Oxford Review of Economic Policy, Volume 36, Number 3, 2020, pp. 579–603

Climate change and monetary policy: issues for policy design and modelling

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Abstract This paper explores the interaction of monetary policy and climate change as they jointly influence macroeconomic outcomes, connecting policy and outcomes in each realm to the implications of the other. It also explores the nature of the macroeconomic model that would be required to explore the links between monetary policy and climate policy. The paper has four parts. First, it reviews the relevant macroeconomic outcomes of emissions mitigation policy and climatic disruption, exploring how negative supply shocks can affect central banks' ability to forecast and manage inflation. Second, the paper reviews basic approaches to monetary policy, including inflation and output targeting, and other responsibilities that may fall to central bankers. Third, we bring together the two sets of issues to consider the appropriate monetary framework in a carbon-constrained and climatically disrupted world and to highlight the climate policy frameworks that can make monetary policies more efficient and effective. We then summarize the nature of the macroeconomic modelling framework that is needed to better analyse climate and monetary policy interactions. We conclude that policy responses to climate change can have important implications for monetary policy and vice versa and that, in light of the urgency of ambitious climate action, these policy spheres should be brought together more explicitly and more appropriate macroeconomic modelling frameworks developed.

Keywords: monetary policy, climate change, carbon pricing, G-Cubed, macroeconomic models, multi-sector models

JEL classification: E52, C54, F17, F41, F47, Q43, Q54

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This paper is a substantially revised version of McKibbin, Morris, Wilcoxen, and Panton (2017). The authors thank Donald Kohn, Cameron Hepburn, Louise Sheiner, David Vines, Barrett Walker, Sam Wills, and participants at the *Oxford Review*'s seminar for very helpful comments on this version and earlier versions of the paper. We also thank Larry WeiFeng Liu for his contributions to the development of the G-Cubed model used in this paper. The authors acknowledge financial support generously provided by the Alex C. Walker Foundation.
doi:10.1093/oxrep/graa040

I. Introduction

This paper explores the interaction of climate change and monetary policy as they jointly influence macroeconomic outcomes (McKibbin *et al*., 2017). It also outlines the features of macroeconomic models that policy-makers will need to evaluate climate and monetary policies and their interaction.

In bringing together the literature on climate change and monetary policy, we seek to alert policy-makers in each realm to the implications of the other. The challenge that closely connects climate change and monetary policy is the potential for and response to economic 'shocks'. These are abrupt events that increase or decrease the demands for goods and services (demand shocks) or increase or decrease the supply or cost of goods and services (supply shocks). Aggregate shocks—those that apply to goods and services generally rather than any specific sector—can be temporary or involve more permanent changes in the economy. One can think of the impacts of climatic disruption and ambitious climate policy as both demand and supply shocks, some aspects of which would be transitory and some of which would be permanent. For example, extreme weather events and sea-level rise can result in damages to crops, flooding of major cities and industrial areas, coastal erosion that destroys property and physical plant, extensive power outages, infrastructure damage, and the dislocation of workers. These are all negative supply shocks. Spikes in crop prices might be temporary, but sea level rise may permanently destroy productive coastal land. An abrupt and stringent constraint on greenhouse gas (GHG) emissions can permanently increase the prices of fossil fuels, but the degree to which it makes existing capital uneconomic is transitory. Climate events whose effects may appear to be only temporary may affect long-term output as the destruction of capital may affect the growth rate of potential output via hysteresis channels.

Most research on the links between climate change and monetary policy has focused on the financial stability implications of climate change and the transition risks associated with climate policy actions. There is a distinction made between climate-induced physical risks (increased frequency and severity of climate-induced natural disasters) and transition risks (negative supply shocks from climate policy) (Carney, 2015; Batten *et al.*, 2016).

Increased frequency and severity of climate-induced catastrophic events may affect the pace or magnitude of capital replacement, with evidence that high insurance claims (Bank of England, 2015) and falling housing prices (Boustan *et al.*, 2019) following natural disasters pose serious risks to financial stability. Some of the serious risk factors for stability of the financial system following severe or persistent climatic disruptions include declines in private financial flows (Yang, 2008); weak households and firms' balance sheets (Batten *et al.*, 2019); increased permanent risk-aversion tendencies following exposures to natural disasters or climatic variations (Cameron and Shah, 2013) and increased legal risks (NGFS, 2019).

The transition to a low-carbon economy also poses risks to the financial system, particularly in the form of losses associated with stranded capital and lower future profit prospects from carbon-intensive investments (NGFS, 2019). The magnitude of such losses is a function of the extent to which the policy is orderly and efficient, along with the market characteristics of different industries and the relevant demand and supply elasticities. Our focus is on the interaction between climate policy and the design of monetary frameworks in the face of different climate policies.

We proceed in six parts. First, the paper reviews basic emissions-mitigation policy options and the different ways in which they can impact output, relative prices of particular goods, and overall price levels. It also reflects on how the manifestations of climatic disruption can impact prices and output levels. Such outcomes can affect central banks' ability to forecast and manage inflation.

Second, we briefly review the basic approaches to monetary policy, including various types of inflation and output targeting rules. We also outline some other responsibilities that may fall to central bankers related to legal differences across jurisdictions. Third, we bring together the two sets of issues to consider the optimal monetary framework in a carbon-constrained and climatically disrupted world and to highlight the climate policy frameworks that can make monetary policies more efficient and effective.

A core message of this paper is that policy responses to climate change can have important implications for monetary policy and vice versa. Different approaches to imposing a price on carbon will impact energy and other prices differently; some would provide stable and predictable price outcomes, and others could be more volatile. All else equal, more volatile prices pose greater challenges to central bank authorities than more predictable prices, in part because they complicate the forecasting of inflation and other economic variables that central banks use to benchmark their policies.

Similarly, ambitious climate policy can affect output, both in aggregate and disproportionately in select emissions-intensive sectors. Policies that are the least costly and most predictable can minimize the extent to which monetary policy-makers must anticipate their effects in their overall stewardship of the macroeconomy.

Likewise, monetary policy could have important impacts on the macroeconomic outcomes of emissions abatement policy and extreme weather events. For instance, if continuously rising prices from carbon policy induce the central bank to raise interest rates to slow inflation, this would exacerbate the fall in overall economic activity from the carbon policy—thus lowering gross domestic production (GDP), employment, and welfare relative to other ways a central bank could react. The political backlash from such macroeconomic outcomes may create fewer incentives for political actions on emissions reduction. Second, a sustained rise in the relative price of carbon could enter into wage negotiations, for example, if workers anticipate a decline in the buying power of their earnings, even if carbon-tax revenues are recycled. In this case, an inappropriate monetary policy response could lead to a wage–price spiral as people find it harder to forecast inflation and therefore lose an important anchor for inflation expectations. Untethered inflation expectations could lead to a costly long-lived inflationary process.

