TIME-INCONSISTENT ENVIRONMENTAL POLICY AND OPTIMAL DELEGATION

Dieter Helm[†], Cameron Hepburn[‡] and Richard Mash[*]

Oxford University Department of Economics
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Abstract

Time consistency problems can arise when environmental taxes are employed to encourage firms to take irreversible abatement decisions. Setting a high carbon tax, for instance, would induce firms to invest in low-carbon technology, yet once investment has occurred the government can then reduce the carbon tax to better achieve other objectives: lower energy prices, redistribution, and electoral success. The resulting time inconsistency discourages firms from investing in the first place. We propose an institutional solution to this problem, adapted from the monetary policy literature: the commitment outcome can be achieved through delegation to an 'environmental policymaker', akin to a conservative central banker.

Keywords: time inconsistency, environmental taxation, monetary policy, delegation

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[†] New College, Oxford University.

[‡] New College and Nuffield College, Oxford University.

[*] New College and Department of Economics, Oxford University.

Email for correspondence: richard.mash@new.ox.ac.uk.

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1 Introduction

When regulation is designed to induce firms to take irreversible actions, problems of time inconsistency are often not far away. For instance, reducing carbon emissions is likely to require significant irreversible investment from the private sector. To encourage firms to invest in low-emissions technology, governments around the world are beginning to price emissions using a tax or a permits system. If firms believe that a carbon price is not a temporary measure, irreversible investment in low-emissions technology may appear profitable. However, once investment costs are sunk and emissions decline, the government can reduce the emissions price to achieve other objectives, including lower energy prices, redistribution, enhanced 'international competitiveness', and political aims.[1] Knowing this, firms are reluctant to invest in the first place.

There many examples of such time-inconsistency problems in environmental policy. Gersbach and Glazer (1999) cite several. Such problems are pressing today.[2] Surprisingly, however, the problem of time-inconsistency in environmental policy has not received a great deal of attention in the literature. Several recent papers propose models where the time-inconsistency arises from distributional objectives. For instance, in the two-period model of Abrego and Perroni (2002), the policymaker employs an emission tax in order to encourage investment in a clean production process. However, once investment has taken place, it is optimal for the policymaker to lower the tax in order to minimise unwanted distributional impacts. Realising this, private agents conclude that the promise of high future emission taxes is not credible.

The time-inconsistency problem examined in the two-period model of Marsiliani and Renström (2000) also results from a dynamic trade-off between environmental and redistributive goals. In the first period, the government employs an energy tax to encourage (irreversible) investment in energy efficient durables. In the second period, however, the government uses the energy tax to redistribute revenue from richer (higher productivity) individuals to poorer (lower productivity) individuals.[3] Hence, unlike Abrego and Perroni (2002), here the government has an incentive to deviate towards a higher — not a lower — energy tax in the second period for redistribution purposes: once investment has taken place the elasticity of the tax base is lower.

Distributional concerns, however, are not a necessary condition for dynamic consistency problems. Gersbach and Glazer (1999) propose a hold-up model where firms in the first period choose whether to invest in a lumpy technology. This technology permits emission reductions in the second period. After observing firm investment levels, the government

[1] With a full set of policy instruments and taxes, these other objectives can be achieved with other instruments, avoiding time inconsistency. However, governments rarely avail themselves of the optimal combination of instruments given their mix of objectives.

[2] For instance, in 2003 the UK government consulted upon changes to the rules on the eligibility of co-firing for Renewable Obligation Certificates (ROCs), as outlined in DTI (2003). Such changes would cut the price of ROCs and reduce the profitability of investment in renewable energy.

[3] Note that energy taxes are typically viewed as being highly regressive. Nevertheless, Poterba argues that such taxes are less regressive when measured over the lifetime rather than in terms of annual income: Poterba (1989) and Poterba (1991).

determines the total number of emission permits available and allocates them equally to each firm. In the second period, firms choose their optimum emission reductions and trade emissions permits. Gersbach and Glazer (1999) show that with permits, subgame perfect equilibria exist where firms make the lumpy investment. In comparison with emission taxes, emission permits are said to better solve the hold-up problem by providing an incentive for firms to invest.[4]

In contrast, Biglaiser et al. (1995) propose that emission taxes are preferable to emission permits for they avoid time-inconsistency problems. They show that, as firms respond to pollution regulation by investing to reduce the cost of pollution control, the optimum number of pollution permits falls. Firms, recognising this effect, behave strategically and reduce the level of investment relative to the first best.[5] In contrast, the optimum emission tax is equal to the marginal social damage, which is typically independent of pollution control costs. Hence Biglaiser et al. (1995) conclude that while emission permits are time-inconsistent, emission taxes are not.

All these models share the feature that the regulator has only a single instrument to achieve two competing goals, and where private expectations about the use of the instrument are important. Typically, the regulator wants to convince firms that it will use the instrument to achieve one goal (e.g. compliance with emission standards), but *ex post* has an incentive to use it to achieve the other (eg, higher output). The time-inconsistency posed by the introduction of a carbon tax is also of this variety. In other words, policymakers want to persuade firms that carbon taxes will be high enough to render (irreversible) investment in new infrastructure profitable. However, once such investment is made the government has an incentive to reduce the level of the carbon tax, supporting its domestic export industries and free-riding on other countries' efforts to control climate change.

This type of dynamic inconsistency has been examined in great detail in the monetary policy literature. There, as is well known, the policymaker wants to convince firms that it will use interest rates to achieve low inflation, but *ex post* it has an incentive to employ rates to influence output. Since the seminal papers of Kydland and Prescott (1977) and Barro and Gordon (1983), efforts have been made to find solutions to the dynamic consistency problem and the resulting 'inflation bias'. Rogoff (1985) showed that delegation of monetary policy to a 'conservative' central banker lead to a Pareto improvement in terms of flexibility of policy and a reduction in the inflation bias. Evidence since has appeared to support his prediction that greater central bank independence is associated with lower inflation.[6]

More recently, Walsh (1995) demonstrated that, in theory at least, the resolution of this

[4]This claim, however, is not entirely fair, as it is based upon a comparison between a system of revenue-neutral emission permits with revenue-raising taxes. As such, the permit system provides a greater financial incentives for investment than the tax system. The permit system should be compared with a revenue-neutral tax equivalent.

[5]This is the same concept as the 'ratchet effect' in microeconomic theory. Such a ratchet effect could be applicable to our model when viewed on a broader scale — for instance, British firms might anticipate that if Britain outperforms its emission target, it is likely to have more stringent targets imposed at the next round of international negotiations.

[6]See, eg, Alesina and Summers (1993).

credibility-flexibility trade-off is remarkably simple. An optimal contract exists between the government (principal) and the central banker (agent). The contract merely imposes a tax on the bank for inflation levels in excess of the inflation target. Moreover, Svensson (1997) then showed that a suitably specified inflation target, at a level below the socially optimal inflation rate, can produce an equivalent result.

