_{j,e,t} - \frac{\chi}{2}\left(\frac{P_{j,t}}{P_{j,t-1}} - 1\right)^2 q_t \Bigg)$

Subject to $q_{j,t} = \left(P_{j,t}\right)^{-\eta} q_t$ and equations **(16)**, **(17)** and **(18)**.

Here P_{j} is the price set by firm j, P_{M} denotes the domestic price of imported intermediates and q is aggregate non-energy output. Again, τ_{c} denotes the carbon tax – denoted in pounds sterling per ton of carbon – which firms pay on their consumption of petrol and gas; $\varpi_{p,q}$ denotes the amount of carbon emissions associated with non-energy goods producers using one unit of petrol; and $\varpi_{g,c}$ denotes the amount of carbon emissions associated with non-energy goods producers using one unit of gas. Note that since the non-energy good is the numeraire, P_{j} will also equal the price of firm j relative to the average price of non-energy goods.

Solving this problem, and integrating over all non-energy firms, implies the following demand curves for labour, capital, imports and energy:

$$w_t = \mu_t \left(1-\alpha_q\right)^{\frac{1}{\sigma_q}} \left(1-\alpha_{k,q}-\alpha_B\right) \left(\frac{q_t}{B_t}\right)^{\frac{1}{\sigma_q}} \frac{B_t}{h_{NE,t}} \tag{19}$$

$$\frac{r_{k,t}}{P_t} = \mu_t \left(1-\alpha_q\right)^{\frac{1}{\sigma_q}} \alpha_{k,q} \left(\frac{q_t}{B_t}\right)^{\frac{1}{\sigma_q}} \frac{B_t}{k_{NE,t}} \tag{20}$$

$$\frac{P_{M,t}}{P_t} = \mu_t \left(1-\alpha_q\right)^{\frac{1}{\sigma_q}} \alpha_B \left(\frac{q_t}{B_t}\right)^{\frac{1}{\sigma_q}} \frac{B_t}{M_t} \tag{21}$$

$$\frac{P_{p,t}+\tau_C \varpi_{p,q}}{P_t} = \mu_t \alpha_q^{\frac{1}{\sigma_q}} \psi_{n,p}^{\frac{1}{\sigma_n}} \left(\frac{q_t}{en_t}\right)^{\frac{1}{\sigma_q}} \left(\frac{en_t}{I_{p,t}}\right)^{\frac{1}{\sigma_n}} \tag{22}$$

$$\frac{P_{g,t}+\tau_C \varpi_{g,q}}{P_t} = \mu_t \alpha_q^{\frac{1}{\sigma_q}} \psi_{n,g}^{\frac{1}{\sigma_n}} \left(\frac{q_t}{en_t}\right)^{\frac{1}{\sigma_q}} \left(\frac{en_t}{I_{g.q,t}}\right)^{\frac{1}{\sigma_n}} \tag{23}$$

$$\frac{P_{e,t}}{P_t} = \mu_t \alpha_q^{\frac{1}{\sigma_q}} \left(1-\psi_{n,p}-\psi_{n,g}\right)^{\frac{1}{\sigma_n}} \left(\frac{q_t}{en_t}\right)^{\frac{1}{\sigma_q}} \left(\frac{en_t}{I_{e,t}}\right)^{\frac{1}{\sigma_n}} \tag{24}$$

where w denotes the real (producer) wage and μ denotes real marginal cost.

Finally, since all firms in this sector are identical, they will all set the same price (equal to unity in steady state as the non-energy good is our numeraire). So, taking a first-order approximation of their pricing equation around a zero-inflation steady state gives us the New Keynesian Phillips curve:

$$\pi_{n,t} = \frac{\eta-1}{\chi} \widehat{\mu_t} + \beta E_t \pi_{n,t+1} \tag{25}$$

where π_n is the rate of non-energy inflation and $\hat{\mu}$ denotes the log deviation of real marginal cost from its steady state value of $\frac{\eta-1}{\eta}$.

Figures 1 and 2 below show the structure of the consumption and non-energy production parts of the model.

Figure 1: Model structure for the household sector

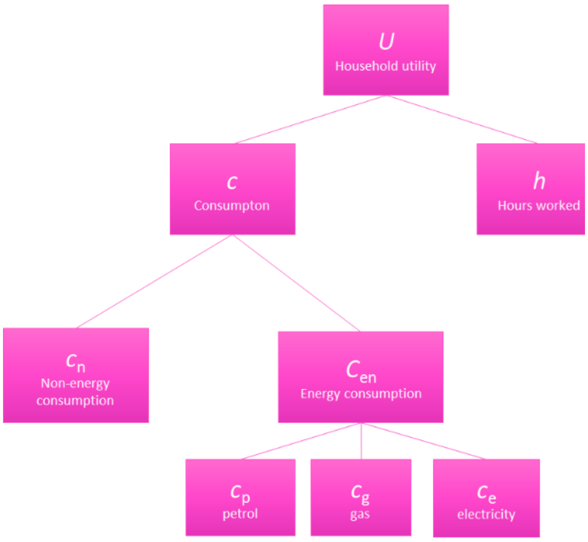
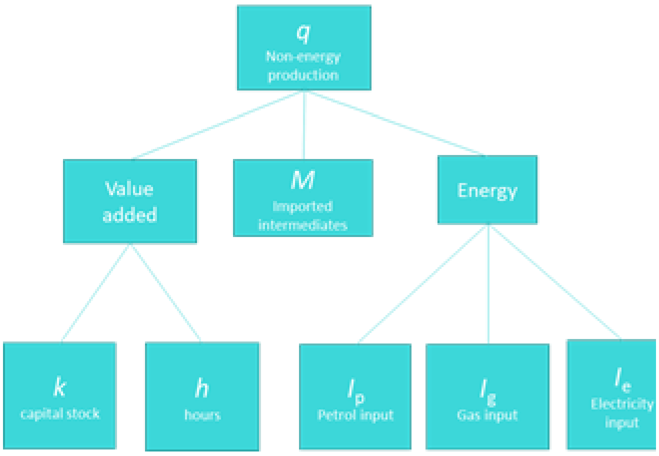


Figure 2: Model structure for non-energy producers



3.3 Electricity producers

We assume that electricity is produced in a perfectly-competitive market using labour, h_e, natural gas, $I_{g,e}$, and capital, k_e. We can think of the capital used by electricity producers as including the technology associated with renewables. That is, we assume the renewable energy sources are freely available and output of electricity depends on the labour and capital used in the renewables sector. Intuitively, the economy does not 'produce' sunlight or water, but it does need to produce and invest in the capital to turn sunlight or water into electricity. So, as electricity producers switch from using gas towards using renewables, this would show up in our model as them switching from using gas towards using capital. It is worth noting, however, that we do not assume any spill-over from investing in renewables technology to productivity in the rest of the economy. This means that there is no mechanism in our model for green investment to lead to higher growth in the economy.

We assume that the production function is Cobb-Douglas in labour, capital and energy input:

$$q_{e,t} = k_{e,t}^{\alpha_{k,u}} h_{e,t}^{\alpha_{h,u}} I_{g,e,t}^{1-\alpha_{k,u}-\alpha_{h,u}} \qquad \textbf{(26)}$$

The problem for the representative electricity producer will be to maximise their profits. Hence, we can write their problem mathematically as:

Maximise $P_{e,t}q_{e,t} - (P_{g,t} + \tau_C\varpi_{g,e})I_{g,e,t} - W_t h_{e,t} - r_{k,t}k_{e,t}$ **(27)**

Subject to equation **(26)**.

The first-order conditions for this problem imply:

$$\frac{P_{g,t}+\tau_C\varpi_{g,e}}{P_{e,t}} = (1-\alpha_{k,u}-\alpha_{h,u})k_{e,t}^{\alpha_{k,u}}h_{e,t}^{\alpha_{h,u}}I_{g,e,t}^{-\alpha_{k,u}-\alpha_{h,u}} \tag{28}$$

$$\frac{W_t}{P_{e,t}} = \alpha_{h,u}k_{e,t}^{\alpha_{k,u}}h_{e,t}^{\alpha_{h,u}-1}I_{g,e,t}^{1-\alpha_{k,u}-\alpha_{h,u}} \tag{29}$$

$$\frac{r_{k,t}}{P_{e,t}} = \alpha_{k,u}k_{e,t}^{\alpha_{k,u}-1}h_{e,t}^{\alpha_{h,u}}I_{g,e,t}^{1-\alpha_{k,u}-\alpha_{h,u}} \tag{30}$$

Note that electricity producers are having to pay the carbon tax on their gas input. Again, τ_C denotes the carbon tax – denoted in pounds sterling per ton of carbon – and $\varpi_{g,e}$ denotes the amount of carbon emissions associated with electricity generators using one unit of gas. We have also assumed that electricity prices are completely flexible.

3.4 Monetary and fiscal policy

Monetary policy is assumed to follow a Taylor rule with the central bank responding to deviations of inflation from target (ie, zero) and GDP, y, from trend:

$$i_t - \left(\frac{1}{\beta}-1\right) = \theta_{rg}\left(i_{t-1} - \left(\frac{1}{\beta}-1\right)\right) + (1-\theta_{rg})(\theta_\pi\pi_t + \theta_y\hat{y}_t) \tag{31}$$

where $\hat{y}$ denotes the log-deviation of GDP from its trend.