Thus, in light of the urgency of ambitious climate action and the clear conceptual relationship between the policy frameworks, we argue that monetary and climate policy should be considered jointly. From a monetary perspective, climate change and climate policy are both supply and demand shocks, and the monetary policy literature has long emphasized the importance of supply shocks versus demand shocks in the choice of a monetary regime. Thus, the insights from this large historical literature can inform the climate/monetary policy discussion of today. In a world characterized by continual climatic disruptions, especially on the supply side, the need for rethinking the monetary policy framework in the context of how to price carbon is high.

Given the theoretical discussion, we then outline the key features needed in economy-wide macroeconomic models for policy-makers, that would enable an analysis of climate and monetary regimes and their interaction. We then present an overview of G-Cubed, a model that has these features. Finally, in section VI we present results from G-Cubed to show how three different monetary regimes lead to different inflation, output, and emission outcomes under a carbon tax.

II. Climate policy

In this section, we discuss basic options for GHG emissions mitigation policy, which fall broadly into two categories: (i) establishing an explicit, economy-wide price for emitting carbon dioxide (CO_2), or (ii) adopting a suite of regulatory measures and subsidies. Any of these approaches can impose burdens on the economy, but they also provide environmental benefits that can justify their costs. Although we focus here on the economic costs of climate policy, we emphasize that important positive net benefits can accrue from efficiently controlling GHG emissions and reducing the risks of climatic disruption and ocean acidification. Hepburn (2006) provides a complete discussion of the choice of climate policy instruments. Here we focus on the design details of these approaches that have different implications for monetary policy.

(i) Carbon pricing

Economists widely agree that the most efficient approach to reducing GHG emissions is to establish a price on those emissions. Policy-makers can set the price directly on fossil-fuel-related CO_2, the largest constituent of overall GHG emissions, and several other GHG emissions via a tax. For fossil CO_2, the tax could fall on the carbon content of fossil fuels or the CO_2 emitted from burning fuels. Alternatively, policy-makers can impose a price indirectly through a tradable permit system, or through a hybrid policy that has a mix of the characteristics of tax and permit programmes.

Carbon taxes

A carbon tax is the most direct and transparent approach for establishing a price on carbon emissions. Policy-makers have many options for the design of a carbon tax trajectory and the related provisions of the policy, including the use of the revenue. For example, the tax could be set equal to an estimate of the marginal social cost of carbon (SCC) which would internalize the externalities associated with climate change. The tax could be designed to achieve particular emissions or revenue goals. A typical proposal would set a starting value for the tax and specify a rate at which the tax should rise over time in real terms.

The magnitude of the carbon tax can depend on the emissions goal and, importantly, when the policy starts.

A carbon tax has three key features that matter for the monetary authority: (i) the trajectory of the tax is known in advance; (ii) there will be a significant initial impact on the price level when the tax is first established; and (iii) the growth of the tax in real terms over time will introduce an upward trend in prices and, other things equal, push the economy toward a higher overall rate of inflation—at least through the medium run. Also, although a carbon tax establishes a predictable price, its impact on emissions will vary from year to year with economic conditions, technological change, and other factors.

Research has shown that the ultimate economic impact of a carbon tax depends on the use of the revenue that it raises. For example, reducing marginal rates on other taxes, such as those on labour and capital, can reduce the existing distortions in those markets and thus offset some of the macroeconomic burdens of the carbon tax (Pearce, 1991; Metcalf, 2007). McKibbin *et al.* (2012) find that using carbon-tax generated revenue to offset capital income tax burdens leads to a more pro-growth effect of a carbon tax on the US economy. In contrast, Metcalf (2007) and Perry and Williams (2010) find that using the revenues to reduce labour taxes generates higher welfare gains than when used to reduce capital taxes. Although there is no empirical consensus on the optimal use of the tax revenues, there is a strong consensus that carbon tax policies whose revenues are recycled efficiently can promote emissions abatement at lowest cost (McKibbin *et al.* 2018; Liu *et al.*, 2019). The policies can also have, importantly different distributional consequences.

Tradable permits

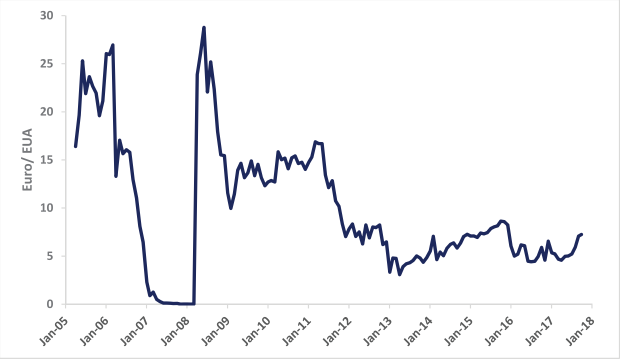
An alternative way to limit GHG emissions would be to establish a system of tradable emissions permits. For example, a regulator could require fossil fuel producers or users to have a permit for each metric ton of CO_2 emissions that would be associated with those fuels. The regulator would then choose a target level of emissions for each year, issue that number of permits (a range of mechanisms for distributing permits are discussed in the literature), and allow trading. To emit a ton of CO_2, a fuel user would need to buy a permit at the market price (or would have to forgo selling a permit at that price), so the market price would become the *de facto* price of emitting CO_2. This approach establishes a predictable level of emissions. With a fixed supply of permits (assuming no banking or borrowing across compliance periods), any change in the demand for permits, such as fluctuations in economic conditions, will cause the carbon price to vary from year to year along a vertical supply curve for permits. Thus, from the perspective of the monetary authority, this approach is quite different from a carbon tax because the number of permits (and hence the level of emissions) in each future year may be known in advance. The initial price would not be known in advance and would be determined by market forces after the implementation of the policy. Finally, the rate of growth of the price would be determined by market forces as well.

Both the implementation of the policy and business-cycle shifts can greatly influence the level and volatility of permit prices in a cap-and-trade system. For example, the programme can allow banking and borrowing of emissions allowances across compliance periods or establish a floor and ceiling on permit prices (Fell *et al.*, 2012).

To illustrate the potential volatility of emissions permit prices in practice, Figure 1 reports the history of the futures prices of the emissions allowances in the European Union's Emissions Trading System (ETS).

Some of the factors that contributed to the volatility included an inadvertent oversupply of allowances in the early phases of the programme and a major financial and economic crisis in 2008 that dramatically reduced demand for allowances.

Figure 1: The futures price of allowances in the EU ETS from January 2005 to October 2017. *Notes*: Unit of trading: one lot of 1,000 Emission Allowances. Each Emission Allowance is an entitlement to emit one metric ton of CO_2 equivalent gas. Contract series: consecutive contract months to March 2008, and then December contract months only from December 2008 to December 2012. *Source*: Bloomberg.



