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How to price carbon in good times...and bad!

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Abstract

Emissions trading systems and carbon taxes are two market-based policy instruments for responding to the climate change externality. This article focuses on the relationship between the design of these carbon pricing instruments and business cycle fluctuations. In particular, whether and how these instruments should respond to business cycles is a topical policy question. To answer it, the article brings together the relevant empirical and theoretical results from the academic literature. It finds that building responsiveness into the design of carbon pricing instruments can reduce the burden of regulation by distributing it more evenly over time. Specifically, relative to a fixed cap emissions trading system, this can be achieved by relaxing the cap during economic expansions and tightening it during recessions. Similarly, a carbon tax regime in which the tax is higher during expansions, and lower during recessions, is likely to improve welfare compared to a cyclically unresponsive tax. In practice, a mechanism which renders real-world carbon pricing instruments responsive is a challenging task. The article provides an overview of the trade-offs involved by focusing on the broad classes of mechanisms explored in the literature. The choice of responsiveness-inducing mechanism must crucially consider country characteristics such as the properties of fluctuations in the country's GDP and emissions, any relevant political economy concerns and its institutional background.

1. Introduction

The recovery from the economic slowdown following the financial crisis saw a substantial expansion of interest in how fluctuations in economic activity – known as business cycles, expansions and recessions, or boom and bust cycles – interact with climate change policies. Of particular interest are the operation and design of two carbon pricing instruments aimed at reducing emissions: emissions trading systems (ETSs) and carbon taxes. An ETS is a quantity instrument in which the government sets a cap on aggregate emissions and issues emissions permits equal to the cap, which the regulated firms must then surrender to the government against their emissions. Crucially, an ETS does not fix the price of a permit; rather it is determined by firms' trading activities within the market for permits. On the other hand, a carbon tax is a price instrument whereby regulated firms must pay a fixed price for each unit of carbon emitted, but where the total quantity of the emissions is not predetermined. Business cycles can influence the efficacy by which both instruments operate. A clear example in the case of ETS is the European Union Emissions Trading System (EU ETS), the world's largest ETS by some margin. EU ETS observers have suggested that the collapse and continuing low level of the carbon price since 2008 is due to a combination of the recession cutting demand for permits and the system being unable to respond to changes in economic circumstances.[1] These factors have in turn undermined the price signal which the system is designed to generate.

This article brings together the key results from empirical and theoretical studies relevant for the relationship between business cycles and carbon pricing instruments. Based on these results, it argues for responsive carbon pricing instruments which reduce the overall burden of regulation by distributing it more evenly over time.[a] To this end, the article reviews the practical proposals for implementing responsive carbon pricing instruments. For instance, it may be beneficial to condition the stringency of carbon pricing policy on observable indicators of the business cycle. These instruments are known as intensity targets or indexed regulation. In a similar vein, hybrid instruments aim to combine the desirable features of ETSs and carbon taxes by limiting excessive permit price movements. They work by committing the regulators to intervene when certain predefined conditions are met. Finally, some have called for the creation of an independent body, akin to a central bank, to manage the carbon price. The mandate of such body would be to evaluate the appropriateness of the carbon price in light of the broader climate change policy goals and, if necessary, adjust the stringency of policy.

2. Scope and links to related literature

There is a vast literature on taxes and tradable permits aimed at correcting environmental externalities. This section does not attempt a comprehensive review of this literature, nor indeed of its subset concentrating on climate change. Such reviews are the focus of articles in this journal and elsewhere.[2, 3] Moreover, a basic understanding of carbon taxes and ETS is assumed throughout. A non-technical refresher can be found in Metcalf's Journal of Economic Perspectives article.[4] For the more technical reader, Weitzman's seminal article provides an excellent treatment.[5] Finally, this article does not review the emerging literature on the ex post evaluation of existing carbon pricing instruments where several studies find that carbon pricing has been effective, but that in some instances the effects have been small.[6-9]

In order to analyse the effect of business cycles on carbon pricing instruments in isolation from other uncertainties, this article assumes that the long-run target for global climate change policy – e.g. limiting average temperature increases to 2°C above pre-industrial levels – and the national emissions trajectories consistent with achieving it, are agreed upon and being implemented. Moreover, it is assumed that this target is stringent enough so that it has real implications for emissions for all fluctuations. In other words, the paper abstracts from scientific uncertainties related to climate change, from economic uncertainties (other than those due to business cycles) and from political challenges in determining how the burden of the global target will be shared among nations. In practice, it is difficult to reduce scientific uncertainties,[10] to distinguish persistent, yet temporary business cycle deviations from permanent, structural deviations from the norm[11] and to implement national policies consistent with the global target when free-riding incentives abound.[12]