In this paper, we draw upon the monetary policy literature to propose a novel solution to the time-inconsistency problem of environmental policy. Unlike Abrego and Perroni (2002), who show that the effects of dynamic inconsistency can be mitigated by employing investment subsidies in conjunction with emission taxes, or Marsiliani and Renström (2000), who argue that that tax hypothecation provides a partial remedy, we propose an institutional solution. We show that environmental policy credibility can be obtained by delegating responsibility for achieving emission targets to an independent authority. Three forms of delegation are considered. First, if the authority is able to establish and maintain a good reputation, it can be delegated the true social welfare function. Second, as with the Bank of England, this authority could be granted control of a single instrument, the carbon tax, in order to achieve compliance with a paramount goal, a carbon emissions target. Third, discretion might be granted to an authority constituted by an 'environmentalist policymaker' akin to a conservative central banker.

In section 2 of the paper, we present a model which sets up the credibility problem and illustrates that the delegation of responsibility for achieving emission targets to an independent body, coupled with an optimal contract, can solves the time-inconsistency problem. In section 3, we consider the impact of providing the government with an additional instrument; an output tax or subsidy. In section 4, we consider some of features of the new institution that would be required to ensure that it does not merely *relocate* rather than *resolve* the problem, as asserted by McCallum (1995). Section 5 concludes.

2 A model of time-inconsistent carbon taxation

We develop a stylised, deterministic model of government and firm interaction when production of a good (eg energy) produces carbon dioxide emissions. The model is solved for two cases: first, when the government commits to an announced carbon taxation rate; and second, when the government retains the discretion to alter the tax rate. While the model is discussed with reference to the energy sector, it is applicable more generally to any situation in which irreversible investment by the private sector generates different *ex ante* and *ex post* incentives for the government.

2.1 Firm behaviour

Suppose that energy demand exhibits constant elasticity and is given by:

$$Q = \alpha P^{-\epsilon} \tag{1}$$

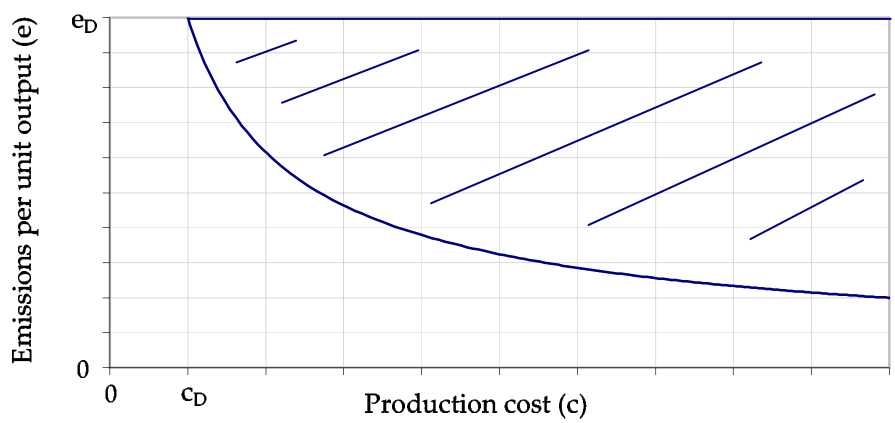

Figure 1: Technology possibility set.

where P is an energy price index, $\epsilon > 0$ is the price elasticity of demand and $\alpha > 0$ is a constant. Production of energy produces emissions E according to a linear function:

$$E = eQ \tag{2}$$

where $e \in (0, e_D]$ is a dirtiness parameter of the generating technology and e_D is the emissions per unit output of the dirtiest technology, which has the lowest cost of production, c_D. Emissions per unit output can be reduced by increasing production costs, c, where the set of possible (e, c) combinations is given by:

$$e \geq \beta c^{-\sigma} \tag{3}$$

where σ is an elasticity parameter and $\beta = e_D c_D^{\sigma}$. Assuming firms maximise profits, equation (3) binds. This technology frontier is shown in Figure 1. Firm production costs are represented by the single parameter, c, so that total costs in the industry are cQ. As such, c represents an aggregation of (fairly small) marginal costs and (fairly large) fixed costs, but in the model below the distinction between marginal and fixed costs is not important.

For the moment, we assume that the government has a single policy instrument — a carbon tax, t — to influence firm technology choices.[7] Taking account of the tax, when firms are identical, total average costs are $c + te$.

A simple yet relatively realistic assumption is that firms engage in Cournot competition with free entry. Under such circumstances, entry will occur until zero profits are reached, implying price equals average cost.[8] Given such a market structure, firms choose their operation point within the technology possibility set in order to minimise expected costs, $c + \mathbb{E}[t]e$, subject to equation (3). Optimal cost and cleanliness choices for a given carbon

[7] In section 3 we consider the addition of an output instrument.

[8] See, for example, Varian (1992), p. 220. We abstract from firm integer issues which imply that equilibrium price will be slightly above minimum average cost.

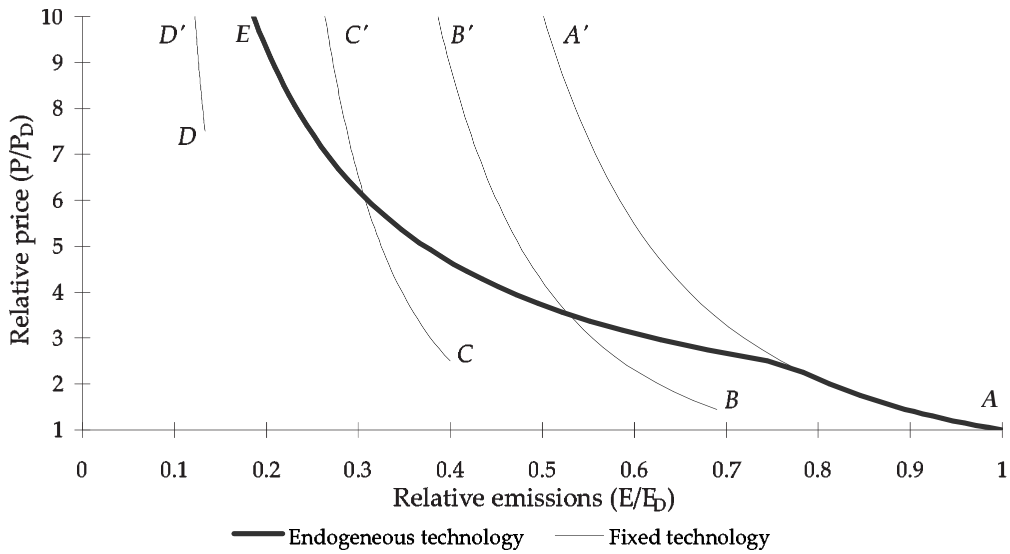

Figure 2: Relationship between relative prices and relative emissions.