Hybrid policies

A third approach would be a hybrid of the tax and permit policies. McKibbin and Wilcoxen (2002) develop such a policy. This approach is analogous to how the US Federal Reserve (the Fed) sets short-term interest rates while the bond market sets the long-term interest rate through market transactions (McKibbin, 2012). In this policy, the cumulative emissions target for a country is used to determine a declining annual flow of emissions which achieves the target at a specified date in the future. Each year's desired annual emissions level is used to determine a matching annual quantity of emission permits. These annual permits are then combined to create a long-term emissions bond, where the annual coupons on the bond are the annual emission permits. The allocation of these long-term bonds to current individuals and firms should be undertaken at the beginning of the programme. An agency that might be called a 'central bank of carbon' then announces a short-term maximum carbon price, or price ceiling for the current year or several years into the future. Fixing the short-term carbon price is much like the approach of the Fed which announces a short-term interest rate. In the current year, the central bank of carbon makes available as many annual permits as demanded at the ceiling price, effectively capping the price of carbon in that year. If a small number of long-term permits are made available in the early years of the policy, then the short-term carbon price cap will always be binding unless there is a substantial reduction in emission at low cost. The long-term price of carbon, however, will be determined in the futures market for carbon emission rights available in future years (much like the long-term bond market determines long-term interest rates). In the market for future emission rights, the carbon targets are balanced against expectations of future short-term prices, where each year's expectation is either the market equilibrium price in that year or the ceiling price set by the agency, whichever is lower. Thus, the short-term price is equivalent to a carbon tax (when the cap is binding, which is likely if few long-term permits are issued), but the long-term price is determined by future cap and trade markets. In terms of its impact on monetary policy, a hybrid policy would be midway between standard tax or permit policies. It would: (i) establish a ceiling price trajectory known in advance; but (ii) allow actual prices to be lower than the ceiling when market conditions warrant; and (iii) allow variation in emissions from year to year.

(ii) Non-price emissions abatement policies

Although pricing carbon and other GHGs has many attractive features, a number of other climate policies have been proposed. For example, the US Environmental Protection Agency (EPA) drafted the Clean Power Plan as a regulatory approach to reducing emissions from the electric sector. Under that regulation, states were required to achieve specified targets for average CO_2 emissions per kilowatt-hour of electricity generated from existing power plants (they could also opt instead to achieve a target having an equivalent mass of CO_2). Other policies aimed at reducing emissions include tighter fuel efficiency standards for vehicles; production and investment tax credits for renewable electricity; renewable portfolio standards for electric utilities; and tax credits for a range of goods such as residential solar systems, electric vehicles, and home and business weatherization. At their core, these policies impose implicit prices on the use of fossil fuels because they impose a cost or monetary incentive on incremental emissions-reducing activities. However, unlike the explicit carbon pricing policies discussed above, the prices are not directly observable, differ from one sector and state to the next, and do not have clear predictable trajectories. They are also likely to yield higher carbon abatement costs because of the nature of the policy. As a result, accounting for them in setting monetary policy is far more difficult. For example, a regulatory approach like the Clean Power Plan can raise electricity prices by amounts that are hard to predict and differ significantly across the country owing to regional variations in stringency and implementation strategy.

(iii) Policy impacts

Whether implemented as a broad-based emissions price or as a suite of narrower actions, a carbon abatement policy affects the economy in two ways. First, it increases production costs and the relative prices of carbon-intensive goods and services, negatively affecting real wages, consumption, investment, and, ultimately, output. Second, the policy may exacerbate the distortionary effects of existing taxes in the economy, particularly in the labour market. This occurs because existing taxes on labour income reduce the incentive to work by reducing the returns to labour. A carbon tax raises price levels, thereby lowering the real wage, further decreasing the incentive to work and exacerbating the existing distortions in the labour market. This 'tax interaction effect' is potentially quite large, suggesting the benefits of using the carbon tax revenue to reduce other tax rates may be significant. Indeed, modelling has supported this finding (McKibbin *et al.*, 2012).

Although each climate regime can be designed to achieve the same emissions target at the same point in time, the various climate policy frameworks can produce different inflation and output dynamics. In particular, it is this that matters for the short-run response of monetary policy.

III. Monetary policy

How the objectives of monetary policy—price stability and employment expansion—are achieved for any economy depends on many factors, notably the structure of the economy and the nature of macroeconomic shocks to which the economy is susceptible. While the broad macroeconomic stability experienced throughout the 'Great Moderation' may have partly been explained by the introduction of inflation targeting across much of the developed world, the global financial crisis (GFC) and the ensuing Great Recession have reignited the longstanding debate (see Meade, 1978; Henderson and McKibbin, 1993; Taylor, 1993) on the optimal monetary policy framework. Among the leading central banks, the search for the optimal framework suitable for the rapidly changing economy is ongoing (Bernanke, 2017; Clarida, 2019). Towards such an end, the recent literature has compared macroeconomic performance under inflation targeting with counterfactual outcomes under two main rules: price-level targeting and nominal income targeting. In this section, we provide a summary of these rules (see McKibbin and Panton, 2018; Svensson, 2020).

(i) Inflation targeting

Typically, inflation targeting involves making discretionary decisions on how to respond *flexibly* to the deviations of inflation from target and output (or employment) from the long-term target. Implementation of this framework requires the forecasting of the values of the relevant policy values (Bernanke *et al.*, 1999; Svensson, 2020). This process is complicated by rapidly changing macroeconomic conditions in a climatically disrupted world.

In practice, central banks that use inflation targeting must anticipate how the economy will adjust over future periods to a change in policy today (Bernanke and Gertler, 1999; Bernanke, 2007). An example appears in equation 1 below, used for setting the interest rate, where $\pi_{t,t+1}$ is the bank's forecast at time t of the inflation rate at time $t+1$ and $\bar{\pi}_t$ is its inflation target:

$$i_t = i_{t-1} + \alpha \quad (\pi_{t,t+1} - \bar{\pi}_t) \tag{1}$$

This approach makes clear that an accurate forecast of inflation is critical to the central bank's success and credibility. And the key to that forecast is the measurement of the output gap: the difference between the actual and potential output[1] of the economy. For example, a forecasting rule might be that inflation will be the target rate adjusted by an increasing function f of the difference between real output of the economy, Y_t, and the central bank's assessment of the economy's maximum potential output, Y_t :

$$\pi_{t,t+1} = \bar{\pi}_t + f(Y_t - \bar{Y}_t) \tag{2}$$

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[1] Potential output is the maximum sustainable output the economy could produce given: (i) optimal use of the economy's supplies of labour, capital, and other primary factors; and (ii) the levels of total and factor-specific productivity.

If the actual output is equal to potential output, the bank will expect inflation to be at its target rate$\bar{\pi}_t$. In contrast, if actual output is below potential output, then it will expect inflation to be lower than $\bar{\pi}_t$, and if the output is above potential output, then it will expect inflation above $\bar{\pi}_t$. However, both Y_t and $\bar{Y}_t$ are estimates and are inherently uncertain. Thus, the central bank may make errors in forecasting the output gap and thus use a poor forecast of inflation in its targeting strategy.