The article is agnostic about the debate on the relative merits of carbon taxes versus ETSs to reduce emissions. Instrument choice is not directly relevant here, and was recently reviewed by Goulder and Schein as well as the references therein.[3] In that debate, Weitzman's original insight regarding the marginal costs and benefits of abatement plays a critical role. Specifically, if for a small increase in abatement the change in the marginal costs is greater than that in the marginal benefits, then a price instrument is preferred. Against this backdrop, a unique feature of carbon as a pollutant is that marginal costs depend on the flow of emissions whereas marginal benefits are determined by the stock in the atmosphere, having accumulated since the Industrial Revolution.[b] This stock is vast relative to business cycle variations in the flow of emissions, making marginal benefits approximately constant and creating a general preference for carbon taxes.[13-17]

Why, then, have policymakers in the real world so often chosen to regulate CO2 emissions with ETSs? Indeed, the World Bank identifies 35 nations (31 of which are regulated at the supranational level) and 13 subnational jurisdictions which are currently taking this approach, with 13 additional ETSs at various stages of development.[18] This suggests that policymakers' preferences include factors that are not explicit in the analysis of the economic efficiency of the instruments. For example, Stavins emphasises the current political unacceptability of carbon taxes in the USA and adds that it may be easier to construct a well-designed ETS than a well-designed carbon tax.[19] Hepburn points out that if there are tipping points in the climate system, a quantity instrument might be preferred to preclude rapid climate change and associated damages.[20] Pezzey and Jotzo highlight the political economy considerations of raising and recycling substantial revenues as factors that work against its wider adoption in practice.[21]

Given the scope of analysis described above, the next section recounts empirical evidence on the fluctuations in economic activity and emissions.

3. Observed fluctuations in economic activity and emissions

Over long time horizons, aggregate economic activity typically increases. This is largely driven by technological progress, capital accumulation and population growth. For example, global real gross domestic product (GDP) – a key measure of economic activity – increased about six-fold between 1960 and the present. If this increase had progressed uniformly over time, it would have entailed a constant annual growth rate of 3.4%. However, due to economic fluctuations, annual global GDP growth was far from uniform in reality.

In fact, global GDP growth fluctuated within a wide range, from a 2.1% contraction up to 6.6% growth. Focusing on individual countries, the fluctuations in GDP growth rate were even higher. For example, the Asian financial crisis in the late 1990s turned high growth rates of close to 10% into negative values for several countries in the region, with Indonesia and Thailand's economies contracting by more than 10%.

Economic fluctuations can be analysed at various levels of aggregation and frequency, and using a number of indicators. The National Bureau of Economic Research provides a non-technical discussion of these choices in the US context.[22] One way to study the interplay between carbon pricing instruments and economic fluctuations is to use annual real GDP data at the country level to identify recessions and booms, defined as years in which real GDP is respectively below or above what is considered normal for the country. Although determining the norm for a given year can be a technical and controversial question, it is innocuous for the question at hand.

While all countries are affected by economic fluctuations, they do not all experience them in the same way. It would be surprising if China and the UK experienced fluctuations similarly in light of their different stages of development, economic structures, institutions, trading partners and so forth. The relationship between emissions and economic fluctuations is also likely to differ because China and the UK have vastly different energy systems and endowments. Consequently, the same instrument for pricing carbon might trigger different outcomes in different countries.

This paper focuses on three important characteristics for describing fluctuations in GDP and emissions. When a country enters a recession, its GDP declines relative to normal times and the opposite happens during a boom. The **size of economic fluctuations** measures how large these departures are from the norm. It can be summarised by the volatility of GDP growth rates, or one can use more complex times series filters to decompose an observed time series into growth and cyclical components, and focus on the volatility of the latter. Regardless of the method, several studies focusing on this question have produced robust findings to show that advanced countries experience smaller GDP fluctuations.[23-27]

How emissions change over the business cycle is captured by the **correlation of emissions fluctuations with GDP fluctuations**. One would expect emissions to be lower than normal in recessions and higher in expansions. This expectation is confirmed in a number of studies which analyse historical data for advanced and developing countries.[28-31] In other words, these studies suggest that emissions are procyclical, or positively correlated with GDP over the business cycle.[c] There is also evidence that the strength of the association is greater in advanced countries, so when the economy is in a boom, it is more likely that the emissions will be higher than normal compared with developing countries.[28]