We assume that the government buys only non-energy goods. It sets a carbon tax and meets any further budget shortfall (surplus) via lump-sum taxes on (transfers to) households.

We can write its budget constraint as:

$$B_t = (1+i_{t-1})B_{t-1} + gov_t - \tau_C(\varpi_{p,c}c_{p,t} + \varpi_{g,c}c_{g,t} + \varpi_{p,q}I_{p,t} + \varpi_{g,q}I_{g,t} + \varpi_{g,e}I_{g,e,t}) + T_t \tag{32}$$

Where gov_t denotes government spending. Further, we assume, without loss of generality, that the supply of domestic government bonds is zero in all periods; that is, the government balances its budget in all periods via lump-sum taxes or transfers.

3.5 Foreign sector

In our model, producers export final non-energy goods and import non-energy goods, which are used entirely as intermediates in the domestic production of final goods. Oil and gas can be exported or imported depending on demand for these products relative to the economy's endowment. Our model is designed to represent a small open economy such as the United Kingdom: for this reason, world prices are assumed to be exogenous. We assume that petrol and gas prices adjust immediately to their world prices:

$$P_{p,t} = \frac{P^*_{p,t}}{s_t} \tag{33}$$

$$P_{g,t} = \frac{P^*_{g,t}}{s_t} \tag{34}$$

Where P^*_p denotes the world petrol price and P^*_g denotes the world gas price.

We assume a unit continuum of UK importers. The representative importer, j, buys imports at the world price of exports, P^*_X, converted into sterling using the nominal exchange rate, s, and sells them on domestically at the price $P_{\mathrm{m,j}}$. The importer also faces Rotemberg (1982) costs of adjustment, where these costs are also indexed to the lagged rate of aggregate import price inflation (to account for the additional persistence we see in import price inflation in the data). The importer's problem will then be given by:

Maximise $E_0 \sum_{t=0}^{\infty} \beta^t \left(\left(P_{m,j,t} - \frac{P^*_{X,t}}{s_t}\right) M_{j,t} - \frac{\chi_m}{2} \left(\frac{P_{m,j,t}}{P_{m,j,t-1}(1+\pi_{m,t-1})^{\iota}} - 1 \right)^2 P_{m,t} M_t \right)$

Subject to $M_{j,t} = \left(\frac{P_{m,j,t}}{P_{m,t}}\right)^{-\eta} M_t$

where π_{m} is the rate of inflation of non-energy import prices and we have assumed the same elasticity of demand in the import sector as in the non-energy sector, η. Noting that, since all importers are identical, they will impose the same price, integrating across all importers and taking a log-linear approximation implies the following equation for import price inflation:

$$\pi_{m,t} = \frac{\iota}{1+\beta\iota} \pi_{m,t-1} + \frac{\beta}{1+\beta\iota} E_t \pi_{m,t+1} + \frac{\eta}{\chi_m (1+\beta\iota)} \left(\widehat{P^*_{X,t}} - \widehat{s_t} - \widehat{P_{m,t}} \right) \tag{35}$$

Finally, we assume the following demand function for UK exports of non-energy goods, X_{n}:

$$X_{n,t} = \kappa_x X_{n,t-1}^{\psi_x} \left(s_t^{-\eta_x} \bar{x} \right)^{1-\psi_x} \tag{36}$$

Where ψ_x captures the idea that foreign preferences exhibit a form of ‘habit formation’ and $\bar{X}$ denotes ‘world demand’ (assumed to be exogenous and constant).

3.6 Market clearing

We close the model with the following market-clearing conditions:

$$h_t = h_{e,t} + h_{n,t} \tag{37}$$

$$k_{t-1} = k_{e,t} + k_{n,t} \tag{38}$$

$$\bar{G} + M_{g,t} = c_{g,t} + I_{g,q,t} + I_{g,e,t} \tag{39}$$

$$\bar{O} + M_{p,t} = c_{p,t} + I_{p,t} \tag{40}$$

$$q_{e,t} = c_{e,t} + I_{e,t} \tag{41}$$

$$q_t = c_{n,t} + I_t + gov_t + X_{n,t} \tag{42}$$

Where M_g denotes (net) imports of gas and M_o denotes (net) imports of petrol (oil). Equation **(37)** captures market clearing in the labour market, equation **(38)** the market for physical capital, equation **(39)** the market for gas, equation **(40)** the market for petrol, equation **(41)** the market for electricity and equation **(42)** the market for the non-energy good.

We define nominal GDP by expenditure:

$$P_{GDP,t} y_t = P_t c_t + I_t + gov_t + X_{n,t} - P_{g,t} M_{g,t} - P_{p,t} M_{o,t} - P_{m,t} M_{n,t} \tag{43}$$

Where PGDP is the implicit GDP deflator and we can note that investment, government consumption and exports are all of non-energy goods and so have unit price.

Finally, combining the consumers’ and government’s budget constraints with the definition of profits in each sector implies the balance of payments equation:

$$\frac{B_{f,t}}{s_t} - \frac{B_{f,t-1}}{s_t} = X_{n,t} - P_{g,t} M_{g,t} - P_{p,t} M_{o,t} - P_{m,t} M_{n,t} + i_{f,t-1} \frac{b_{f,t-1}}{s_t} - \frac{\chi_{bf}}{2} \left(\frac{B_{f,t}}{s_t} \right)^2 \tag{44}$$

The left-hand side of this equation denotes the capital account and the right-hand side the current account. These equations complete the description of the model.

4 Data and calibration

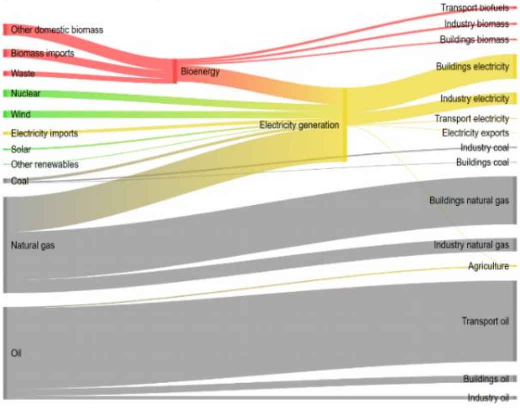
4.1 Data

The economic variables used in the calibration of the model – nominal GDP, nominal aggregate consumption expenditure and consumption of liquid fuels, electricity and gas; nominal business investment, net capital stock and government total actual final consumption – come from the UK National Accounts. Trade data are from the ONS international trade statistics and include total imports and exports of goods and services, and imports and exports of crude petroleum, refined petroleum products, natural gas and electricity.

Energy consumption data come from the Digest of UK Energy Statistics (DUKES) published by the UK Department for Energy Security & Net Zero (DESNZ) and include (quantities of): net imports of crude oil, petrol and gas, input of petrol into non-energy production, consumption of gas, input of gas into electricity production and input of gas into non-energy production. Nominal values of inputs of gas and petrol in energy and non-energy production come from the UK supply and use tables.

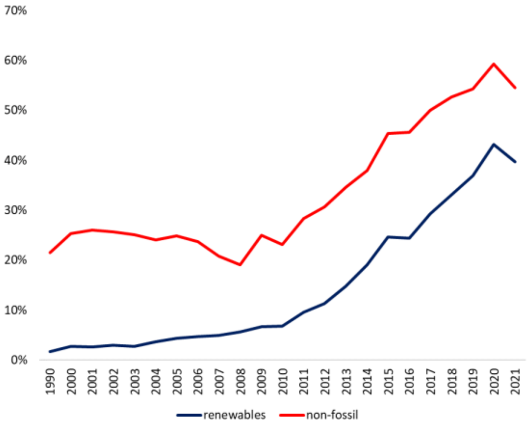
As shown in Figure 3, over a half of natural gas in the United Kingdom is used for heating, around a third for electricity generation, and the rest in industry and agriculture. Crude oil is used predominantly as transport fuel and coal use is negligible. In 2021, the United Kingdom produced around 40 per cent of its electricity needs from renewable sources (i.e., hydro, solar PV, onshore and offshore wind, landfill gas and other bioenergy) and around 55 per cent from non-fossil sources, which include nuclear power in addition to renewable sources (Chart 1).

Figure 3: UK energy generation and end uses (2021, TWh)



Source: DUKES 2022 and authors' calculations

Chart 1: UK electricity generation by source



Source: DESNZ: UK energy in brief 2022

4.2 Calibration

We proceed to calibrate the model as follows. First, there are a set of standard parameters that appear in many macroeconomic models and the values we use for these are shown in Table 1. In every case, we set these in line with Harrison *et al.* (2011). We set the discount rate, β, to 0.9925 implying a steady-state real interest rate of 3 per cent per annum, the intertemporal elasticity of consumption to 0.66 and the inverse Frisch elasticity of labour supply to 0.43. The cost of adjusting the foreign bond portfolio is set to 0.001. This is set to a small number so that we ensure the model has a stationary steady state, while not affecting household decisions by too much. We set the depreciation rate for capital to 10 per cent per annum and the elasticity of our investment adjustment cost function to 5.74. For the elasticities of substitution between non-energy and energy in consumption, σ_{en}, and between petrol, gas and electricity in energy consumption, σ_{p}, we use values of 0.4 and 0.1, again following Harrison *et al.* (2011). We also followed that paper in setting the elasticity of substitution between energy and non-energy in the production, σ_{q}, to 0.15. But, we set the elasticity of substitution between gas, petrol and electricity in energy production, σ_{n}, to 0.5 (where Harrison *et al.* use a Leontief production function).