tax are therefore given by:

$$c(\mathbb{E}[t]) = \max\left[c_D,\ (\sigma\beta\mathbb{E}[t])^{\frac{1}{1+\sigma}}\right] \tag{4}$$

$$e(\mathbb{E}[t]) = \min\left[e_D,\ \beta\,(\sigma\beta\mathbb{E}[t])^{\frac{-\sigma}{1+\sigma}}\right] \tag{5}$$

For a particular technology choice of cost and dirtiness $(\bar{c}, \bar{e})$, the relationship between prices and emissions can be parameterized by the tax rate, t. From equations (1) and (2):

$$E(t) = \bar{e}dP(t)^{-\epsilon} \tag{6}$$

It follows that $dE/dP < 0$ and $d^2E/dP^2 > 0$, so the relationship between prices and emissions for fixed technology is strictly downwards sloping and convex. Figure 2 illustrates the relationship between prices and emissions relative to a baseline with no carbon tax and the dirtiest technology in which $P = P_D \equiv c_D$, and $E = E_D \equiv e_D\alpha c_D^{-\epsilon}$. The curves AA' to DD' each represent a particular fixed technology $(\bar{c}, \bar{e})$, where AA' reflects the most polluting technology and BB' to DD' reflect successively cleaner technologies. For a given technology, increasing the carbon tax will increase prices and reduce emissions, corresponding to a movement north-west along one such curve. Point A therefore marks the baseline with no carbon tax and dirtiest technology, where $P = P_D$ and $E = E_D$.

When firm technology choice is not fixed, but responds endogenously to the tax rate, an increase in t will induce firms to switch to cleaner technology. Hence, with endogenous technology, emissions are more responsive to changes in the tax rate. The relationship between emissions and prices is now given by:

$$E(t) = e(t)dP(t)^{-\epsilon} \tag{7}$$

where $e(t)$ is given by equation (5). Assuming expectations are fulfilled such that $\mathbb{E}[t] = t$, substituting equation (5) to equation (7) defines the curve labelled AE in Figure 2. AE

is coincident with the AA' until the tax rate is high enough to induce $e < e_D$. From this point leftwards, AE is shallower than the fixed technology curves: with endogenous technology, carbon tax increases are more effective at reducing emissions.

2.2 Welfare

The welfare function in our partial equilibrium framework comprises three elements: change in consumer surplus $s(P)$; tax revenues $r = tE$; and disutility from pollution $z(E)$.[9] Hence:

$$\mathcal{W} = s(P) + \nu r - \lambda z(E) \tag{8}$$

where λ is the weight on the pollution term and ν is the marginal benefit of public funds from the emission tax, each relative to consumer surplus. For an isoelastic demand curve, the change in consumer surplus relative to a given baseline price level P_D is given by:

$$s(P) = \frac{\alpha}{1-\epsilon}\left[P_D^{1-\epsilon} - P^{1-\epsilon}\right] \tag{9}$$

A simple specification of the disutility of emissions is:

$$z(E) = E^{\gamma} \tag{10}$$

where $\gamma > 0$. Note that $\gamma > 1$ implies increasing marginal damage of pollution. Combining equations (9) and (10) welfare can be expressed as a function of the tax rate:

$$\mathcal{W}(t) = \frac{\alpha}{1-\epsilon}\left[P_D^{1-\epsilon} - P(t)^{1-\epsilon}\right] + \nu t E(t) - \lambda E(t)^{\gamma} \tag{11}$$

2.3 Solution under commitment

When the government can commit in advance to the carbon tax rate, the situation can be modelled as a simple dynamic game of complete information. The moves of the game are: (1) the government announces and commits to a carbon tax rate t; and (2) the private sector forms expectations of the tax rate, with $\mathbb{E}[t] = t$ under commitment, and hence makes its technology choice (c, e).

The game is solved by backward induction. For a given carbon tax, the private sector cost and emissions choices are simply $c(t)$ and $e(t)$ in equations (4) and (5). The private section reaction function is simply the endogenous technology curve in Figure 2. Taking this reaction function into account, the policymaker sets the carbon tax to maximise the welfare function in (8). The first order condition for the policymaker is therefore:

$$\left.\frac{d\mathcal{W}}{dt}\right|_{t=\mathbb{E}[t]} = \frac{\partial \mathcal{W}}{\partial t} + \frac{\partial \mathcal{W}}{\partial c}\frac{dc}{dt} + \frac{\partial \mathcal{W}}{\partial e}\frac{de}{dt} = 0 \tag{12}$$

[9] This welfare function is consistent with Target 4 of the DTI Public Service Agreement 2003-2006 to '[e]nsure that the UK ranks in the top 3 most competitive energy markets in the EU and G7 in each year [and] to help to reduce greenhouse gas emissions by 12.5% from 1990 levels': see HM Treasury (2002).

Solution of (12) yields an optimal tax rate, t^*, from which firm technology choices are given by substitution to equations (4) and (5). In graphical terms, the optimal tax for the government is merely the point on the firm reaction function in Figure 3 which maximises its welfare function. This occurs at a point of tangency with a welfare contour (marked by a diamond on Figure 3). At an interior solution — one where the tax rate is non-zero and some abatement occurs — the welfare function is concave and the firm reaction function is convex. This ensures uniqueness of optimal tax rate.

Proposition 1 *There exists a unique interior commitment solution,* (t^*, c^*, e^*).

Proof 1 *See Appendix.* ■

The importance of commitment is clear from Figure 3. Once the tax has been announced and firms have invested in cleaner technology resulting in the solution marked by the diamond on Figure 3, if $\nu < 1$ the government has an *ex post* incentive to lower the tax rate, moving down the fixed technology curve and lowering prices, improving welfare. This *ex post* incentive gives rise to the time-inconsistency problem, rendering commitment valuable.

2.4 Solution under discretion

When the government retains the discretion to adjust the tax rate *ex post*, another dynamic game of complete information is appropriate. In this case, however, the private sector move first. The move order is: (1) the private sector forms their expectation of the tax rate $\mathbb{E}[t]$ and thus chooses their optimal (c, e); and (2) the government chooses the tax rate, t, given the firms' technology choice.

Solving by backwards induction, the government reaction function, $t(c)$, is given by the solution to the first order condition:

$$\left.\frac{\partial \mathcal{W}}{\partial t}\right|_{t=\mathbb{E}[t]} = 0 \tag{13}$$

In other words, the policymaker chooses the carbon tax which, for a fixed technology curve such as AA', will maximise its welfare function. The resulting reaction function is the locus of tangency between the welfare contours and the fixed technology lines. The equilibrium tax rate, $\hat{t}$, in which the firms' expectations are fulfilled, yields a solution marked by the circle in Figure 3.

Proposition 2 *There exists a unique interior discretion solution,* $(\hat{t}, \hat{c}, \hat{e})$.