The final characteristic is the **size of emissions fluctuations**, especially relative to the size of GDP fluctuations. One can measure it by the volatility of emissions growth rates, or of cyclical components of the filtered emissions series. In a study of cross-country historical data on emissions fluctuations over business cycles, Doda shows that the size of emissions fluctuations is larger than the size of GDP fluctuations.[28] These results are consistent with those obtained, using a different methodology, by Newell and Pizer for the 19 largest emitters.[31] The former study also shows that the size of emissions fluctuations declines as countries develop, both in absolute terms and relative to GDP. However, emissions always remain cyclically more volatile than GDP. For example, in an average advanced country, GDP and emissions may fluctuate within 2% and 4% of their normal values, respectively, while in an average developing country the analogous figures are more like 3% and 10%.

A common feature of the aforementioned studies is their focus on short-run GDP and emissions fluctuations. This is distinct from these variables' secular long-term trends. Indeed, both short– and long-run dynamics exhibit large uncertainties. These issues are illustrated elsewhere using the US as an example.[28, 29] It is crucial to keep the distinction in mind. For example, Jakob, Haller and Marschinski find that emissions and GDP growth are partially decoupled, in that they are uncorrelated in advanced countries.[32] However this finding is based on data averaged over five years and therefore is only informative about the long-term relationship. Put differently, it is possible that while emissions and GDP are positively correlated at business cycle frequencies (procyclical), there may be no significant long-term relationship.

To summarise, GDP fluctuations affect all countries but the size of these fluctuations differ greatly across countries. Emissions fluctuations are typically procyclical and more volatile than GDP fluctuations. These properties of emissions vary across countries as well. These observations suggest that it may be possible to improve the design of carbon pricing policies by explicitly taking business cycle fluctuations into account.

4. Theory of carbon pricing in good times...and bad

Putting a price on carbon is generally considered an effective way to address the climate change externality.[33] However, it is not obvious whether carbon pricing instruments can work better by responding to economic fluctuations. For example, the price of ETS permits will fall during a recession due to reduced demand, whereas the scarcity of permits in a boom will increase their price. The extent of these price fluctuations is influenced by the ETS design. A well-designed system can prevent prices from falling too low during a recession, maintaining the abatement incentive, and from overshooting in a boom and excessively constraining firms precisely when they are at their most productive. Economic theory can help determine how low is too low, what is excessively high, and what governments can do about it.

In a recent study, Heutel uses a standard dynamic stochastic general equilibrium (DSGE) model and modifies it to study first– and second-best emissions.[29] He finds that in the first-best scenario, the social planner increases emissions during expansions and decreases them during recessions. To achieve such optimally procyclical emissions, carbon pricing instruments must be responsive, that is, adjustable in each period to account for total factor productivity shocks. Specifically, the ETS cap in Heutel's framework is tightened in recessions and relaxed during booms. Alternatively, if a carbon tax is used, then it is higher in booms and lower in recessions.[d] Both instruments imply lower variability in emissions relative to when there is no policy intervention.

There have been other DSGE models focusing on the cyclical behaviour of climate change policy. Using a more general model, Lintunen and Vilmi also find that the optimal carbon tax, or ETS cap, is procyclical.[34] Annicchiaricoa and Di Dio show that in a New Keynesian framework with sticky prices, the cyclical behaviour of optimal climate change policy is consistent with these findings, but quantitatively, the level of prices stickiness exerts a significant influence.[35] Fisher and Springborn use a DSGE model to evaluate the welfare implications of three fixed and comparable, as opposed to optimal, climate change policies: an ETS with a fixed cap, a fixed carbon tax and an ETS with a cap that is proportional to output.[36] They find that the latter has desirable welfare properties. This result is confirmed by the findings of Annicchiaricoa and Di Dio, except when the degree of price rigidity is high.[e]

Another way to view the procyclicality of carbon pricing policy instruments is through the lens of dynamic general equilibrium models of climate change which do not explicitly account for stochastic business cycle fluctuations. A classical result in this literature, see for example Golosov et al[37] and references therein, is that the optimal carbon price increases in the growth rate of the economy. Growth is exceptionally high in periods of boom so the carbon price is optimally higher in these periods. However, a fixed ETS cap delivers too high a carbon price, and in the case of a fixed carbon tax the price is suboptimally low for the boom period. Consequently, an optimally responsive policy increases the level of each instrument in booms and decreases them in recessions.