We assume that non-energy producers have a steady-state mark-up of 1.1, which implies a value for η of 11. Given that value for η, we set χ to 117, which implies the same New Keynesian Phillips curve slope as would be obtained in the Calvo model with prices changing on average once a year (Calvo, 1983). For importers, we also assume a steady-state mark-up of 1.1 but set χ to 41, which implies the same New Keynesian Phillips curve slope as would be obtained in the Calvo model with prices changing on average once every seven and a half months. We also set the degree of indexation of import prices, ι_{pm}, to 17 per cent. On the export side, we set the elasticity of export demand, η_{x}, to 1.5 and its persistence, ψ_{x}, to 0.24. Finally, we used the original values in Taylor (1993) for the response of interest rates to inflation and output deviations (1.5 and 0.125, respectively) and the value in Harrison *et al.* (2011) for the persistence of interest rates (0.81).

Second, we set a number of parameters to ensure that steady-state shares in the model matched their average values in UK data. These are shown in Table 2. We set ψ_{e} equal to 4.8 per cent, the sum of the 2021 weights of ‘petrol’, ‘electricity’ and ‘gas’ in the CPI basket. Similarly, we calibrate ψ_{g} to 0.25, the share of gas in total energy spending implied by the CPI weights and ψ_{p} to 0.3541, the share of petrol in total energy spending implied by the CPI weights. We set α_{q} to 0.0438 to match the share of energy in the non-energy producing firms’ total costs. We set α_{B} to 0.2326 to match the share of imported intermediates in non-energy producing firms’ non-energy costs. And we set $1-\alpha_{k,q}-\alpha_B$ to match the share of labour in non-energy producing firms’ non-energy costs, implying a value for $\alpha_{k,q}$ of 0.3424.

Table 1: Standard parameters

Parameter	Value	Description
β	0.9925	Discount factor
σ_h	0.43	Inverse Frisch elasticity of labour supply
σ_c	0.66	Intertemporal elasticity of consumption
χ_{bf}	0.001	Cost of adjusting portfolio of foreign bonds
δ	0.025	Depreciation rate
$S''(1)$	5.74	Elasticity of investment adjustment costs
σ_{en}	0.4	Elasticity of substitution between non-energy and energy in consumption
σ_p	0.1	Elasticity of substitution between petrol, gas and electricity in energy consumption
σ_q	0.15	Elasticity of substitution between energy and everything else in non-energy production
σ_n	0.5	Elasticity of substitution between petrol, gas and electricity in energy production
η	11	Elasticity of demand in the non-energy sector
χ	137	Price adjustment costs in the non-energy sector
θ_π	1.5	Taylor rule coefficient on inflation
θ_y	0.125	Taylor rule coefficient on output
θ_{rg}	0.81	Taylor rule coefficient on lagged interest rate
χ_m	41	Price adjustment costs in the import sector
ι	0.17	Indexation in import price setting
ψ_x	0.24	Persistence of export demand
η_x	1.5	Elasticity of demand for exports

Table 2: Parameters set to match spending, cost and revenue shares

Parameter	Value	Description
α_q	0.0438	Set to match the cost share of energy in non-energy production
α_{kq}	0.3424	Set to match the cost share of labour in non-energy production
α_b	0.2326	Set to match the cost share of imports in non-energy production
α_{ku}	0.7895	Set to match the cost share of gas in electricity production
α_{hu}	0.0689	Set to match the cost share of labour in electricity production
ψ_e	0.0480	Share of energy in household consumption spending
ψ_g	0.2500	Share of gas in household spending on energy
ψ_p	0.3541	Share of petrol in household spending on energy
$\psi_{n,p}$	0.3135	Set to match the cost share of petrol in non-energy production
$\psi_{n,g}$	0.1478	Set to match the cost share of gas in non-energy production

We normalise the prices of petrol, gas and electricity and the nominal exchange rate to unity in steady state. We also normalise aggregate real consumption to unity in steady state. We then set $\psi_{n,p}$ and $\psi_{n,g}$ so as to match the cost shares of petrol, gas and electricity in production of the non-energy good. Doing so implies values for $\psi_{n,p}$ and $\psi_{n,g}$ of 0.3135 and 0.1478, respectively. Data from the 2018 SUTs suggest that the labour share in electricity costs is 0.0689 and the share of gas in electricity costs is 0.1416. So we set $\alpha_{h,u}$ to 0.0689 and $\alpha_{k,u}$ to 0.7895. We assume a steady state in which net exports of oil and gas are zero. Given our calibration this implies a gas extraction sector worth 1.9 per cent of GDP and an oil extraction sector of 2.4 per cent of GDP. This is a little higher than the one per cent contribution of the 'oil and gas extraction sector' towards UK Gross Value-Added at Basic Prices. Based on 2018 National Accounts data, we set steady-state government spending to 0.2866 times aggregate consumption spending.

Finally, we need to set the parameters governing the carbon emissions associated with household consumption of petrol and gas and petrol and gas used in production of electricity and non-energy goods. This is so that we can apply a tax of a given amount per kilogram of CO_2 emissions. The UK Government publishes a set of greenhouse gas emissions conversion factors for company reporting and we apply the 2021 values in our work. Using 1 tonne of petrol (which we associate with household use) results in emissions of 2947.62kg of CO_2 whereas using 1 tonne of diesel (which we associate with use in production) results in emissions of 2969.07kg of CO_2. For gas, using 1 kWh (on a gross calorific value basis) results in emissions of 0.18316kg of CO_2. DUKES data suggests that final consumption of petrol in 2020 was 9.144 million tonnes and of diesel was 19.693 million tonnes. This suggests that one unit of petrol used by households in our model is associated with 1.586 billion tonnes of CO_2 whereas one unit of petrol used by firms in our model is associated with 2.081 billion tonnes of CO_2. Similarly, in 2020, 299,301 GWh of gas were used for domestic purposes (ie, 'consumed' by households). This suggests that one unit of gas in our model is associated with 4.568 billion tonnes of CO_2. Given all that, we set $\varpi_{p,c}$, $\varpi_{p,q}$, $\varpi_{g,c}$, $\varpi_{g,q}$ and $\varpi_{g,e}$ to 1.586, 2.081, 4.568, 4.568 and 4.568, respectively. Aggregate nominal consumption in 2020 was £1,231.580 billion. In the steady state of our model, aggregate real and nominal consumption are both equal to 1. So, a price of 1 unit in our model will correspond to a price of £1,231.58 billion. Hence, a carbon tax of, say, £100 per tonne of CO2 emissions would correspond to a τ_c of 0.081.

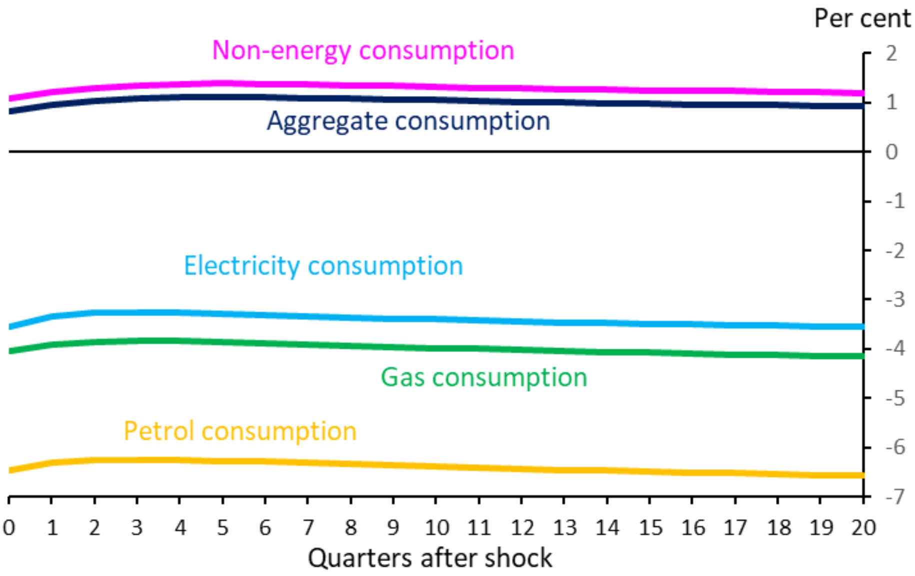
5 Results

5.1 What are the effects of a carbon tax?

We start by examining the effects of the imposition of a carbon tax in our model. In particular, we start from a situation of no carbon taxes and then permanently impose a tax of £100 per tonne of CO_2 emissions.