Proof 2 *See Appendix.* ■

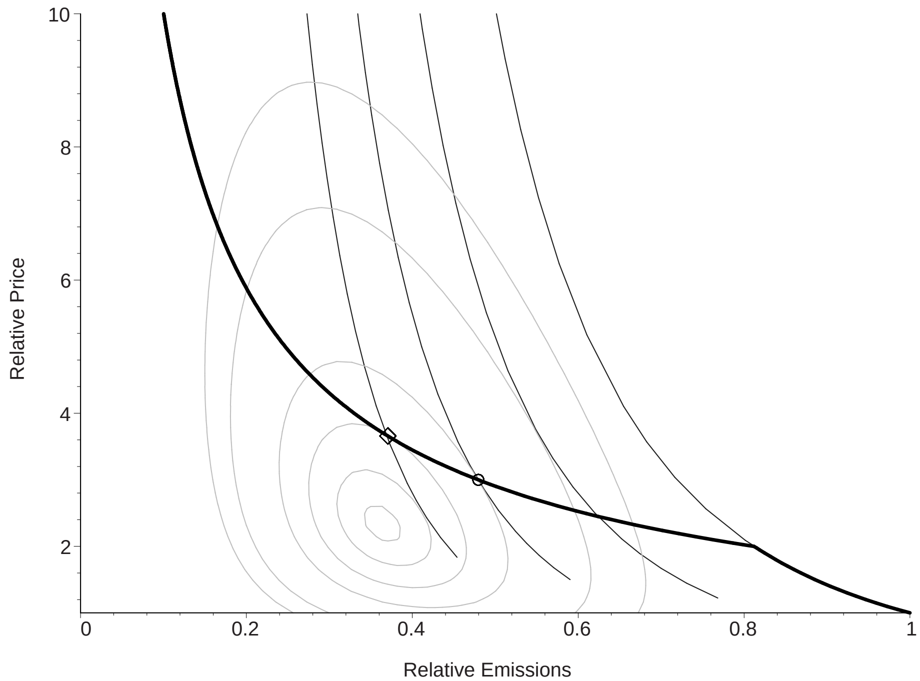

Figure 3: Discretion and commitment solutions for $\nu = 0.8$

2.5 Comparison of results

At interior solutions, de/dt and dc/dt are non-zero and thus the solution of equation (12) is, in general, different from the solution to (13). The difference between the discretion and commitment outcomes arises because the marginal effect of the tax is different before and after technology choice. After technology choices have been made, damage from emissions is less responsive to the tax rate, such that $\partial z/\partial t < dz/dt$. This implies that *ceteris paribus* the optimal tax *ex post* will be lower than that *ex ante*. In contrast, tax revenues are more responsive than they were before investment, such that $\partial r/\partial t > dr/dt$. This effect works in the opposite direction: other things being equal a higher tax is optimal *ex post*. The responsiveness of consumer surplus to the tax rate before and after investment is obviously unchanged.[10]

The existence and direction of the time inconsistency problem depends upon which of these two effects — the increased elasticity of tax revenues or the reduced elasticity of emissions — dominates. If it is the former (latter), the tax is higher (lower) under discretion than under commitment. In Proposion 3, we demonstrate that this depends upon the value of ν. This result is illustrated in Figure 4.

Proposition 3 *For an interior solution, when $\nu < 1$ the tax rate is higher under com-*

[10]This is an application of the envelope theorem: when firms are minimising prices, it follows that $dc + tde = 0$.

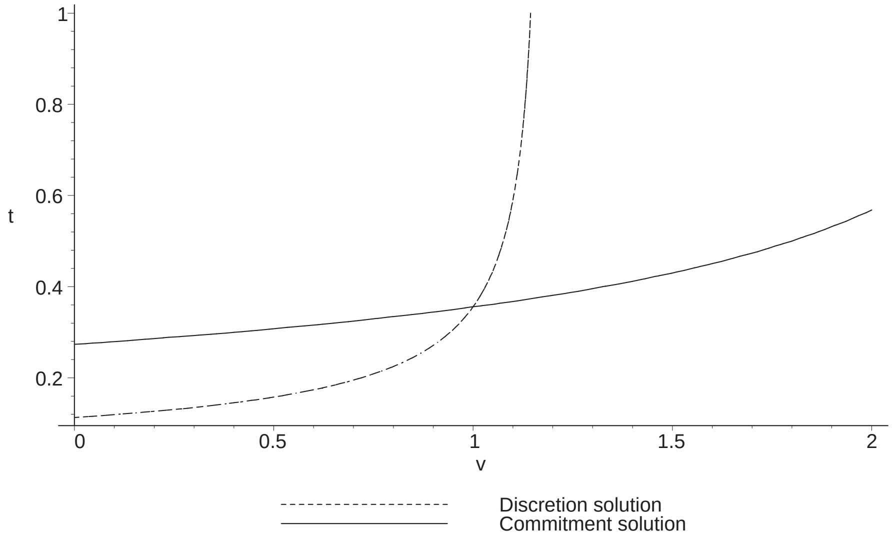

Figure 4: Discretion and commitment emission taxes for various ν

mitment than under discretion ($t^* > \hat{t}$). When $\nu = 1$, the discretion and commitment solutions are identical and Pigouvian. When $\nu > 1$, taxes are lower under commitment.

Proof 3 *See Appendix.* ∎

Proposion 3 accords with conventional Pigouvian logic: for $\nu = 1$, the optimal tax is the marginal damage from emissions, $\hat{t} = t^* = \lambda\gamma E^{\gamma-1}$. There is no divergence between the commitment and discretionary solutions.

In the classical analysis developed by Pigou (1947), Harberger (1964), Browning (1976) and Browning (1987), the marginal cost of public funds (MCF) is greater than one whenever there are distortions in the revenue raising process, which in practical terms is almost inevitable.[11] However, Atkinson and Stern (1974) and Stiglitz and Dasgupta (1971) demonstrate that it is possible for the MCF to be less than one when the additional revenue is obtained in a way that reduces the distortionary effects of pre-existing taxes. For instance, in a model with pollution Ballard and Medema (1993) find that a Pigouvian externality-correcting tax has an MCF of 0.73. While the appropriate MCF for an energy tax is a moot point, it is probably likely to be slightly above one. This would suggest that environmentalists need not be concerned that governments will renege on promised rates of carbon taxes.

Nevertheless, in practice, the direction of the time inconsistency problem will be affected by other considerations which are not explicitly accounted for in our model. In particular, as noted above, distributional concerns are relevant as energy taxes are typically viewed

[11]See the review in Ballard and Fullerton (1992).

as being highly regressive. Including distributional concerns in the welfare function may increase the incentive to reduce the tax *ex post*. Similarly, including political economy considerations, such as an electoral need for the government to be supported from by fossil fuel and manufacturing lobby groups would further increase the incentive to reduce the tax *ex post*. These considerations suggest that government may in practice behave as if $\nu < 1$ — revenue from environmental taxation brings concomitant political economy drawbacks such that the effective marginal benefit of environmental taxation is less than one.