(ii) Price level targeting

Price level targeting (PLT) is similar to inflation targeting, but the target is the price level itself rather than the inflation rate. If there is a rise in inflation above target, the central bank not only acts to eliminate the excess inflation but induces a period of below-target inflation in order to return the price level to its target trajectory. In this sense, the initial price level casts a long shadow over the future path of prices. An example of setting central bank interest rates with PLT appears in equation 3, where the actual price level is P_t and the target level is $\bar{P}_t$:

$$i_t = i_{t-1} + \alpha \quad (P_t - \bar{P}_t) \tag{3}$$

With the core objective of maintaining the price level along the desired path by compensating for lower past inflation with higher current inflation, PLT is an effective policy rule for anchoring expectations as long as private agents correctly account for its implicit history dependence (Svensson, 1996). This requires that monetary policy is credible enough to be the main anchor of price expectations (Amano *et al.*, 2011). Under a binding zero lower bound (ZLB) constraint, Bernanke (2017) proposes a state-contingent temporary PLT framework that involves combining inflation targeting with price-level targeting.

That is, via forward guidance, the central bank can commit to maintaining an accommodative policy stance following a deep recession until achieving average inflation, and employment targets. However, during normal times, monetary policy is conducted using inflation targeting, although switching the policy stance during recessions may render monetary policy less effective in anchoring expectations (Bodenstein *et al.*, 2019).

(iii) Henderson–McKibbin–Taylor Rules

In contrast to rules focused only on inflation or the price level, Henderson–McKibbin–Taylor (HMT) rules include an explicit balancing of a central bank's goals of price and output stability. Henderson and McKibbin (1993) outlined a general set of rules that specified the way in which interest rates could respond to both inflation and the output gap. This is shown in equation (4):

$$i_t = i_{t-1} + \alpha \quad (\pi_t - \bar{\pi}_t) \quad + \beta(Y_t - \bar{Y}_t) \tag{4}$$

Parameters α and β govern how the central bank balances its goals for inflation and output. They can either reflect the preferences of policy-makers or could be calculated optimally given the structure of the economy.[2] They showed that these parameters are

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[2] Typically, the latter would be done by representing the central bank's objective via a loss function that is quadratic in deviations in inflation and output. The parameters of the rule would then be chosen to minimize the expected loss.

especially dependent on the stickiness of nominal wages, meaning the tendency of wages to respond slowly to changes in the performance of a company or the broader economy. Taylor (1993) used this general form of the rule and selected specific values of α and β to replicate the historical behaviour of the Fed between 1984 and 1992. Others have since econometrically estimated the parameters of the HMT rule for the Fed and found results close to Taylor's original calibration.

A more general HMT rule is implemented in the G-Cubed multi-country model (McKibbin and Wilcoxen, 2013). G-Cubed allows the modelling of a wide variety of central bank policy rules, including exchange rate targeting, money supply targeting, or a variety of explicit trade-offs between variables that reflect policies adopted by central banks in different countries. Equation (5), for example, is a generalization of equation (4) that includes potential weights on the exchange rate (e_t with target $\bar{e}_t$) and the money supply (M_t with target $\bar{M}_t$).

$$i_t = i_{t-1} + \alpha \left(\pi_t - \bar{\pi}_t\right) + \beta\left(Y_t - \bar{Y}_t\right) + \delta\left(e_t - \bar{e}_t\right) + \sigma(M_t - \bar{M}_t) \tag{5}$$

These additional terms allow the equation to represent a wide variety of rules. For example, a central bank in a small country that aims to peg its currency to the US dollar would have $\alpha = \beta = \sigma = 0$ and a very large value for δ. The Bank of China, on the other hand, might be represented by a rule with roughly equal values for α, β, and δ (that is, assigning equal importance to the first three objectives) and set $\sigma = 0$.

(iv) Nominal income and nominal GDP targeting

Monetary policy-makers can target a measure of nominal economic activity instead of inflation or price levels. Targeting nominal economic activity means that policymakers try to avoid recessions (in nominal terms) to maintain a steady increase in economic activity or a particular rate of growth. There are several different measures of economic activity that central banks could target. Nominal GDP is a measure of the value-added in an economy at current prices. Nominal income is a measure of the value of income generated by economic activities, including by individuals and businesses, measured at current prices. Nominal gross output is the value of final plus intermediate goods produced in an economy. In a single good model, such as most macroeconomic models, nominal GDP and nominal output would be equivalent. In a multi-sector model, intermediate goods production would imply a difference between total gross production and value-added. In the US economy, the concepts of nominal GDP and nominal income are similar. In a small open economy with a large amount of foreign capital, the two measures diverge due to payments of dividends to foreign capital owners. In the following discussion, we will use nominal income targeting (NIT) as shorthand for each type of rule. Equation 6 represents a nominal income rule where nominal income is represented by PY_t and the bank's target for it is $\bar{PY}_t$:

$$i_t = i_{t-1} + \alpha \quad (PY_t - \bar{PY}_t) \tag{6}$$

The rule can also be written in terms of the rate of change in nominal income, where g_t is the growth rate of nominal income rather than its level, and $\bar{g}_t$ is the bank's target:

$$i_t = i_{t-1} + \alpha \quad (g_t - \bar{g}_t) \tag{7}$$

There is a large and long literature supporting NIT rules (see Meade, 1978; Bean, 1983; Henderson and McKibbin, 1993; McCallum, 2011, 2015; Frankel, 2012; Woodford, 2012; Sumner, 2014; Beckworth and Hendrickson, 2016). The advantage of an NIT rule is that it has implicit weighting on both prices and output. Moreover, in its growth rate form, it applies equal weights to inflation and output growth. Both can be shown to be equal to α.

NIT rules respond to demand shocks in the same direction as inflation targeting: i.e. raising interest rates in the face of a positive demand shock. However, the magnitude of the change may be different from inflation targeting since the rule includes implicit weighting of output changes as well as inflation. Under the NIT approach, there is no need for the existence of 'divine coincidence' (Blanchard and Galí, 2007) for the output and price stability objectives to be achieved in the face of demand shocks (Bean, 1983; Rogoff, 1985; Ball and Mankiw, 1995; Frankel, 2012; McKibbin, 2015).

The main difference between nominal income and inflation targeting is the rule's response to a shock to aggregate supply. As inflation rises and output falls under an aggregate supply shock, an NIT rule weights the changes equally. For example, a central bank facing a shock that raised the price level and reduced output by equal percentages, thus leaving nominal GDP unchanged, would leave the interest rate unchanged. Thus, the major advantage of nominal GDP targeting highlighted in the literature is that it gives the central bank the ability to handle permanent supply shocks with close to optimal monetary policy outcomes (Rogoff, 1985; Henderson and McKibbin, 1993; Frankel, 2012; Garin *et al.*, 2015). In the case of a persistent change in real trend growth, the implication of not changing the nominal GDP target would be a permanent change in the rate of inflation.