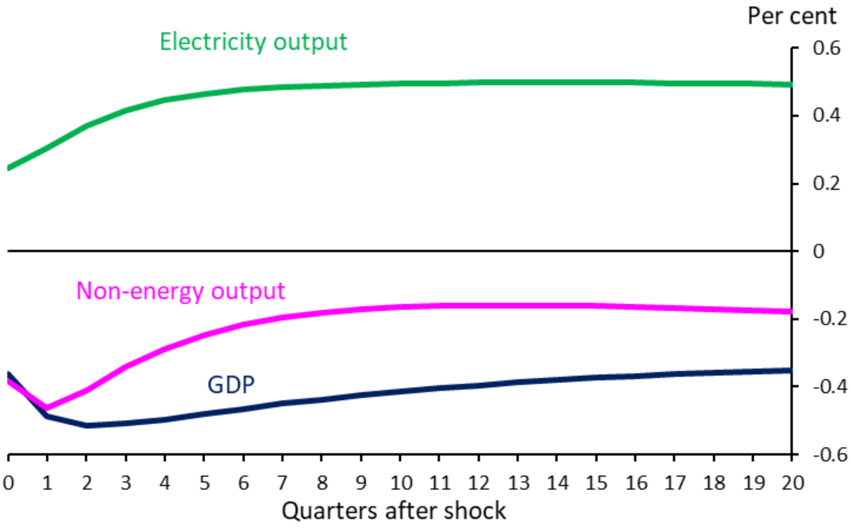
Chart 2 shows that the carbon tax leads to an immediate and permanent reduction in the consumption of energy. The tax has its largest effect on the consumption of the most carbon-emitting fuel, petrol. It also leads to a reduction in consumption of electricity, despite electricity consumption not being directly taxed. This is because electricity producers must pay the tax on their input of gas, and this leads them to raise the price of electricity, which leads to reduced consumption of electricity. The effect on aggregate consumption is relatively small as a slight rise in non-energy consumption (95.2 per cent of the consumption basket) offsets most of the fall in energy consumption. It should be noted that there is no habit persistence in consumption in our model, consumers do not face any constraints on their ability to borrow or lend, and there are no other frictions that would slow down the response of consumption to the shock. Hence, households adjust almost immediately to a new long-run level of consumption.

Chart 2: Effects of a carbon tax on consumption



On the output side, gross output of non-energy and GDP both fall as shown in Chart 3. This results from the increase in costs that the tax brings about. As non-energy production forms the bulk of value-added output, GDP also falls. The effect on electricity output, on the other hand, is more nuanced. The tax raises the cost of producing electricity since electricity producers use gas, but electricity producers are more able to substitute away from gas towards capital (i.e., renewable) than non-energy producers meaning the rise in costs is lower. In addition, the demand for electricity in the production of non-energy rises (Chart 4). The net result is that electricity output rises despite the fall in electricity consumption. Although firms can respond relatively quickly to the change in energy prices, they still face frictions that slow down their response relative to households. In particular, non-energy firms are not able to adjust their prices immediately without having to pay a cost and the costs of adjusting investment mean that it takes time to bring the capital stock up to its new steady-state level. As a result, it takes around two years for both non-energy and electricity output to adjust to their new levels in response to the shock.

Chart 3: Effects of a carbon tax on output and GDP



As can be seen in Chart 4, the use of petrol in production of non-energy falls substantially, as does the use of gas in producing both non-energy and electricity. Given that there are no frictions affecting energy usage in our model – firms only face frictions in their ability to set prices and invest in new capital – these falls happen immediately. The increase in the cost of using gas to produce electricity results in an increase in the use of capital by electricity producers. That is, electricity production switches from using carbon-emitting technology towards using renewables technology. But the cost of producing electricity still rises, which means non-energy producers do not substitute into electricity as much as would be expected given the fall in its relative price resulting from it not being taxed directly. We can note that the falls in energy inputs are much larger proportionately than the fall in the gross output of non-energy.

Chart 4: Effects of a carbon tax on energy inputs

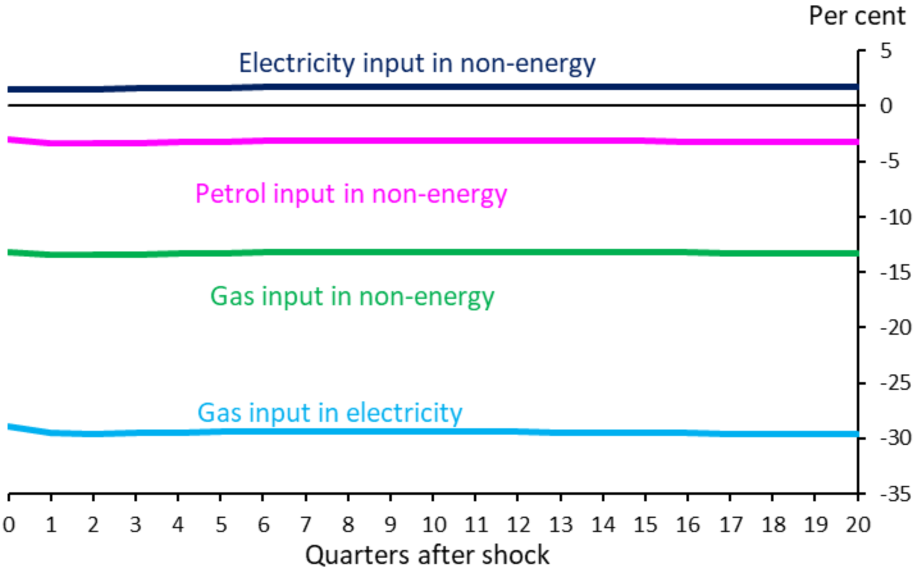
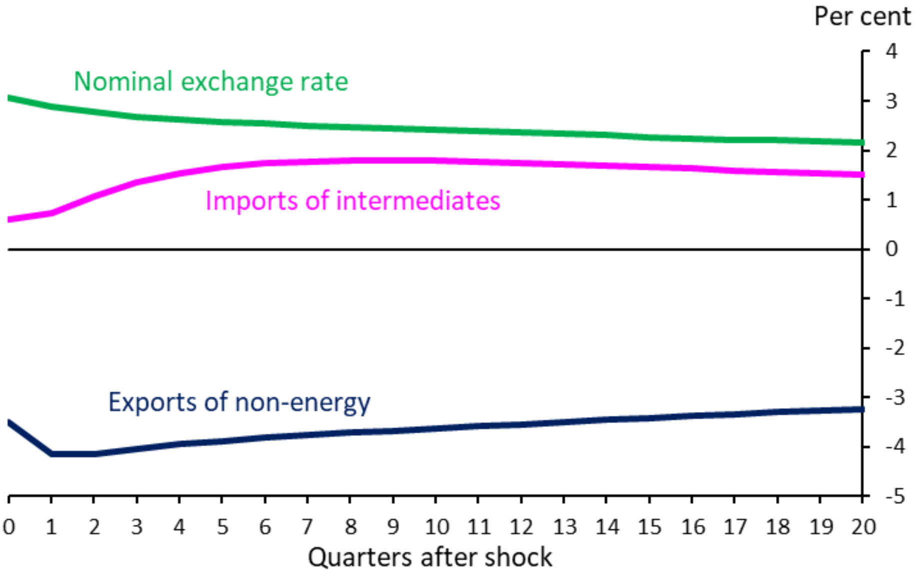


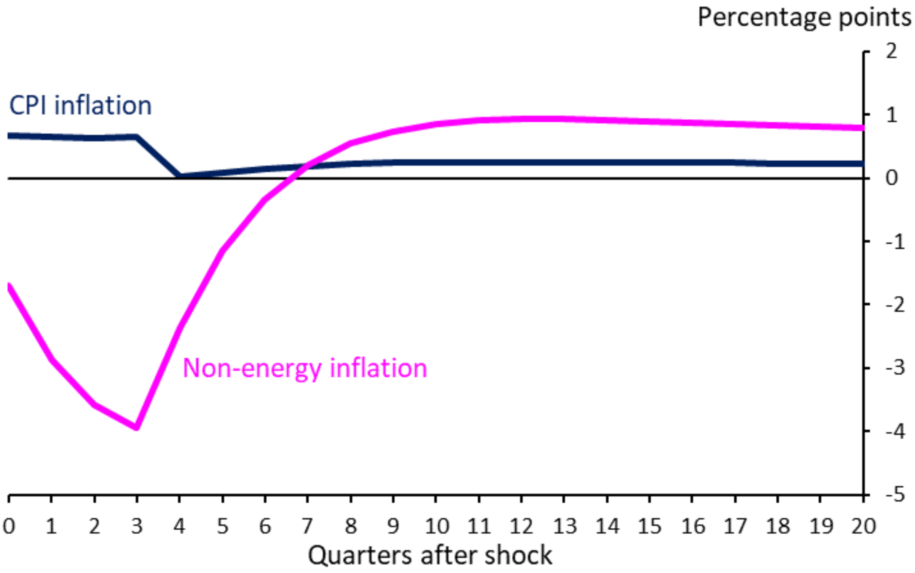
Chart 5 shows that non-energy firms increase their use of imported intermediates in response to the tax, switching away from energy usage. At the same time, their exports fall as their costs – and so prices – increase. These effects are amplified as a result of the appreciation in the exchange rate that, in turn, results from the monetary tightening we discuss later. Given the costs of adjusting import prices and persistence in export demand in our model both imports and exports take time to adjust to their new equilibrium. The increased trade deficit resulting from the rise in imports and fall in exports acts to put downwards pressure on GDP. Exports of oil and gas increase (not shown). This reflects two key features of our model. First, we have only taxed the *use* of fossil fuels but not their *production*. Assuming there is demand, it pays for any country to keep producing fossil fuels. Second, we have assumed that it is only the United Kingdom where fossil fuel use is taxed. This ensures that there continues to be demand for fossil fuels elsewhere in the world. If UK exports of fossil fuels were subject to a ‘border carbon adjustment tax’ in those countries where our exports are sent and/or UK production of fossil fuels was subject to a carbon tax, then the tax would result in lower oil and gas production in the United Kingdom.