If so, a government promise to implement the efficient carbon tax is not credible. Knowing this, investment by firms in low-carbon technology will be sub-optimal. There are several potential ways to try to circumvent the time-inconsistency problem. We consider first the additional of a further instrument — an output subsidy — and then the delegation of taxation policy to an independent energy agency.

3 Results with an additional instrument

Suppose the government can employ an additional instrument in the form of an output subsidy payment, s, based on the amount of energy produced. With $s < 0$, the instrument operates as an output tax. Given the assumed market structure, the output subsidy will lower prices and increase industry output with entry. It does not alter each individual firm's tradeoff between cost and emissions. Hence the impact is that equilibrium price is now given by:

$$P(t, s) = c + te - s \tag{14}$$

Equally, the welfare function in equation (11) is altered to account for the reduction in government funds:

$$\mathcal{W} = \frac{\alpha}{1-\epsilon}\left[P_D^{1-\epsilon} - P^{1-\epsilon}\right] + \nu(te - s)Q - \lambda E^{\gamma} \tag{15}$$

Consider the discretion case with the move order as described in section 2.4 above, and where the government sets the capacity payment simultaneously with the emissions tax. *Ex ante*, unlike the emissions tax, the capacity payment has no effect on technology choice. However, once firms have made their technology choice, the capacity payment and the emissions tax are equivalent instruments: neither affects technology, and both affect consumer surplus and emissions through their impact on price. The marginal effect of the output subsidy is therefore the same *ex post* and *ex ante*. From equations (14) and (15) it is clear that:

$$\frac{d\mathcal{W}}{ds} = \frac{\partial \mathcal{W}}{\partial s} = -\frac{1}{e}\frac{\partial \mathcal{W}}{\partial t} \tag{16}$$

Under discretion, then, the output instrument is not orthogonal to the subsidy, and its addition does not resolve the time inconsistency problem; with $t = \hat{t}$, there is no role for the subsidy and $s = 0$ is optimal. Indeed, rather than solving the time inconsistency problem, the extra instrument might accentuate it. If firms believe that the government might employ an output tax rather than the emissions tax *ex post*, the incentive to switch to cleaner technology is blunted and emissions will increase.

Under commitment, however, things are different. With $\nu < 1$, it is optimal to set the tax at a modified Pigouvian level, and provide output subsidy $s > 0$ to reduce the equilibrium price of the good. For instance, with $\gamma = 1$, the marginal damage of emissions is λ and the optimal tax is simply $t = \lambda/\nu$. The corresponding output subsidy is $s = \frac{1-\nu}{1-\nu+\nu\epsilon}\left(c + \frac{\lambda e}{\nu}\right)$. Thus for $\nu < 1$, the tax is set above the marginal damage of emissions to induce a switch to cleaner technology, with a strictly positive subsidy to offset the price increase.[12] When $\nu = 1$, there is no role for the subsidy, as the Pigouvian tax rate achieves both emissions reduction and optimal revenue raising objectives. Finally, for $\nu > 1$, the tax is set at less than the marginal damage, and as $s < 0$ the extra instrument is employed as an output tax. In contrast to the emissions tax, the output tax raises additional revenue without inducing technology that is too clean and too expensive.

Hence, under commitment, the additional output instrument is welfare improving because it eliminates the tradeoff between internalising the pollution externality and achieving the optimal tax mix. However, under discretion, the extra instrument does not help, and might be problematic. In other words, the problems that result from the inability of government to commit to environmental policy do not appear to be resolved by the addition of more instruments. A different solution is required.

4 Delegation to an Energy Agency

Section 2 demonstrated the costs of time-inconsistency and the advantages of the ability to commit to a specified carbon tax. Section 3 demonstrated that the addition of an output instrument will not generally resolve the problem created by government discretion. In this section, we consider the features of several institutional solutions to the time-inconsistency problem.

The first, and obvious, possibility is the delegation of the power to set carbon policy to an independent energy agency, much like the delegation of monetary policy to the Bank of England.[13] Various forms of delegation are possible.

- The agency could be asked to maximise the social welfare function, provided that it is able to develop and retain a good reputation.
- The agency could be given a single objective (the optimal level of emissions) to achieve, twinned with an appropriate policy instrument (the carbon tax rate, the number of emissions permits, or a hybrid instrument).
- The agency could be constituted by people who place a different weight on emissions than the government. For instance, $\nu < 1$ appointing an 'environmentalist policy-maker' could achieve the standard commitment outcome, much like the appointment of a conservative central banker in a monetary policy setting.

[12]In the limit as $\nu \to 0$ and revenue requirements do not matter, the first best is achieved by a tax and subsidy approaching infinity.

[13]See Helm et al. (2003) for the various arguments in favour of delegation, and Helm (2003) on wider energy issues.

We consider each of the options in turn.

4.1 Delegation of the social welfare function

If the agency is able to develop and retain a reputation for fulfilling its promises, it could be delegated the social welfare function. If the agency is a long-lived institution removed from short term political pressures, concern for its reputation would provide it with an incentive to implement the commitment outcome, despite short term gains from reneging. This is addressed by Barro and Gordon (1983) for monetary policy.

4.2 Delegation of a single objective

Under this approach, the agency would have a mandate to use its economic instrument (setting a carbon tax or a number of carbon emission permits) to achieve a single objective. In other words, the function maximised by the energy agency would be simply:

$$\mathcal{W}_A = (E - \bar{E})^2 \tag{17}$$

where $\bar{E} > 0$ is an emissions target fixed (in advance) by the government.[14]

With such a function, the agency does not face trade-off between emissions and price objectives, unlike the government, and hence the problem of time inconsistency is eliminated. The energy agency simply sets the tax to achieve $E = \bar{E}$. Indeed, time inconsistency problems of this type can only arise when one instrument is employed to achieve two objectives. When one objective is removed from the welfare function, the dynamic inconsistency disappears, as does the distinction between commitment and discretion.

The interesting question concerns the setting of $\bar{E}$. For a government unconstrained by an international regime, it is evident that $\bar{E}$ should be set taking into account the private sector reaction function. It is immediately clear that the optimal level of $\bar{E}$ is that obtained in the commitment solution to the model in section 2.

4.3 Delegation to an 'environmentalist policymaker'

A third possibility is to delegate carbon tax policy to an agency with preferences that differ from those of society. The distortion resulting from the divergence between agency and social preferences may be tuned to offset the distortion from the inability to commit. If the time inconsistency problem arises because the effective $\nu < 1$, one would delegate to an agency with a higher λ, denoted λ^P. Figure 5 superimposes isowelfare curves for

[14] This welfare function would also be applicable in the case of a binding international regime on carbon dioxide emissions with credible punishment of defectors, in which case commitment is achieved without delegation.