Allowing firms to raise production – along with emissions – above normal takes advantage of the temporarily higher productivity of boom periods; but in order to the meet long-term emissions targets, this must be compensated for with lower than normal emissions during recessions when productivity is low. The trade-off is feasible because climate change damages are due to the accumulated emissions in the atmosphere, rather than the amount emitted each year.

In theory a government can exploit this trade-off to improve welfare but doing so in practice requires timely and accurate information regarding the state of the economy. For example, in Heutel's model perfect knowledge of the economic environment and random productivity shocks allows the social planner to construct optimal policy functions whose form and parameters synthesize all relevant information.[f] In other words, with the aid these functions the planner can determine the welfare maximizing level of the ETS cap or carbon tax each period conditional on the realization of the productivity shock.

However, even when a real world policymaker has accurate knowledge of the economic environment, shocks are imperfectly observable, if at all, in real time. Assuming the policymaker's best information on today's shock is last period's realized GDP, Heutel shows numerically that the second-best adjustments to the ETS cap or carbon tax are procyclical, linking his work with the literature on indexed regulation discussed below. Similarly, using a more general model Lintunen and Vilmi speculate that indexing the policy instrument to observables will improve welfare, especially if the substitutability between fossil fuels and clean energy sources is low. However, this result is not demonstrated rigorously.

As with any quantitative model, the magnitude of implied policy response to business cycles is sensitive to the calibrated parameter values. Taking their calibration at face value, a common finding of models which analyse optimal carbon pricing policy is that substantial cyclical adjustment to ETS caps and carbon taxes is required.[29, 34, 35] In spite of this, Lintunen and Vilmi also find that the welfare gain of an optimal (cyclically varying) carbon tax relative to a constant tax is small. This likely reflects the small variation in marginal damages due to emissions fluctuations. That said, additional research is needed on the quantitative exploration of welfare in DSGE models because welfare in these models also depend on fluctuations in consumption which varies substantially across countries.

Recent DSGE models have made substantial contributions to our understanding of cyclically varying policy instruments. The literature on indexed regulation and intensity targets, which rely on partial equilibrium models, is also relevant.[g] Such models are used to analyse how the ETS cap can be indexed to some observable variable – often real GDP – and have revealed a number of important insights. [30, 38-41] First, a higher correlation between the index variable and emissions indicates a greater preference for indexation. Second, indexation is also preferred if the volatility of the index variable is small relative to the volatility of emissions. Third, it is generally possible to design an indexation formula which improves welfare relative to a fixed cap, although this typically makes the instrument more complex. These insights suggest that, given the findings in Section 3, indexed ETS caps are likely to improve welfare, provided the indexation mechanism properly accounts for country characteristics.

Against this background, Edenhofer and Marschinski cast doubt on the magnitude of the benefits of intensity targets, suggesting that they may not warrant the extra cost in terms of added policy complexity.[42] However, their conclusion can be challenged in a number of ways: First, their arguments are based on simple static abatement cost-minimization models. Second, the empirical evidence underpinning their conclusion, i.e. their estimates of the variance and correlation parameters, are at odds with the evidence reviewed above. Third, the net benefits of intensity targets are likely to be greater in a dynamic general equilibrium setting because they provide greater room for optimizing decisions on consumption, saving and production. Finally, while unlimited banking and borrowing can indeed substitute for an intensity target, intertemporal permit trade is not without its problems.

Carbon pricing instruments can also be made responsive to business cycle fluctuations by mixing elements of a carbon tax into an ETS – a possibility first recognized by Roberts and Spence.[43] These are known as hybrid instruments. They impose a price ceiling and/or a price floor in an otherwise standard ETS. When the market price reaches these bounds, the government commits to intervention. At price floor, permits are removed from the market which effectively reduces the cap. At price ceiling, new permits are introduced, relaxing the cap.

Adapting Robert and Spence's original insight to climate change, several recent studies find that hybrid instruments can improve welfare relative to a simple quantity instrument.[17, 44-46] As in the case of formulating indexation mechanisms, determining the price bounds, and the quantity of permits to be injected or withdrawn at these bounds, requires careful consideration of the country's circumstances.[h]

It is worth noting that an ETS with unlimited intertemporal trade of permits, assuming no capital market imperfections, can approximate the outcomes under first-best responsive policies rather well.[47, 48] Through banking and borrowing regulated firms, rather than government, would effectively adjust period-by-period constraints to spread the effect of cost shocks over time. However, unlimited borrowing by firms can lead to adverse selection. This in turn raises questions of appropriate borrowing constraints, intertemporal allocation of permits and the specification of trading ratios over time. As a consequence, existing ETSs often feature unlimited banking and minimal borrowing provisions.