Chart 5: Effects of a carbon tax on exports and imports



We next consider the interaction of a carbon tax with monetary policy. Chart 6 shows that the imposition of a permanent carbon tax of £100 per tonne of CO_2 emissions leads to an increase in CPI inflation of around 0.6 percentage points. In our model, we can think of the rate of inflation of non energy goods and services as being equivalent to 'core inflation' in the data. Interestingly, the rise in energy prices leads to a strong enough fall in demand for non-energy – given that non energy and energy are complements in consumption – that core inflation falls significantly, acting to ameliorate the rise in headline inflation.[11] After a year or so, core inflation starts to recover and ends up permanently higher.

Chart 6: Annual CPI and non-energy inflation rate



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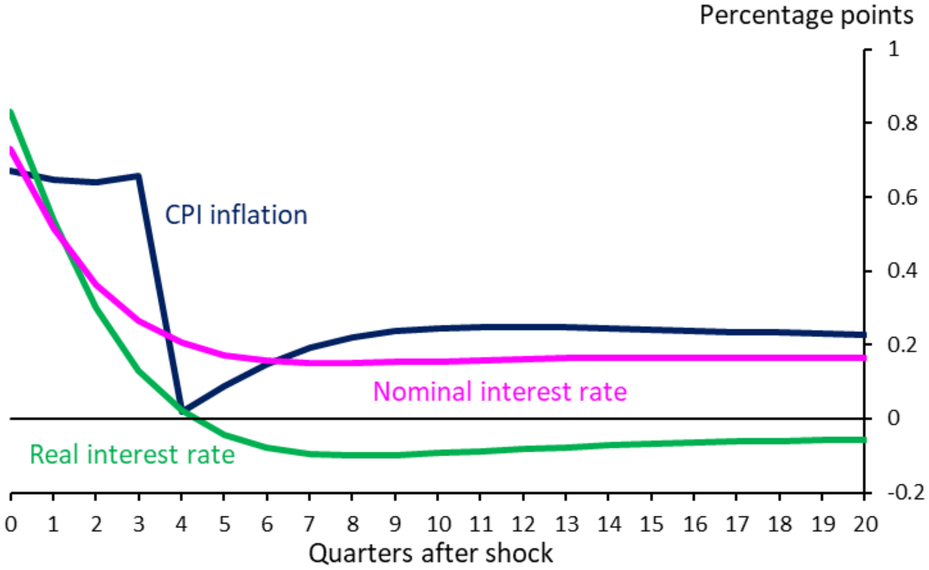
[11] This is consistent with the kind of general equilibrium effects described, e.g., by Mann (2023).

Given the rise in headline inflation, the Taylor rule implies a tightening in monetary policy, specifically, a rise in the nominal interest rate of around 70 basis points (Chart 7). This rise in nominal interest rates implies an even larger rise in real interest rates given inflation is expected to fall. The rise in real interest rates is initially 85 basis points. Inflation starts falling gently after a quarter, but the large drop in annual inflation occurs a year later as the steep rise in energy prices 'drops out' of the inflation calculation.

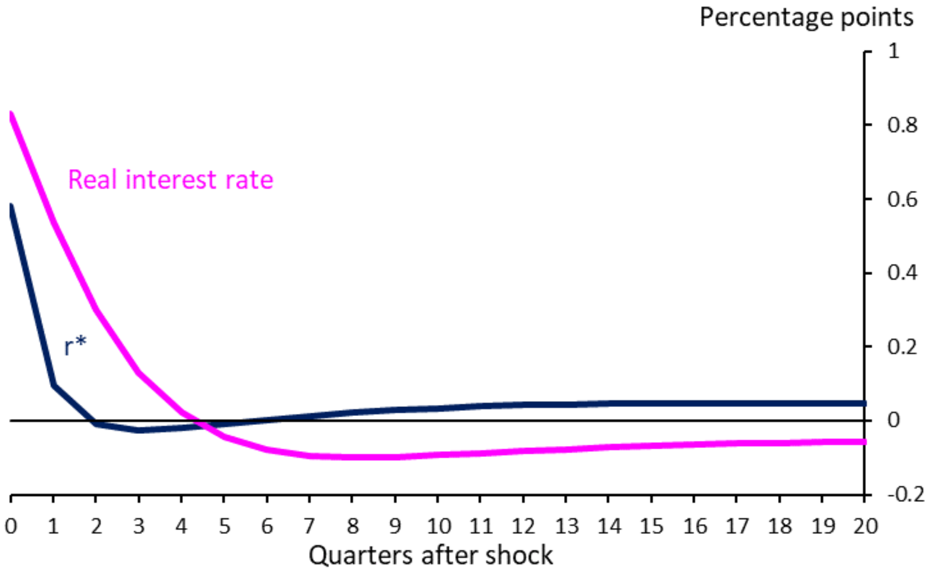
Chart 7: Effects of a carbon tax on interest rates and inflation



An obvious question, though, is whether this rise in the real interest rate is warranted. That is, would a better monetary policy response be to 'look through' the shock brought about by the imposition of a carbon tax? This might make sense given that it is a permanent relative price shock, which should only have a temporary effect on inflation. One way of getting at this question is to see what would happen to the 'natural rate of interest' – which we refer to as *r** – in response to the imposition of a carbon tax, i.e., the real interest rate that is compatible with full-employment output while keeping inflation constant. If the actual real interest rate is higher than *r**, then monetary policy is 'tight' and acting to push down on inflation whereas if the actual real rate is lower than *r**, then monetary policy is 'loose' and acting to push up on inflation. Within our model, we can calculate *r** by examining the effect of the carbon tax shock in a world of flexible prices where inflation remains constant. Movements in the real interest rate in this counterfactual world will correspond to movements in the natural real rate of interest in response to the carbon tax shock.

Chart 8 shows the response of the real interest rate in our model to the imposition of a permanent carbon tax of £100 per tonne of CO_2 emissions together with its response in the alternative (flexible-price) world, the latter giving us the response of *r**. Our results suggest that the monetary policy tightening leads to a much larger response of the real interest rate than is indicated by the response of *r** to the shock. In fact, after the quarter in which the initial shock hits, the natural real interest rate falls quickly back to its previous equilibrium (and, indeed, new equilibrium as the shock will not affect *r** in the long run). This suggests that the monetary policy response resulting from the application of the Taylor rule may be to raise the nominal interest rate by more than is optimal. More specifically, in responding to movements in the headline rate of inflation driven by the large increase in energy prices resulting from the tax, monetary policy is tightened by around 20 basis points too much and stays tight for too long. Our results suggest that, as is the case for supply shocks more generally, it may be possible to achieve a better outcome by 'looking through' the initial shock to where inflation is expected to move in the future. Of course, this ignores any effect the rise in inflation may have on the subjective inflation expectations of firms and workers, which would argue for an aggressive monetary policy response to such a shock. For more on these issues see Dixon *et al.* (2023).

Chart 8: Effects of a carbon tax on the real interest rate and r



5.2 Effects of bans on the consumption of petrol and gas

In this subsection, we consider the effects of direct restrictions on the use of petrol and gas by households. This is an example of 'command and control' climate policy. More specifically, we first look at the effects of an unanticipated permanent ban on petrol usage by households; think of a regulation that prohibits the use of petrol cars, forcing households to replace them with electric cars. We then look at the effects of an unanticipated permanent ban on domestic gas usage; here we think of households having to use electric heat pumps to heat their houses.[12] In future work, we would like to consider the effects of announcing a ban today that will come into effect at some point in the future.

We start with the effects of a ban on petrol usage. Chart 9 shows that consumers switch out of petrol into non-energy consumption. Since we have assumed that gas and electricity have a very low elasticity of substitution with petrol, consumption of both gas and electricity also falls. The reduction in petrol consumption means that aggregate consumption falls initially but then settles around one per cent higher than in the baseline. Chart 10 shows that output of non-energy goods and services falls together with output of electricity. As was the case for the carbon tax shock, GDP also falls. As households increase their consumption of non-energy, output in this sector rises, reaching it

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[12] To implement these bans within the model, we simply replaced the equations determining the demand for petrol and gas, respectively, coming from households with equations setting this demand to zero. In producing the results, we rely on a log-linear approximation of the model around its non-stochastic steady state. Clearly, for the size of shock we are considering, there are likely to be approximation errors. In a future work, we intend to use a non-linear solution method in order to reduce this approximation error.

previous trend after a year and a half and then remaining above its previous trend. Given we have assumed that the petrol ban is only applied in the United Kingdom, exports of oil rise as the country exports all its oil endowment, again adding to GDP. Finally, Chart 11 shows that the shock leads to a large increase in inflation and interest rates.