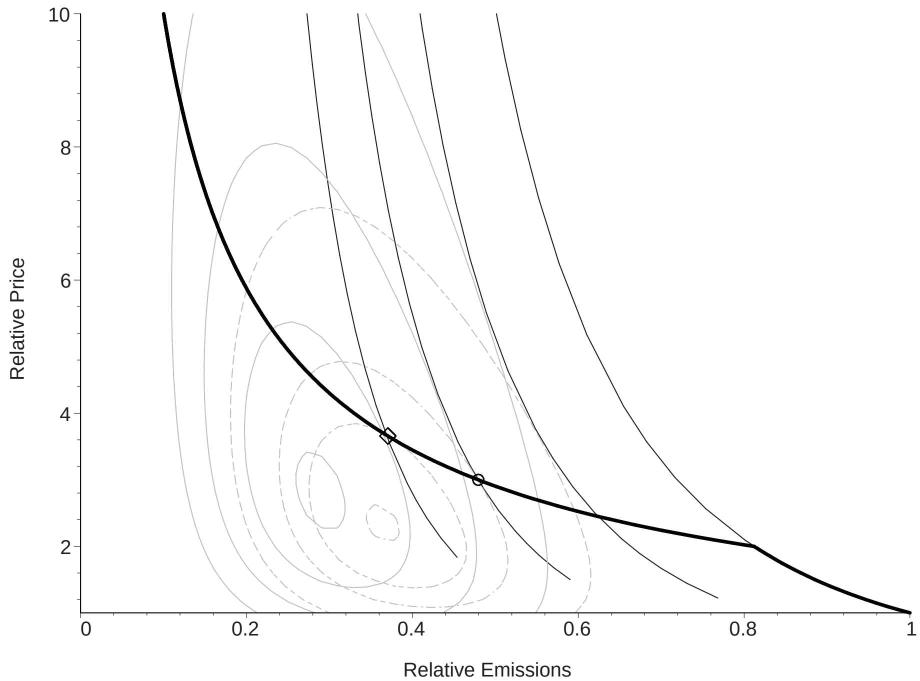

Figure 5: Commitment optimum achieved by the environmentalist policymaker

the 'environmentalist' policymaker upon the standard isowelfare curves from Figure 3 drawn as dashed grey ellipses. The bliss point for an environmentalist policymaker is at a higher relative price and lower relative emissions. Figure 5 further illustrates that the commitment outcome may be obtained by choosing a λ^P such that the 'discretion' outcome (which we refer to as delegation) for the environmentalist policymaker is the commitment solution with standard preferences. As earlier, this solution is marked by the diamond.[15]

Proposition 4 *If commitment is not feasible, delegation to a policymaker with a different weight on emissions, $\lambda^P \neq \lambda$, can achieve the commitment solution.*

Proof 4 *See Appendix.* ∎

5 Conclusion

This paper has demonstrated that a time-inconsistency problem is likely to arise in carbon policy. Firms are being encouraged to make irreversible investments in a context where governments have dual objectives to reduce emissions and keep energy prices low. The

[15] Of course, if $\nu > 1$, the appropriate agency would be one governed by an 'industrialist policymaker' who placed less weight on emissions than society at large, such that $\lambda^P < \lambda$.

time-inconsistency problem arises when the optimal government policy *ex ante* investment in low-carbon technology is different to that *ex post*.

We demonstrate that the addition of an output subsidy does not resolve the problem. Instead, we put forward an institutional solution to the problem. We argue that delegating the control over energy prices and environmental objectives to an independent, long-lived, energy agency can resolve the time-inconsistency problem.

If the energy agency is able to develop and maintain a reputation for fulfilling its promises, it could be delegated the social welfare function and the concomitant authority to announce and commit to an appropriate tradeoff between emissions and prices. If the establishment of a credible reputation is likely to be difficult, the agency could either be delegated a single objective, or an 'environmentalist' policymaker could be appointed, in a manner analogous with the literature on the conservative central banker.

However, energy policy is complicated by the presence of additional market failures, not least of which is security of supply. Efforts to correct these additional market failures may be stymied by further time inconsistency problems. Whether a long-lived and reputable energy agency may be able to achieve the commitment solution in the presence of multiple market failures is a question for further research.

Appendix

We prove Proposition 3 before proceeding to prove propositions 2, 1 and 4.

Proof of Proposition 3

We seek to prove that for $\nu = 1$ there is no time-consistency, while for $\nu < 1$ there is an *ex post* incentive to lower the emission tax and for $\nu > 1$ there is an *ex post* incentive to raise taxes. It is instructive to examine the effect of the tax on the three components of welfare.

Consumer Surplus. Under discretion, hence assuming technology (c, e) is fixed, the effect of the emissions tax on consumer surplus is:

$$\frac{\partial s(P)}{\partial t} = -e\alpha P^{-\epsilon} \tag{18}$$

In the commitment solution when technology responds to the emissions tax, the impact of tax on consumer surplus is:

$$\frac{ds(P)}{dt} = -\alpha P^{-\epsilon}\left[e + \frac{dc}{dt} + t\frac{de}{dt}\right] \tag{19}$$

However, for cost minimising firms, the envelope theorem implies that this simplifies to:

$$\frac{ds(P)}{dt} = \frac{\partial s(P)}{\partial t} = -e\alpha P^{-\epsilon} \tag{20}$$

In other words, the marginal impact of the emissions tax on consumer surplus is identical in the discretion and the commitment solutions.

Tax Revenue. Under discretion the effect of increasing the tax rate on tax revenues, r, is given by:

$$\frac{\partial r}{\partial t} = e\alpha P^{-\epsilon}\left[1 - te\epsilon P^{-1}\right] \tag{21}$$

Under commitment, firms respond to the tax by choosing cleaner technology, such that:

$$\frac{dr}{dt} = \frac{\partial r}{\partial t} + t\alpha P^{-\epsilon}\frac{de}{dt} \tag{22}$$

Noting that $de/dt < 0$, it is clear that tax revenue is less responsive to changes in the emissions tax rate under commitment.