IV. Jointly optimizing climate and monetary policies

Having reviewed the basics of both climate policy and monetary policy, we now consider the interactions between the two. Following that, we discuss the implications of extreme weather events and other climatic disruptions for joint management of climate and monetary policy.

(i) Climate policies

This section examines each climate policy regime to consider the implications of each major monetary policy for that particular climate policy regime.

Carbon taxes

From a monetary perspective, a carbon tax is a complex aggregate supply shock. On the one hand, the tax increases cost in the fossil energy sector and thus reduces the total output that can be produced for a given set of primary factors. On the other hand, if revenue from the tax is used to lower other distortionary taxes, that component of the policy would be a supply shock in the other direction, lowering costs and increasing potential output. To keep things simple, in the discussion below we assume that the net macroeconomic impact, not accounting for the environmental benefits of the policy, is negative; that is, that any positive supply impacts from reductions in other taxes are not sufficient to fully offset the negative impact of the carbon tax itself. Thus, real output may return to its baseline rate of growth but the level of output would be lower at each point in time relative to what it would have been.

First, consider a simple scenario. Suppose a central bank has set a target rate of inflation at 3 per cent per year and has been achieving it for several years. The government then imposes a carbon tax that takes effect immediately (at $t = 0$), has not been anticipated by private agents, and once established is held constant indefinitely. Overall economic output would decline and inflation would spike up.

With no response by the central bank, and assuming that private agents recognize that the policy is effectively a one-time change in relative prices and thus do not expect subsequent changes in the underlying inflation rate, the inflation rate would quickly return to its original level. The price level would step up to a higher level overall. The relative price of carbon-intensive goods would be permanently higher. The level of real output would be permanently lower but the rate of growth of real output would return to baseline.

Now consider various ways a central bank might respond to this 1-year spike in inflation. A central bank using strict inflation targeting would see the inflation spike at $t = 0$ and respond by raising the interest rate. That would slow the economy further than the carbon tax did on its own, and it would also cause the exchange rate to appreciate, making imported goods cheaper but exports uncompetitive. Both impacts would reduce the underlying inflation rate in the economy, partially offsetting the increase in overall inflation caused by the tax. However, the decline in output would be worse than if the central bank had not responded. Moreover, lags in the propagation of interest rate changes through the economy could easily cause the impact of the rate increase to occur at $t = 1$ or later when inflation would otherwise have returned to baseline.

A central bank using *flexible inflation targeting* (FIT) might avoid exacerbating the output effect of the tax if it recognized that the carbon tax was a one-time step in the price trajectory and did not change interest rates. In practice, however, fluctuations in the economy from year to year will mean that the bank may have difficulty separating the impact of the carbon tax from that of other events that may have caused it to miss its target for year 0. A central bank that was aware of the tax and was using FIT would want to raise interest rates slightly in year 0 and somewhat more in year 1 to offset the baseline component of the inflation rate. However, it would be challenging in practice to separate the baseline component from the portion due to the carbon tax. Without understanding the interaction of monetary and climate policies, the bank may mistake all of the inflation in year 0 for a baseline deviation and thus raise interest rates far more than would be desirable.

Understanding the nature of the climate policy response would be even more critical for a central bank using PLT. Without an appropriate rule, the bank would not only offset the inflation shock but would tighten monetary policy even further to return the price level to the original trajectory.

If the bank does not understand the nature of the carbon abatement policy, both HMT and NIT (as automatic rules) will perform better than inflation targeting because both rules would lead to less tightening of monetary policy. A central bank using an HMT rule would weigh the rise in inflation against the fall in output, and it would thus raise interest rates less than a bank using inflation targeting. The bank might even lower interest rates if the rule's weight on output or the output decline itself were sufficiently large. Similarly, a central bank using an NIT rule would implicitly account for the fall in output: although P would rise, the decline in Y would mean that PY would rise less than P alone would suggest.

In practice, a critical element in determining how a central bank would react would be the bank's assessment of inflationary expectations. This is particularly important because the most likely carbon tax policy is not a single once-and-for-all step, but rather an initial step followed by a rise in the carbon tax rate in real terms over time. This is more complicated for the central bank because the shock potentially changes the rate of inflation as well as the price level, and possibly changes the rate of growth of actual and potential output as well. Accommodating the carbon tax policy would thus require that the bank raise its target inflation rate. However, doing so is relatively straightforward since the carbon tax is known in advance. The bank could anticipate the impact it would have on the inflation rate and adjust its target accordingly.

Tradable emission permits

The issues discussed for the interaction of the carbon tax with the monetary regime would also apply under a tradable permit policy. However, the main difference is that the future trajectory of permit prices would be less certain than the carbon tax (which would be set explicitly in the policy). Permit prices would be uncertain for at least two reasons: (i) uncertainties in the marginal cost of abatement at the emissions limit; and (ii) variations in economic conditions that affect the demand and supply of fossil energy. As a result, the impact of the policy on prices would be uncertain, and it would thus be more difficult for the central bank to adjust monetary policy to deal with the volatility of prices generated by the permit trading system.

Hybrid policy

The advantage of a hybrid policy over a permit trading system would be that the carbon price in the short term would have the same predictability as does the carbon tax as long as the ceiling price was binding (which it would be designed to be in practice). The long-term expected carbon price would be clear from the long-term permit market. Depending on the length of time of the fixed price on a hybrid policy, the problems for the central bank would be smaller than in a more volatile trading system.

Regulatory and other responses

Relative to a carbon pricing policy, regulations, subsidies, and standards to control GHG emissions would be more difficult for a central bank to anticipate and respond to since the effects on output and prices would be opaque and hard to predict. This would be true under each monetary rule because of the challenge in assessing the consequences of such policies on current and potential output and current and expected inflation.

(ii) Climatic disruption and output volatility

There is strong empirical evidence that extreme weather events reduce economic growth (Cavallo and Noy, 2010) in the short run. For example, droughts and floods can disrupt agricultural activity and damage crops (Gandhi and Cuervo, 1998). Extreme weather can also reduce the effective labour supply due to climate-induced health impacts (Fankhauser and Tol, 2005), and it can increase the rate of capital depreciation (Stern, 2013). In short, as climate disruption leads to more frequent (or more damaging) extreme weather events, monetary policy-makers will need to respond to more frequent (or larger) negative supply shocks.

A central bank following strict inflation targeting would react to an extreme weather event by tightening monetary policy to stem the rise in inflation. A bank following PLT would react even more strongly, raising interest rates enough to reduce the price level back down to its target. In both cases, the bank would worsen the impact of the shock on economic activity.

A central bank using FIT might avoid exacerbating the fall in output if it accounted for the transitory nature of the event and chose to use its discretion to adjust the timing of policy adjustment. However, its task would be made difficult by imperfect real-time measurement of the output gap (Orphanides, 2000). There is substantial evidence indicating that the Fed's estimates of the output gap under normal economic conditions have been prone to large errors (Orphanides, 2000, 2004; Sumner, 2014). For example, using a New Keynesian model with imperfect information, Beckworth and Hendrickson (2016) show that the Fed's output gap forecasts over 1987–2007 explain only 13 per cent of the fluctuations in the actual output gap. Estimates during periods of unusually persistent and unpredictable productivity shocks, as would be the case with increased climatic disruption, could be even worse, although the output may be adjusted to account for such shocks (Panton, 2020). In general, more frequent or intense shocks make inflation forecasting more difficult for both the central bank and private actors, which erodes the rationale for basing monetary policy primarily on inflation forecasts.