Chart 9: Effects of a ban on petrol consumption

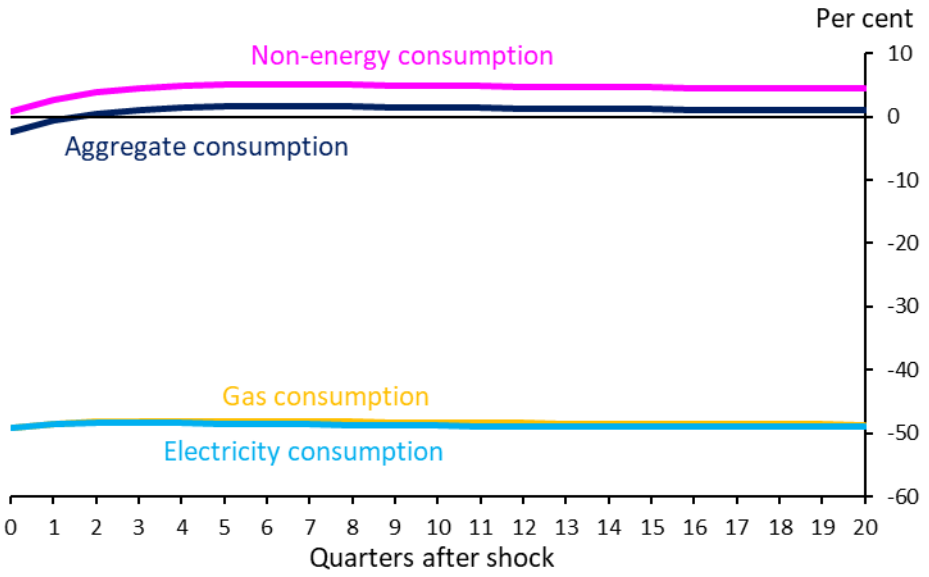


Chart 10: Effects of a ban on petrol consumption on output

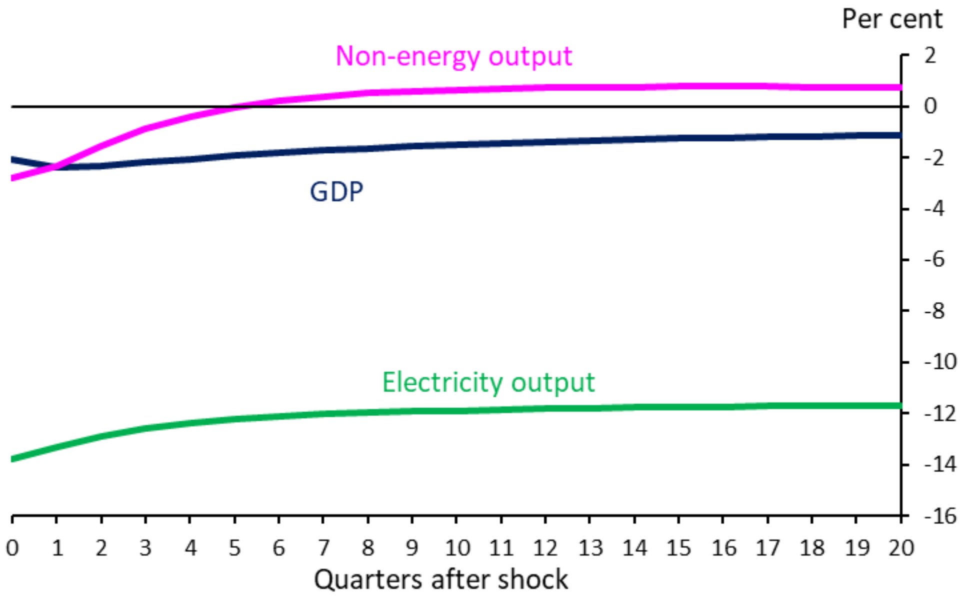
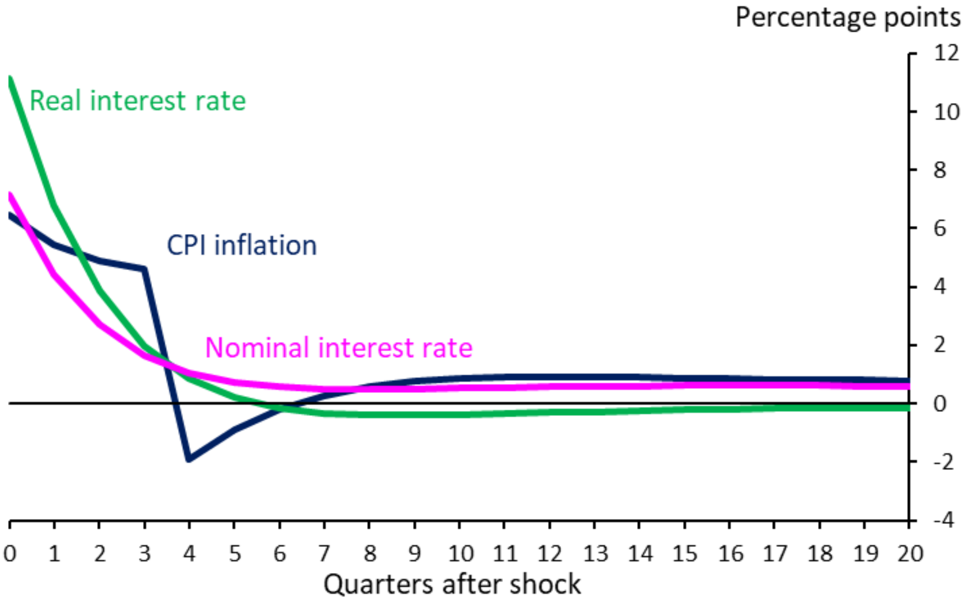


Chart 11: Effects of a ban on petrol consumption on inflation and interest rates



In practice, we would expect such a ban to be implemented over a period of time and not immediately. For example, the Zero Emission Vehicle Mandate in the United Kingdom, requires 80% of new cars and 70% of new vans sold in Great Britain to be zero emission by 2030, increasing to 100% by 2035. This means that, in practice, households are likely to be much more able to substitute between petrol and electric cars. To investigate this, we also considered the effects of an immediate ban on household consumption of petrol in a case where petrol, gas and electricity were more substitutable. Specifically, we set the elasticity of substitution between different energy sources in consumption to 0.4. The results for this calibration are shown in Charts 12 and 13. Chart 12 shows that, with greater substitutability between petrol, gas and electricity, gas and electricity consumption increase in response to the ban on petrol. We can think of this as households substituting electric for petrol cars and increasing their spending on heating. As a result of the increased demand for electricity from households, electricity output increases over time as shown in Chart 13. However, the effect on GDP remains negative.

Chart 12: Effects of a ban on petrol consumption, σ_p = 0.4

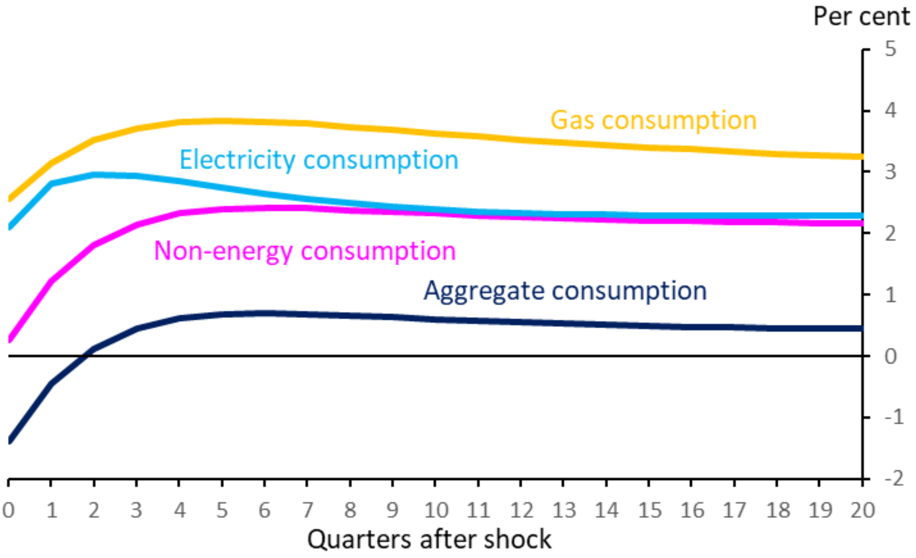
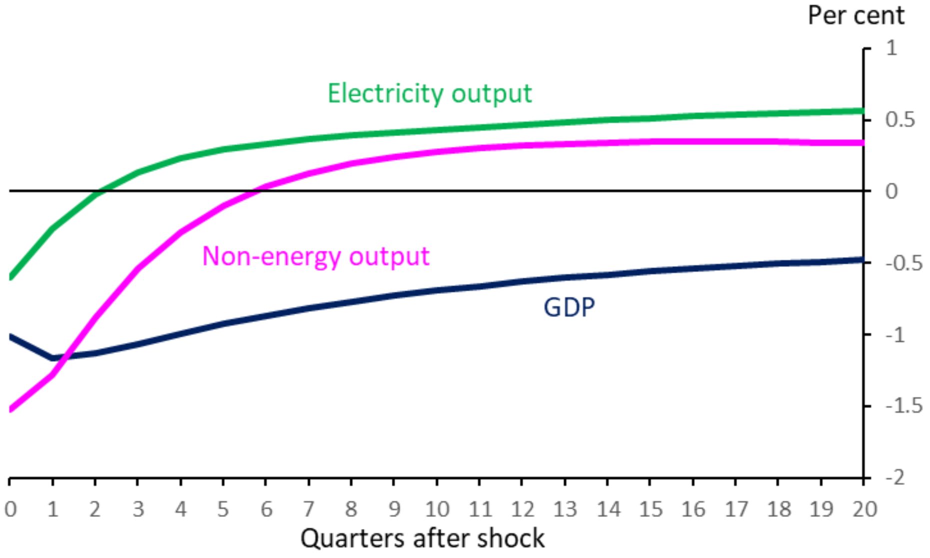