Emissions. Under discretion, higher taxes reduce emissions damage through the price mechanism alone:

$$\frac{\partial z}{\partial t} = -\epsilon\gamma e^{\gamma+1}\alpha^{\gamma}P^{-\epsilon\gamma-1} \tag{23}$$

Under commitment, the tax is more effective because firms adapt their technology choice:

$$\frac{dz}{dt} = \frac{\partial z}{\partial t} + \gamma e^{\gamma-1}\alpha^{\gamma}P^{-\epsilon\gamma}\frac{de}{dt} \tag{24}$$

Welfare. Combining the three partial derivatives above together, under discretion we have:

$$\frac{\partial \mathcal{W}}{\partial t} = -e\alpha P^{-\epsilon} + \nu e\alpha P^{-\epsilon}\left[1 - te\epsilon P^{-1}\right] + \lambda\epsilon\gamma e^{\gamma+1}\alpha^{\gamma}P^{-\epsilon\gamma-1} \tag{25}$$

$$= (\nu - 1)e\alpha P^{-\epsilon} - \nu\alpha e^2 t\epsilon P^{-\epsilon-1} + \lambda\epsilon\gamma e^{\gamma+1}\alpha^{\gamma}P^{-\epsilon\gamma-1} \tag{26}$$

In comparison, under commitment the relevant derivative is:

$$\frac{d\mathcal{W}}{dt} = \frac{\partial \mathcal{W}}{\partial t} + \nu t\alpha P^{-\epsilon}\frac{de}{dt} - \lambda\gamma e^{\gamma-1}\alpha^{\gamma}P^{-\epsilon\gamma}\frac{de}{dt} \tag{27}$$

In other words, the impact of the emissions tax under commitment is as for discretion, except that the tax has a smaller effect on tax revenues, and a larger effect on pollution. However, comparing equations (26) and (27), it can be seen that the additional effects of the tax under commitment can be expressed as a function of the effect under discretion, namely:

$$\frac{d\mathcal{W}}{dt} = \frac{\partial \mathcal{W}}{\partial t} - \frac{P}{e^2\epsilon}\frac{de}{dt}\left[\frac{\partial \mathcal{W}}{\partial t} + (1-\nu)e\alpha P^{-\epsilon}\right] \tag{28}$$

And thus

$$\frac{d\mathcal{W}}{dt} = \left(1 - \frac{P}{e^2\epsilon}\frac{de}{dt}\right)\frac{\partial \mathcal{W}}{\partial t} - (1-\nu)\frac{P^{1-\epsilon}\alpha}{e\epsilon}\frac{de}{dt} \tag{29}$$

Now if $\nu = 1$, because $de/dt < 0$ it follows that $d\mathcal{W}/dt = 0 \Leftrightarrow \partial\mathcal{W}/\partial t = 0$. In other words, when $\nu = 1$ the rules and discretion solutions are identical and there is no time inconsistency. In contrast, if $\nu \neq 1$ and if $de/dt \neq 0$ (which is satisfied if $e \neq e_D$), then time-inconsistency arises. With the tax rate set at the discretionary optima, such that $\partial\mathcal{W}/\partial t = 0$, then if $\nu < 1$ it follows that $d\mathcal{W}/dt > 0$, and the taxation rate under discretion will be lower than under commitment as there is an *ex post* incentive to lower tax rates. In contrast, when $\nu > 1$ the tax rate under discretion will be higher than under rules; the *ex post* incentive is to increase tax rates.

Pigouvian tax. For $\nu = 1$, the corresponding first order condition from equation (26) is given by:

$$\frac{\partial \mathcal{W}}{\partial t} = -\alpha e^2 t\epsilon P^{-\epsilon-1} + \lambda\epsilon\gamma e^{\gamma+1}\alpha^{\gamma}P^{-\epsilon\gamma-1} = 0 \tag{30}$$

Simplification, and substitution for $E = e\alpha P^{-\epsilon}$ yields:

$$t = \lambda\gamma E^{\gamma-1} \tag{31}$$

which is simply the marginal damage from emissions. ∎

Proof of Proposition 2

We prove here that there exists a unique interior discretion solution to equation (13) which we denote $(\hat{t}, \hat{c}, \hat{e})$. We assume an interior solution, such that $\hat{t} > 0$, $\hat{c} > c_D$ and $\hat{e} < e_D$, and then show the welfare function is concave. The first derivative was given above in equation (26). For ease of notation, we rewrite this as:

$$\frac{\partial \mathcal{W}}{\partial t} \equiv \Gamma - \Omega + \Psi \tag{32}$$

where we define $\Gamma = (\nu - 1)\alpha e P^{-\epsilon}$, $\Omega = \nu \alpha e^2 t \epsilon P^{-\epsilon-1}$ and $\Psi = \lambda \alpha^\gamma e^{\gamma+1} \epsilon \gamma P^{-\epsilon\gamma-1}$. Differentiating the welfare function again with respect to t, remembering that e is constant under discretion, yields:

$$\frac{\partial^2 \mathcal{W}}{\partial t^2} = -\frac{\epsilon e}{P}\Gamma + \left(\frac{(1+\epsilon)e}{P} - \frac{1}{t}\right)\Omega - \frac{(1+\epsilon\gamma)e}{P}\Psi \tag{33}$$

To prove that there is a unique interior solution, we seek to demonstrate that the welfare function is globally concave. Our proof proceeds by contradiction. Suppose that the welfare function is nonconcave, such that:

$$\begin{aligned}
\epsilon e \Gamma - (1+\epsilon)e\Omega + \frac{P}{t}\Omega + (1+\epsilon\gamma)e\Psi &\leq 0 && (34)\\
\Rightarrow \Gamma - \frac{1+\epsilon}{\epsilon}\Omega + \frac{1+\epsilon\gamma}{\epsilon}\Psi &\leq -\frac{P}{\epsilon e t}\Omega && (35)\\
\Rightarrow \Gamma - \Omega + \Psi &\leq -\left(\frac{P}{\epsilon e t} - \frac{1}{\epsilon}\right)\Omega - \frac{1-\epsilon(1-\gamma)}{\epsilon}\Psi && (36)\\
\Rightarrow \frac{\partial \mathcal{W}}{\partial t} &\leq -\frac{c}{\epsilon e t}\Omega - \frac{1-\epsilon(1-\gamma)}{\epsilon}\Psi && (37)
\end{aligned}$$

As $\Omega > 0$ and $\Psi > 0$, for reasonable values of the parameters, such as $\gamma > 0$ and $\epsilon < 1$, the right hand side of the inequality in equation (37) is negative, which implies $\partial \mathcal{W}/\partial t < 0$. But if the welfare function is strictly decreasing in t, the optimum tax rate is $\hat{t} = 0$ which a corner solution, contradicting our assumption of an interior solution. Hence we conclude that for an interior solution, the welfare function is concave in t. It therefore follows that the interior solution is unique. ∎

Proof of Proposition 1

We prove here that there exists a unique interior commitment solution to equation (12) which we denote (t^*, c^*, e^*). We assume an interior solution such that $t^* > 0$ and hence $c^* > c_D$ and $e^* < e_D$ and then show the welfare function under commitment is concave, mirroring the approach to the Proof of Proposition 2 above. The first derivative under commitment is given by equation (27) above. For convenience we rewrite this as:

$$\frac{d\mathcal{W}}{dt} = \Gamma - \Omega + \Psi + X_1 - X_2 \tag{38}$$

where $X_1 = \nu t \alpha P^{-\epsilon} \frac{de}{dt}$ and $X_2 = \lambda \gamma e^{\gamma-1} \alpha^{\gamma} P^{-\epsilon\gamma} \frac{de}{dt}$. Differentiating with respect to t, this time treating e as variable yields:

$$\frac{d^2\mathcal{W}}{dt^2} = \frac{\partial^2\mathcal{W}}{\partial t^2} + \frac{1}{e}\frac{de}{dt}\frac{\partial\mathcal{W}}{\partial t} + \Theta_1 X_1 - \Theta_2 X_2 \tag{39}$$

where $\Theta_1 = \frac{1}{e}\frac{de}{dt} - \frac{\epsilon e}{P}$ and $\Theta_2 = \Theta_1 + (1-\gamma)\left(\frac{\epsilon e}{P} - \frac{1}{\epsilon}\right) - \frac{1}{t}$. As above, suppose the welfare function is nonconcave. It follows that:

$$\epsilon e \Gamma - (1+\epsilon) e \Omega + \frac{P}{t}\Omega + (1+\epsilon\gamma) e \Psi - \frac{P}{e}\frac{de}{dt}\frac{\partial\mathcal{W}}{\partial t} - P\Theta_1 X_1 + P\Theta_2 X_2 \leq 0 \tag{40}$$