In contrast, a central bank using an HMT or NIT rule would respond to extreme weather shocks by balancing the rise in prices against the drop in economic output caused by the event. As with the onset of a carbon tax, such a central bank would be less likely than an inflation-targeting bank to exacerbate the damage to the economy. However, implementing an HMT rule in a changing climate would be challenging for a reason mentioned above. An increase in the frequency of extreme weather events raises the difficulty of forecasting potential output and therefore the output gap.

An advantage of NIT is that the central bank using NIT does not need to have a precise estimate of the output gap because only the nominal income target is announced. As a concrete example, suppose the growth rate of potential output is estimated by the central bank to be 3 per cent per year, and the desired inflation rate is 3 per cent. The nominal income target growth rate for a central bank with an NIT rule would, therefore, be the sum of the two: 6 per cent. Now suppose that an extreme weather event causes potential output growth to fall to 2.5 per cent over the forecast period, meaning that the event reduces potential output by 0.5 per cent. If the NIT central bank achieves its 6 per cent nominal income target, output growth would be 2.5 per cent and the inflation rate would be 3.5 per cent. Inflation would have exceeded the bank's preferred value of 3 per cent. However, the discrepancy is too small to undermine the expectation of private agents and financial markets that the bank is committed to a clear rule. That means that with NIT, the bank limits the rise in expectations of higher inflation, preventing a wage–price spiral. Indeed, the central bank does not even need to observe or account for the precise nature of the shock: simple adherence to the policy rule gives a reasonable policy response. Thus, rules like NIT that do not rest on output gap calculations are better for promoting macroeconomic stability than those that do, especially during periods with an unusual number of supply-side macroeconomic shocks.

(iii) Climatic disruption and financial stability

As mentioned in the introduction, some analysts are also concerned that climatic disruption, and the policy responses to it, can weaken financial stability (Carney, 2015; Bank of England, 2015; NGFS, 2019), which some authors argue should be an additional responsibility of central banks. Stability of the financial system in the short run may differ significantly from the stability of output and employment. For example, when debt contracts are secured by assets priced in nominal terms, sharp changes in the price level can trigger widespread cascades of asset sales. These sales would temporarily drive asset prices down much further than the initial changes in output and employment would warrant. Although the empirical evidence on how extreme weather events affect financial stability remains mixed, some believe severe and persistent climate-induced natural disasters pose serious risks to the stability of the financial system (Bank of England, 2015; Carney, 2015). According to the Bank of England (2015), apart from the climate-induced physical risks ranging from severe weather events like flooding, droughts, and disruption of agricultural productivity, insurance firms face losses from climate damages that they may not be able to diversify fully. The potential for abrupt constraints on GHG emissions can also pose risks to financial assets and the balance sheets of fossil energy companies. Highly ambitious climate policy could strand capital and weaken the profitability of firms (Dafermos *et al.*, 2016). Still, policy-makers will take such outcomes into account in their decisions about which policies to adopt.

Research is emerging on how monetary policy could foster climate-related financial stability, with some advocates arguing for 'green' quantitative easing (QE) arrangements by many central banks (Murphy and Hines, 2010; Campiglio, 2016). Some argue that central banks can address credit market failures that impede low carbon investments by expanding their balance sheets with securities of entities engaged in low-carbon activities (e.g. renewable energy) (Campiglio, 2016). Apart from the use of QE programmes, some argue for the inclusion of financial stability as a permanent monetary policy objective, particularly in an economy prone to persistent supply shocks that endanger financial stability (Cecchetti *et al.*, 2000; Woodford, 2012). However, a long-standing argument remains that monetary policy should focus on the traditional goals of price and output stability, with financial stability concerns best handled by regulatory tools such as macroprudential policies (Bernanke and Gertler, 1999, 2001; Bank of England, 2015).

Sheedy (2014) provides strong empirical evidence that when debt contracts are written in nominal terms, NIT outperforms FIT. The results arise from improving financial market risk allocation mechanisms, particularly by insulating households' nominal income from shocks even when there is short-run price stickiness. Sheedy argues that since the ability of borrowers to meet their obligations is more related to their income, a monetary policy rule that puts more weight on nominal income than price stability is most suitable in addressing asset price bubbles. Examples include those that could result from the short-run consequences of a carbon tax (i.e. stranded asset risks). Using a model with default probabilities and bankruptcy costs, Koenig (2013) also reached a similar conclusion, strongly upholding the view that in an economy with adverse supply shocks and nominal debt contracts, targeting nominal income is the optimal monetary policy approach to containing asset price risks.

V. Features needed in macroeconomic models for policy-makers

The discussion above makes it clear that macroeconomic models that are needed to analyse climate shocks, climate policy, and the interaction with monetary policy would need to be more complex than most well-known existing dynamic stochastic general equilibrium (DSGE) models.

A model needs several features to be able to analyse climate shocks and climate policy. First, there needs to be a consistent macroeconomic framework. Second, there needs to be disaggregation of the energy generation sectors, since different energy-producing sectors have different carbon intensities and carbon policies impact on fuel types differently due to the variation in the carbon content of alternative energy sources and the characteristics of the markets they serve. Third, and more importantly, models need sufficient sectoral disaggregation to account for how climate shocks and changes in energy prices impact sectors differently. For example, transportation and manufacturing would be affected differently by changes in carbon prices. These changes across sectors can have macroeconomic implications. Fourth, there needs to be a financial sector with different types of assets and different capital stocks across sectors, so the issue of stranded assets and changes in return to capital from carbon reduction policies can be taken into account. Finally, the model should be global since climate shocks, climate policies, and monetary policies all have impacts that are propagated across countries.

VI. The G-Cubed model and some applications

The G-Cubed multi-country model is an intertemporal general equilibrium model which the original authors describe as a hybrid of DSGE and computable general equilibrium (CGE) models. The model is documented in McKibbin and Wilcoxen (1999, 2013). Some of the key features, particularly the interaction of sectoral relative prices and macroeconomic outcomes, have been highlighted in McKibbin and Stoeckel

(2018). The model is global with the world economy disaggregated into the countries and regions in Table 1.

Within each region, there are multiple firms as well as household and government sectors which all interact in markets for goods, services, and primary inputs. There are also markets for equities, bonds, household capital, and foreign exchange. Production is represented by an explicit set of heterogeneous firms, one for each sector. Table 2 summarizes the 20 sectors in each economy.