Chart 13: Effects of a ban on petrol consumption on output, σ_P = 0.4



The effects of a ban on gas usage by households are very similar to those coming from a ban on petrol usage. With an elasticity of substitution of 0.1 between energy inputs, we again find that households switch out of energy and into non-energy goods and services (Chart 14), whereas if we increase the elasticity of substitution to 0.4, we again find that consumption of petrol and electricity rise (Chart 15). Again, we can think of this as households substituting from gas boilers to heat pumps, while also using their cars more. As before, GDP and output in the non-energy sector all fall, though non-energy output recovers in light of the demand coming from households (Charts 16 and 17). With an elasticity of substitution of 0.1 between consumption of petrol, gas and electricity, electricity output falls (Chart 16). But, with an elasticity of substitution of 0.4, the rise in demand for electricity leads to an increase in electricity output (Chart 17). Finally, the ban again leads to a large rise in inflation, which causes the central bank to raise nominal interest rates, pushing up real interest rates dramatically (Chart 18).

Chart 14: Effects of a ban on gas consumption, σ_P = 0.1

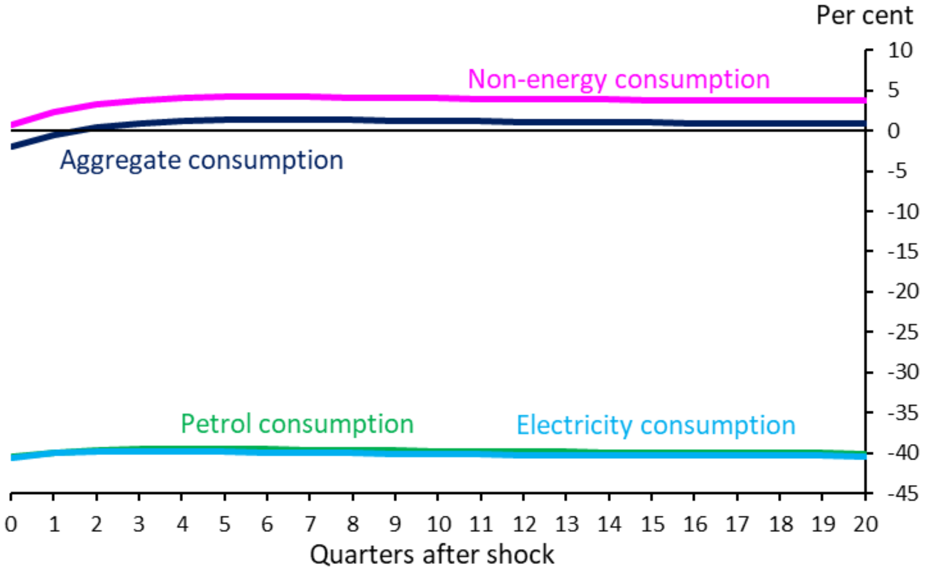


Chart 15: Effects of a ban on gas consumption, $\sigma_P = 0.4$

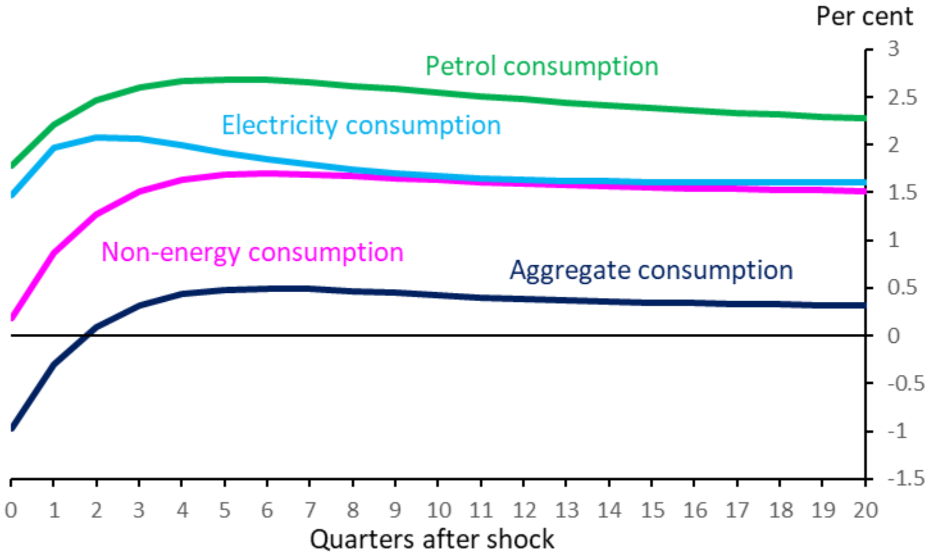


Chart 16: Effects of a ban on gas consumption on output, $\sigma_P = 0.1$

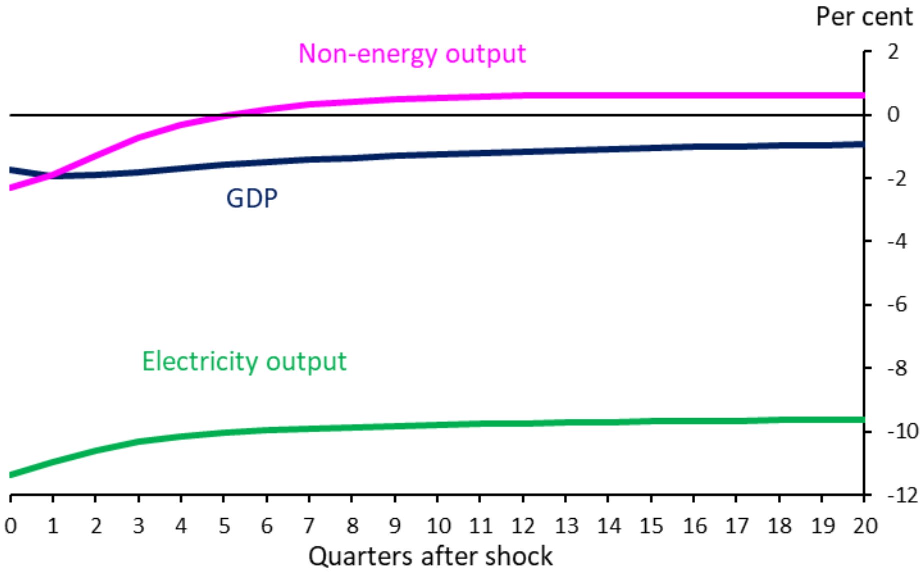


Chart 17: Effects of a ban on gas consumption on output, $\sigma_P = 0.4$

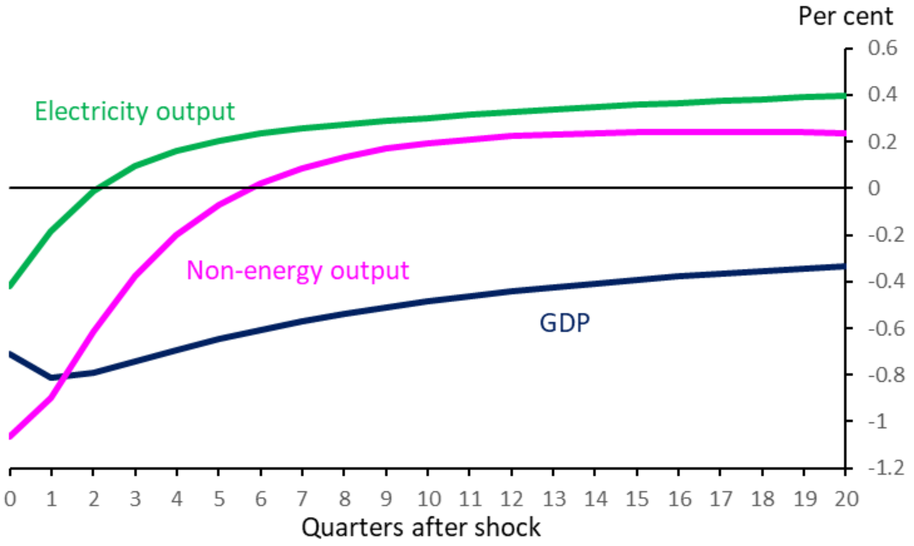
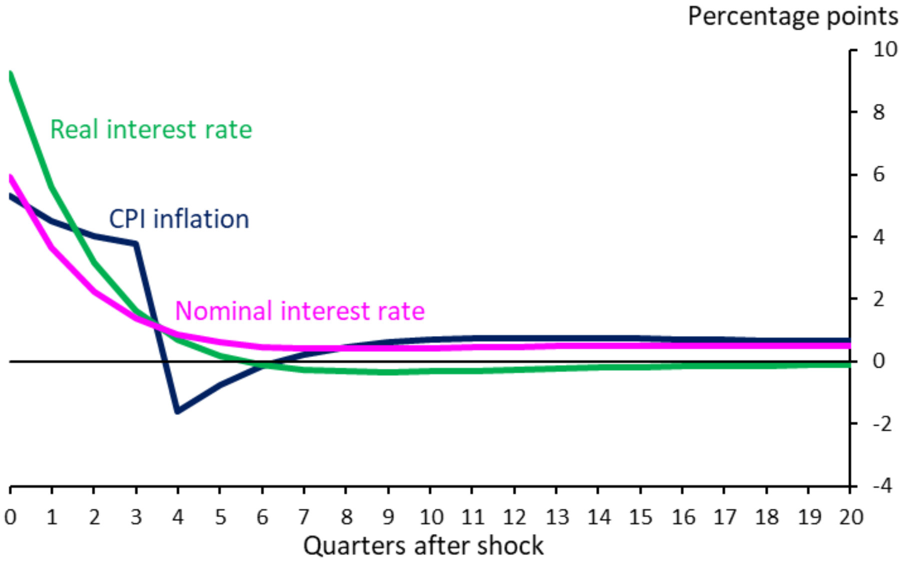


Chart 18: Effects of a ban on gas consumption on inflation and interest rates, σ_P = 0.1



6 Conclusions and future work

In this paper, we have constructed a DSGE model of a small open economy with four sectors: households, firms, the government and a monetary authority. We also included two types of energy sources: fossil fuels (specifically, oil, gas and gas-generated electricity) and electricity generated using renewables. We used our model to analyse the impacts of a carbon tax and bans on household petrol and gas usage on the macroeconomy and monetary policy. The latter are examples of 'command and control' type policies (regulation), which are a way of getting around the unwillingness of households to substitute out of fossil fuels and into green energy in the short run.

We showed how the introduction of the carbon tax has the effect of shifting the production of electricity from fossil fuels (specifically, gas) to renewable sources. At the same time consumption shifts out of energy and into non-energy and, within energy, out of petrol and gas towards electricity. Output of non-energy goods and GDP fall but electricity output rises in response to the carbon tax. Imposing the carbon tax also leads to a temporary increase in inflation and, in turn, a tightening of monetary policy.

We then showed that the effect of bans on the use of fossil fuels on households depended crucially on the elasticity of substitution between different energy sources in consumption. For our baseline parameterisation, a ban on petrol or gas usage also led households to cut down on their use of electricity, whereas if we increased the elasticity of substitution between energy sources to 0.4, then households switched into electricity. Regardless of the elasticity of substitution, aggregate consumption and gross output of non-energy fell on impact in response to the bans before rising over time. But GDP falls permanently in response. Banning petrol or gas usage by households also led to an increase in inflation and interest rates.

We plan in future work to model a wider range of climate policies. In particular, we want to consider different time paths for the carbon tax, as postulated, for example, in the 'Climate change scenarios for stress-testing purposes' (Bank of England, 2021). Following up on that point, we also plan to develop the model in such a way as to enable households and firms to substitute completely out of fossil fuels and into clean energy in the medium to long run while still being relatively unable to do so in the short run. This will make the model more able to generate sensible transition paths over the 30 years or so that governments are considering for the transition to net zero.

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Appendix: Climate policy and net zero targets

This appendix briefly describes the set of policy tools available to policymakers to reduce GHG emissions and mitigate climate change; it then examines existing net zero targets across different countries.

Climate policy instruments are designed to limit the concentration of GHG in the atmosphere – and to mitigate the temperature increases they cause – by reducing the flow of GHG emissions arising from human activities. The broad range of policy instruments available to policymakers for climate change mitigation are summarised in Table A1. Policies can be classified into three main groups: (1) direct regulatory approaches, also called 'command and control' instruments, (2) market based policies and (3) institutional approaches.

Table A1: A Taxonomy of climate policy instruments

	Instrument	**Description**	**Examples**
Command and control instruments (regulation)	Input controls over quantity and or mix of inputs	Requirement to use particular inputs/restriction on use of others	Ban on coal