The theoretical analysis suggests that responsive carbon pricing instruments have the potential to improve upon fixed policies. Despite this, implementing responsiveness faces several challenges. In reality, acquiring timely and accurate knowledge of the state of the economy is crucial but costly, if not impossible. Moreover, implementation lags can make perfectly formulated policy for today's state inappropriate for tomorrow's circumstances. The theory assumes there is effectively one policymaker, one citizen and one firm, but the fragmented and heterogeneous real world gives rise to political economy complications. For example, decision makers in the idealised world are oblivious to the differences between a carbon tax and an ETS; they face no re-election constraint; and are insensitive to lobbying on how revenues are recycled, or on how (many) free permits are allocated to energy-intensive or trade-exposed sectors.[49] Finally, the theory may be omitting relevant features of the problem: there are no market failures other than the climate change externality and no pre-existing distortions in the economy.

5. Making carbon pricing policy responsive to business cycles

Against this backdrop of empirical and theoretical insights, this section reviews the salient features of mechanisms which can render an ETS cap or a carbon tax responsive in practice. The discussion abstracts away from individual instruments and speaks, rather, in terms of stringency of carbon pricing policy. It is based on the understanding that a constant ETS cap is too stringent, relative to first-best, in economic expansions whereas a constant carbon tax is too stringent during recessions.

Should a government institute a rule for policy stringency? If so how should the government pick the parameters of the rule? Alternatively, should the government reconsider the stringency of its policy as circumstances change? If so, what changes in economic, political and scientific circumstances would merit an adjustment to policy stringency? These questions illustrate the long-running debate on rules versus discretion, with their implied trade-offs between predictability and flexibility. A large literature going back to Kydland and Prescott's seminal analysis[50] finds that discretion leads to dynamically inconsistent policies and suboptimal outcomes.

The insights from this literature have been applied to climate change policy in general.[51-53] In particular, they have been used to frame the recent discussion surrounding the reform of the EU ETS.[54] These studies expose the dynamic inconsistency of climate change policy and evaluate the pros and cons of various ways of addressing it. The discussion below views mechanisms which can implement responsive carbon pricing policy in practice through the lens of this literature.

Consider the rule-based determination of carbon pricing policy stringency. The government must choose the parameters of an indexation rule which adjusts stringency based on an observable indicator of the business cycle, such as recent GDP or value added in the sectors covered by the policy. The discussion in sections 3 and 4 suggest the estimation or calibration of these parameters for a given policy rule will yield different results across countries. Moreover, the rule must be shielded from political interference, perhaps by being enshrined in law which is costly to change. Finally, indexed price instruments may be more palatable politically because their stringency is reduced in recessions, as opposed to the increased stringency of an indexed ETS cap. Put differently, political economy aspects of country characteristics are just as crucial for the design and implementation of the rule.

In the case of hybrid instruments, the government must choose an indicator, as well as appropriate trigger points for it, to determine when and how large an intervention is appropriate. Like indexation formulas, these aspects will be sensitive to country characteristics. The academic literature reviewed above has primarily focused on permit price as the indicator. However, quantity-based indicators have also received attention recently in the context of the structural reform of the EU ETS through the introduction of the Market Stability Reserve.[55]

The principal objection to an ETS with a price ceiling, coupled with unlimited permits available at that ceiling, is related to its environmental integrity. If the price ceiling is set too low, the hybrid instrument imposes no real constraint on firms during a period of economic expansion, potentially resulting in suboptimally high emissions. These objections may be addressed by limiting the number of permits that become available at the price ceiling, but only by reducing the benefits of the hybrid instrument. Fell et al provide an analysis of this and similar trade-offs in hybrid instruments design.[44] Another key issue is whether market participants can manipulate the mechanism to their advantage at the expense of society at large, a possibility discussed by Stocking.[56] Finally, to be effective, these policies must be credible by making it costly for the government to alter them even when there are significant short-run incentives to do so.

In comparing intensity targets to hybrid instruments, Webster et al point to a general preference for the latter, provided the probability with which the price ceiling is reached is not too low.[57] By lowering the level of the price ceiling, the government can directly control this probability which is in part determined by the volatility of emissions in a given country. However, this may be exceedingly difficult to achieve in an environment where the politics of a carbon tax is not favourable. Opponents of a too-low price ceiling will be quick to charge the government with introducing a quasi-tax through the back door.