G-Cubed is a 'hybrid' model, in the sense used in the papers published in the 'Rebuilding Macroeconomic Theory Project', in the January 2018 edition of the *Oxford Review of Economic Policy* (see Vines and Wills, 2018; Blanchard, 2018; and Wren-Lewis, 2018). The term 'hybrid' means that the model has features both of a micro-founded DSGE model and of a 'policy model' or 'structural economic model'.

The G-Cubed model includes all of the features of a micro-founded DSGE model: there are optimizing agents who are subject to two important frictions. In this sense the model is

Table 1: Regions in the G-Cubed model

Region	Region description
Australia	Australia
China	China
Europe	Europe
India	India
Japan	Japan
OPEC	Oil-exporting developing countries
ROECD	Rest of the OECD, i.e. Canada, New Zealand, and Iceland
ROW	Rest of the world
Russia	Russian Federation
USA	United States

Table 2: Sectors in the G-Cubed model

	Sector name	Notes
1	Electricity delivery	Energy sectors other than generation
2	Gas utilities	
3	Petroleum refining	
4	Coal mining	
5	Crude oil extraction	
6	Natural gas extraction	
7	Other mining	Goods and services
8	Agriculture and forestry	
9	Durable goods	
10	Nondurables	
11	Transportation	
12	Services	
13	Coal generation	Electricity generation sectors
14	Natural gas generation	
15	Petroleum generation	
16	Nuclear generation	
17	Wind generation	
18	Solar generation	
19	Hydroelectric generation	
20	Other generation	

like the Smets–Wouters (2007) model or the Christiano *et al.* (2005) model. The first friction can be found in the process of capital accumulation in each sector of each economy. This is driven by an investment function that is subject to quadratic adjustment costs. As a result of this friction, investment leads to a gradual adjustment of the capital stock over time; what happens is that investment responds to the value of Tobin's q, with 30 per cent of firms responding to a forward-looking q which evolves in a model-consistent manner with the remaining 70 per cent of firms having a backward-looking q.

The second major friction is in the wage-setting process. Nominal wages are driven by a Calvo–Rotemberg-style Philips curve (in which some workers are backward looking), while prices are set by profit-maximizing firms in each sector. The firms hire labour up to the point at which the marginal product of labour equals the real wage defined in terms of the output price level of that sector. As a result of these assumptions, nominal wages are sticky and adjust over time in a way which depends on labour-contracting assumptions, something which is allowed to differ from country to country. Any excess supply of labour enters the unemployed pool of workers. Unemployment, or the presence of excess demand for labour, causes the nominal wage to adjust over time in a way which—taken in conjunction with the monetary rule and the behaviour of the nominal exchange rate—will ensure that the labour market clears in the long run. In the short run, unemployment can arise both because of structural supply shocks and because of changes to aggregate demand in the economy.

The behaviour of some consumers (30 per cent) is driven by an Euler equation in which consumption in any period responds both to the contemporaneous real interest rate and to a forward-looking expectation of future consumption (one which evolves in a model-consistent manner). The remaining 70 per cent of consumers follow a simple rule of thumb where they consume their entire income each period. This can also be interpreted as if they are liquidity constrained.

As noted, like in the Smets–Wouters model and in the Christiano *et al*. model, there are two fundamental frictions in the model. One is in the process of capital accumulation (because of adjustment costs in the investment function), and the other is in the inflationary process (because of the overlapping nature of the wage-setting process). Together these two features mean that the model has new-Keynesian features and does not behave, in the short run, like a real business cycle (RBC) model. But crucially, in the long run the model does have RBC properties.

The model is much closer than most DSGE models to what Blanchard (2018) calls a policy model, or what Wren Lewis (2018) calls a structural economic model. There are several aspects to this resemblance. First, the model pays attention to the need to disaggregate output into a number of different sectors, whose relative prices may move during simulation. In addition, the model captures inter-industry linkages (in that some of the output of some industries serves as inputs into other industries), and it treats the price of energy and mining as determined in a different manner from that of manufactured goods or services.[3] Because of this there are many features of the model's behaviour which will be familiar to those who have experience with using computable general equilibrium (CGE) models.

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[3] Allowing for changes in the relative prices of the goods produced in these six sectors has been absolutely fundamental in modelling the Baseline simulation for the present study, essentially because the prices of energy and mining have suffered catastrophic downturns as a result of the COVID-19 shock.

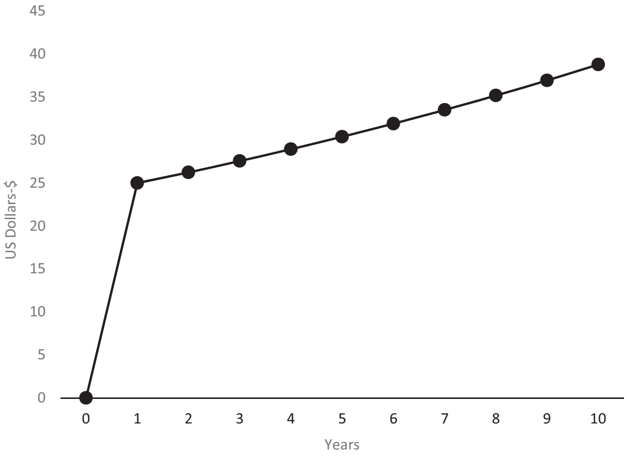
Being global, the model needs to capture the effects of international trade and of international capital flows. Trade balances are determined by carefully modelled export functions and import functions for each country, which map consistently into the equations for imports and exports in other countries; changes in real exchange rates between countries have significant and important influences on trade flows between countries within the model. The model supposes perfect international mobility of capital between countries, and the exchange rate is determined, *à la* Dornbusch, by the uncovered interest parity (UIP) condition, except for countries having pegged exchange rates and for those countries within the European Monetary Union. But there is explicit allowance for risk premia in these UIP equations.

McKibbin and Stoeckel (2018) summarize a large number of applications of this model.

Using the G-Cubed model, we performed simulations that show how the joint optimization of climate and monetary policies may lead to far superior macroeconomic outcomes than when each policy framework is considered separately. To keep things simple, we consider a scenario in which the United States alone adopts a tax of $25 per ton of carbon, growing at 5 per cent per year, with the carbon tax revenue recycled to households via lump-sum rebate. Figure 2 displays the tax.

We considered three alternate monetary policy frameworks based on the discussion in section III. Under the first regime, the central bank follows a pure inflation target (equation 1).[4] Under the second regime, the central bank follows a nominal income target (equation 7).[5] Under the third regime, the central bank follows a more conventional flexible inflation targeting regime as typified by the Henderson–McKibbin–Taylor rule (equation 4).[6]

Figure 2: Annual US carbon tax



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[4] By setting the weight on price stability, α, to 100 in the rule, the central bank seeks to accommodate any deviation of inflation from target.

[5] The nominal income rule is calibrated in growth rates, with α set to 20.