	Technology controls	Requirements to use particular methods or standards	Mandatory CO_2 capture and storage methods on a power plant Standards to increase the energy efficiency of automobiles, appliances, and buildings
	Performance standards	Mandates specific environmental outcomes per unit of product	Limit emissions to a certain number of grams of CO_2 per kilowatt-hour of electricity generated
Economic incentive (market based) instruments	Emission charges/taxes	Direct charges based on quantity and of quality of a pollutant	Carbon taxes
	Emission abatement subsidies	Financial payments designed to reduce damaging emissions	Subsidies for R&D in clean energy generation Subsidies for adoption of clean energy, products or technologies Reduction of direct and indirect subsidies for fossil fuel use
	Marketable (transferable) emission permits	Two types: emission reduction credits (ERCs) or cap-and-trade schemes	Emission trading schemes

Institutional approaches to facilitate the internalisation of externalities	Facilitation of bargaining	To reduce the cost of or remove impediments to bargaining	Emissions disclosure
	Development of social responsibility	Education and socialisation programmes	Energy conservation media campaigns
	Voluntary agreements	Agreements between government authority and private parties to achieve environmental objectives beyond regulatory compliance	Legally binding agreements for industrial energy efficiency improvement

Source: Based on Perman *et al.* (2011); informed by Gupta *et al.* (2007) and Duval (2008)

Regulation is the most restrictive type of policy instrument, since it limits the type of inputs or technology used or sets specific performance standards. An example of this type of policy is a ban on coal in energy production.

Market-based policies rely on economic incentives, for example through the introduction of a 'carbon price'. A carbon price can be achieved either by levying a tax on the use of fossil fuels – a 'carbon tax' – or by a 'cap and trade' system. By setting a carbon tax, the authority fixes the price of carbon, and lets the quantity of emissions be determined endogenously by agents' choices. In a cap-and-trade system, on the other hand, the maximum amount of GHG emissions is fixed by the authority by issuing a certain number of emission permits traded on carbon markets, while the carbon price is generated endogenously. Weitzman (1974) showed that, with complete knowledge and perfect certainty, there exists a formal identity (or 'duality') between the use of prices and quantities as planning instruments. In the presence of imperfect information and uncertainty, on the other hand, the choice depends on the relative slope of the marginal costs and benefits curves (Hepburn, 2006).

The third type of climate policy is the 'institutional approach' to internalise the climate externality. Examples of this type of policy include voluntary agreements and information programmes, for example a policy mandating the disclosure of carbon emissions by businesses.

Global Net Zero targets

Since the Paris agreement, a number of countries have introduced 'Net Zero' targets, mandating that, by a certain future date, any greenhouse gas emissions produced within the country should be eliminated or absorbed by natural carbon sinks (e.g., forests) or by technologies such as carbon capture and sequestration (CCS).

The United Kingdom was the first major economy to introduce, in June 2019, a legally binding 'Net Zero' target by 2050.[13] Achieving the target will require a number of institutional and 'command and control' policies, expansion of the market-based UK Emission Trading Scheme (ETS) as well as public

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[13] UK net zero emissions law. The 2008 Climate Change Act made the UK an international leader in climate policy, by setting out a sequence of carbon budgets that put legal limits on GHG emissions over five-year periods.

and private investment in renewables and carbon-capture technologies, as recommended, for example, by the Climate Change Committee (CCC, 2019) and Chris Skidmore's 2023 Independent review of Net Zero.[14]

In April 2021, the US announced a target to achieve a 50 – 52 percent reduction in economy-wide net greenhouse gas emissions from 2005 levels by 2030, in addition to the Paris Agreement commitment to reaching net zero emissions economy-wide by 2050.[15] The Inflation Reduction Act (IRA),[16] which followed in 2022, contains ambitious action against climate change, including tax credits and direct expenditure towards renewable and nuclear electricity generation, CCS technology, energy efficiency and industrial decarbonisation, putting the U.S. on track to achieve its 2030 emission reduction target (Bistline *et al.*, 2023).

In June 2021, the European Climate Law[17] stated the goal for Europe's economy and society to become climate neutral by 2050, with an intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. In the same month, the Canadian Net-Zero Emissions Accountability Act set Canada's target of net zero emissions by 2050. Other major economies that have set net zero targets by 2050 include: Australia, which has also launched a 'Net Zero Authority' in May 2023;[18] China, which has a target of 'carbon neutrality before 2060' and Russia, which legislated for a similar target in October 2021.

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[14] Independent review of Net Zero.

[15] President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target.

[16] Inflation Reduction Act.

[17] EUR-Lex - 32021R1119 - EN - EUR-Lex (europa.eu).

[18] A new national Net Zero Authority | PM&C (pmc.gov.au).