There is an alternative way to implement responsive policies which is not undermined by dynamic inconsistency, at least in principle. The discretion to adjust policy stringency can be delegated to an independent body of experts whose mandate closely aligns with the objectives of broader climate change policy. Several authors discuss how this might function in reality, drawing an analogy with the role of independent central banks in conducting monetary policy.[53, 58-60] Such an independent institution would be desirable because it retains flexibility without compromising dynamic consistency. It also faces several challenges.

The required political consensus to make this body truly independent is difficult to build. Its mandate and membership is no easier to construct than the parameters of indexation and hybrid instruments. The periods when the incentives are greatest for the government to deviate from dynamically consistent policies are precisely the periods when the accountability of this institution would be called into question. Finally, even if this body exercises its discretion as proficiently as possible under the relevant information constraints, it will likely take several years before it can build a strong track record – an element which proved crucial for good central banking.

6. Conclusion

This article brings together the relevant empirical and theoretical results from the literature to focus on whether and how carbon pricing policy instruments should be designed to respond to business cycle fluctuations. The central conclusion is that, in principle, responsive policies will improve welfare. Such policies may be implemented by raising the cap of an ETS or the carbon tax in economic expansions, and lowering them during recessions so that the long-term target of climate policy is not compromised. In practice, the informational and institutional requirements of optimally responsive policies are onerous. Taking these and other constraints into account, the article provides an overview of broad classes of mechanisms which can make real-world carbon pricing policy instruments responsive: indexed regulation, hybrid instruments and an independent body whose mandate is to ensure the carbon price is consistent with broader climate change policy goals.

No single mechanism emerges as a dominant option for capturing the welfare gains associated with responsive carbon pricing instruments. This is not surprising because a core finding in this analysis is the central role country characteristics play in formulating effective mechanisms, particularly the substantial variations in the properties of business cycle fluctuations in GDP and emissions. Economic theory suggests it is precisely the relative volatility and correlation of these variables which determine the magnitude of welfare gains and how they can be realized. The institutional background can also be critical. It may be futile to introduce a carbon central bank in a country where political interference with nominally independent regulatory bodies is rife. More generally, political economy considerations must be a part of the calculus. Advocating hybrid instruments in a setting where there is political aversion to price instruments is unlikely to bear fruit. Future research contributing to a better understanding of the interaction between these country characteristics and responsiveness mechanisms – particularly under explicitly specified information, institutional and political economy constraints – would therefore be invaluable.

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Notes

[a] This argument assumes problems of adverse selection and informational asymmetries restrict the private means to distribute the burden of regulation over time, for example through intertemporal permit trade or access to perfect capital markets. The absence of unlimited banking and borrowing provisions from existing ETSs suggest these problems are severe in practice.

[b] In the case of a stock pollutant, Weitzman's original analysis must be extended to a dynamic setting. Then additional parameters, including the correlation of cost shocks across time, discount rate, stock decay rate and the rate of benefits growth will also play a role. For the climate change externality, Newell and Pizer (2003) show that in the empirically relevant range for these parameters, a price instrument is preferred under open-loop policies. Karp and Zhang (2005) show that the conclusion remains valid for feedback policies.

[c] In business cycle research, a variable is said to be countercyclical if its fluctuations are negatively correlated with GDP fluctuations. If the fluctuations in a variable and GDP are uncorrelated, then the variable is acyclical.

[d] In principle unlimited banking and borrowing of permits or access to perfect capital markets could achieve a similar outcome as responsive carbon pricing instruments. In practice this is not the case for reasons discussed below.

[e] As stated in the paper, the optimal climate policy is procyclical in Annicchiaricoa and Di Dio (2015) for all considered levels of price stickiness. Consequently, there must be a responsive policy which improves upon both an ETS with a fixed cap and the intensity target.

[f] All relevant information in this context includes, but is not limited to, parameters of the production technology and functions describing the climate-economy interaction; parameters which determine time and risk preferences; properties of the distribution of random productivity shocks such as persistence and volatility.

[g] This literature typically studies how the ETS cap can be indexed to GDP, or equivalently, how to set an intensity target. Newell and Pizer (2008) also discuss the conditions under which indexing a carbon tax improves welfare.

[h] Note that although these studies evaluate the implications of 'price' floor/ceiling/collars in an ETS, there is nothing in principle that precludes the extension of the analysis to 'quantity' floor/ceiling/collars for a carbon tax.