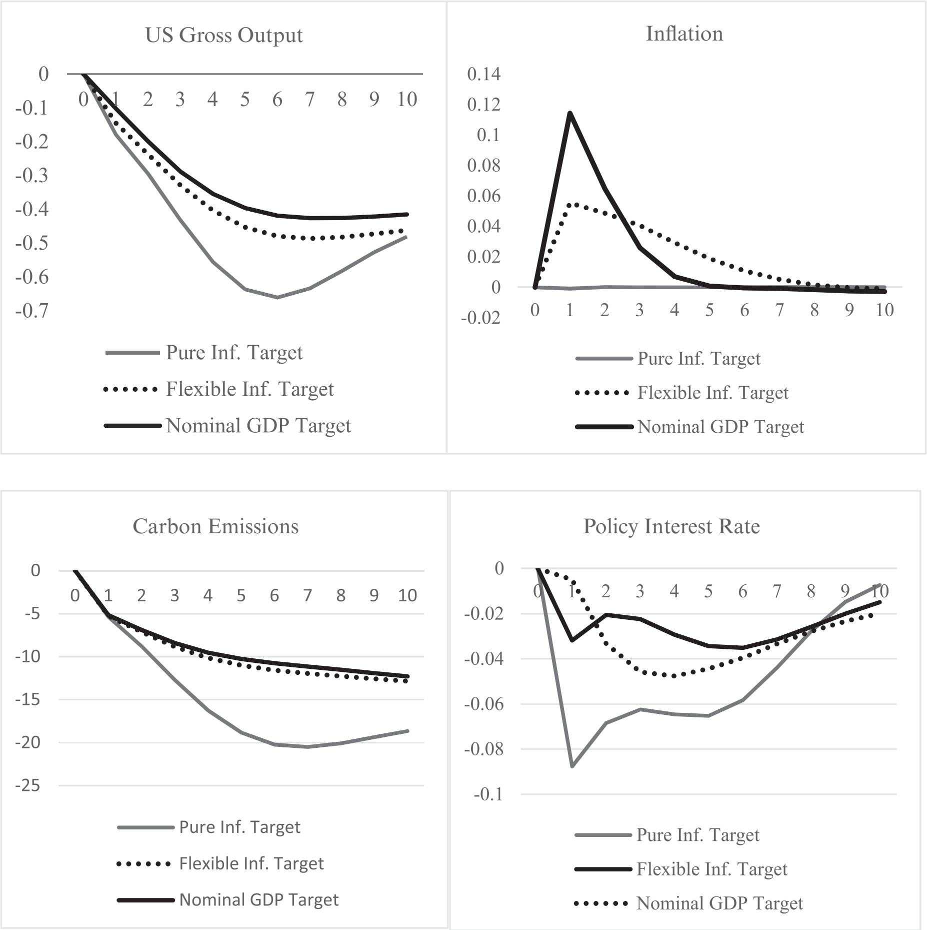
[6] Calibrated with the assumption that the central bank puts more weight on price ($\alpha = 2$) stability and less on output stability ($\beta = 1$)

Figure 3 contains results for output, inflation, CO_2 emissions, and the path of the interest rate for the first decade of the carbon tax shock under the alternate monetary regimes.

While the imposition of a price on carbon leads to output decline and a rise in inflation, the magnitudes of the macroeconomic outcomes depend on the monetary policy framework of the central bank. Pure inflation targeting is associated with the deepest decline in gross output, with nominal income targeting outperforming flexible inflation targeting. However, over the decade, the various regimes converge.

Although carbon-price-induced inflationary pressure is much sharper in the immediate aftermath of the policy under nominal income targeting than flexible inflation targeting, the nominal-income-targeting central bank seeks to stabilize price faster. Both regimes achieve price stability at the end of the decade. Therefore, while the long-run

Figure 3: Effects on US gross output, inflation and CO_2 emissions from a carbon tax under alternate monetary regimes—% deviation from pre-carbon tax baseline.



Source: Authors' calculations, using the G-Cubed model version GGG20Jv152.

policy stance and macroeconomic outcomes appear similar under both monetary regimes, a central bank that targets the growth in nominal income outperforms one that is focused on flexibly balancing price and output stability goals in a carbon-constrained environment. These findings reflect the fact that under nominal income targeting, households' balance sheets can be insulated from macroeconomic shocks when the monetary policy stance seeks to stabilize nominal income or spending. While pure inflation is associated with greater emissions reductions, this is achieved through a substantial costly reduction in output induced by the central bank itself when the bank's sole objective is to maintain its inflation target. Flexible inflation targeting and nominal income targeting are similar to one another in terms of their emissions reductions, but the output and employment outcomes are better under a nominal income target regime. This feature of nominal income targeting—better output performance for similar environmental outcome compared with the conventional flexible-inflation targeting regime—is crucial when considering the political economy of climate policy. Therefore, while the transition to a low-carbon economy may be associated with divergent paths for price and output, subject to the stringency of the price on carbon, jointly optimizing climate and monetary policies may lead to superior outcomes. There is vastly more research needed on these issues.

VII. Conclusion

This paper has argued that, in a carbon-constrained and climatically disrupted world, there are important linkages between climate change and monetary policy regimes. First, the question arises how central banks should anticipate and respond to inflation increases and output decreases that result from climate policy. Responding solely to the inflationary component would lead to larger output losses than using a monetary policy rule that also aims to keep output and employment high. In particular, we argue that nominal income targeting is an attractive approach. It avoids creating public expectations of higher future inflation, and it does not require the central bank to understand the precise nature of the climate policy shock. Simple adherence to the policy rule gives a reasonable policy response. Moreover, nominal income targeting is less vulnerable to imprecise information about the current state of the economy than many other monetary policy rules.

Second, the design of climate policy can significantly affect how hard it is for central bankers to respond to the climate policy itself, as well as to respond to ordinary economic shocks that cause increased economic volatility, as a result of the carbon policy. Fluctuating carbon prices under a cap-and-trade policy would make inflation forecasting more difficult for central banks than a policy such as a carbon tax or a hybrid approach in which carbon prices are more stable and more predictable. Thus, a climate regime based on a carbon tax, or a hybrid policy with stable short-term prices, would simplify the response of a central bank to economic shocks.

A third challenge is that climatic disruption will increase the frequency and severity of negative supply shocks, making it more difficult for central banks to forecast output gaps, and therefore to forecast inflation, a key part of some monetary policy frameworks. We conclude that nominal income targeting, which does not rely on such forecasts, may be better suited to a climatically disrupted world than other monetary rules.

Overall, the interaction between climate policy and monetary policy strongly suggests that the two policy frameworks should be evaluated jointly. Managing each regime separately can easily lead to policies that seem fine in isolation but that perform very poorly in practice.

Finally, we have discussed the type of model needed by policy-makers for analysing climate and monetary policy interactions. Small DSGE models that are currently popular in the macroeconomics literature and used by major central banks are inadequate for this purpose and many other more complex questions. There are other models already available in associated literatures, such as G-Cubed, that have the structure and complexity needed to add considerable understanding of the interdependence of monetary and climate policies.

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