Simplification and rearrangement yield:

$$\left(1 - \frac{P}{\epsilon e^2}\frac{de}{dt}\right)\frac{\partial\mathcal{W}}{\partial t} \leq -\frac{c}{\epsilon e t}\Omega - \frac{1-\epsilon(1-\gamma)}{\epsilon}\Psi - \frac{P}{\epsilon e}\left((1-\gamma)(\frac{\epsilon e}{P} - \frac{1}{e}) - \frac{1}{t}\right) X_2 \tag{41}$$

Noting that $de/dt < 0$, $X_2 < 0$ and that $P > et$, it follows that for reasonable values of the parameters, including $\gamma > 0$ and $\epsilon < 1$, that each component on the right hand side of the inequality is negative. This implies that the welfare function is strictly decreasing in t. This contradicts the assumption of an interior solution. It follows that the welfare function is concave for an interior solution, and that the interior solution is unique. ∎

Proof of Proposition 4

We prove that if commitment is not feasible, the commitment outcome can nevertheless be achieved by delegation of the authority to set the carbon tax to an environmentalist policymaker with $\lambda^P \neq \lambda$. This amounts to showing that there exists $\lambda^P \in \mathbb{R}$ such that:

$$\left.\frac{\partial\mathcal{W}}{\partial t}\right|_{\lambda^P} = \left.\frac{d\mathcal{W}}{dt}\right|_{\lambda} \tag{42}$$

Substituting in for the respective derivatives gives:

$$(\lambda^P - \lambda)\epsilon\gamma e^{\gamma+1}\alpha^{\gamma} P^{\epsilon\gamma-1} = \nu t \alpha P^{-\epsilon}\frac{de}{dt} - \lambda\gamma e^{\gamma-1}\alpha^{\gamma}P^{-\epsilon\gamma}\frac{de}{dt} \tag{43}$$

$$\Rightarrow \lambda^P = \left(1 - \frac{P}{e^2\epsilon}\frac{de}{dt}\right)\lambda + \frac{\nu E^{1-\gamma}P}{\gamma e^2 \epsilon}\frac{de}{dt} \tag{44}$$

Hence the commitment outcome can always be achieved dy delegation to an agency with weight λ^P on emissions, where λ^P is defined by equation (44).

References

Abrego, L. and C. Perroni (2002): "Investment subsidies and time-consistent environmental policy," *Oxford Economic Papers*, 54, 617–635.

Alesina, A. and L. H. Summers (1993): "Central bank independence and macroeconomic performance: some comparative evidence," *Journal of Money, Credit and Banking*, 25(2), 151– 162.

Atkinson, A. B. and N. H. Stern (1974): "Pigou, Taxation and Public Goods," *Review of Economic Studies*, 41, 119–128.

Ballard, C. L. and D. Fullerton (1992): "Distortionary Taxes and the Provision of Public Goods," *Journal of Economic Perspectives*, 6(3), 117–131.

Ballard, C. L. and S. G. Medema (1993): "The marginal efficiency effects of taxes and subsidies in the presence of externalities: A computational general equilibrium approach," *Journal of Public Economics*, 52(2), 199–216.

Barro, R. J. and D. Gordon (1983): "Rules, discretion and reputation in a model of monetary policy," *Journal of Monetary Economics*, 12, 101–122.

Biglaiser, G., J. K. Horowitz, and J. Quiggin (1995): "Dynamic pollution regulation," *Journal of Regulatory Economics*, 8, 33–44.

Browning, E. K. (1976): "The Marginal Cost of Public Funds," *Journal of Political Economy*, 84, 283–298.

——— (1987): "On the Marginal Welfare Cost of Taxation," *American Economic Review*, 77, 11–23.

DTI (2003): *New and renewable energy: Prospects for the 21st Century. The Renewables Obligation (Amendment) Order Statutory Consultation*, Department of Trade and Industry, 29 August.

Gersbach, H. and A. Glazer (1999): "Markets and regulatory hold-up problems," *Journal of Environmental Economics and Management*, 37, 151–64.

Harberger, A. C. (1964): "The Measurement of Waste," *American Economic Review*, 54, 58–76.

Helm, D. (2003): *Energy, the State, and the Market: British Energy Policy since 1979*, Oxford University Press.

Helm, D., C. Hepburn, and R. Mash (2003): "Credible Carbon Policy," *Oxford Review of Economic Policy*, 19(3), 438–450.

HM Treasury (2002): *Spending review 2002: Public service agreements 2003-2006*, The Stationery Office Books, Cm5571, July.

Kydland, F. and E. C. Prescott (1977): "Rules rather than discretion: the inconsistency of optimal plans," *Journal of Political Economy*, 85, 473–491.

Marsiliani, L. and T. I. Renström (2000): "Time inconsistency in environmental policy: tax earmarking as a commitment solution," *Economic Journal*, 110, C123–C138.

McCallum, B. T. (1995): "Two fallacies concerning central bank independence," *American Economic Review*, 85(2), 207–211.

Metcalf, G. E. (1999): "A Distributional Analysis of Green Tax Reforms," *National Tax Journal*, 52, 655– 681.

Pigou, A. C. (1947): *A Study in Public Finance*, London: Macmillan, third edition ed.

Poterba, J. M. (1989): "Lifetime incidence and the distributional burden of excise taxes," *American Economic Review*, 79, 325–330.

——— (1991): "Is the gasoline tax regressive?" *NBER Working Paper 3578*.

Rogoff, K. (1985): "The optimal degree of commitment to a monetary target," *Quarterly Journal of Economics*, 100, 1169–1189.

Stiglitz, J. E. and P. S. Dasgupta (1971): "Differential Taxation, Public Goods and Economic Efficiency," *Review of Economic Studies*, 38, 151–174.

Svensson, L. E. O. (1997): "Optimal inflation targets, 'conservative' central banks, and linear inflation contracts," *American Economic Review*, 87, 98–114.

Varian, H. R. (1992): *Microeconomic Analysis*, WW Norton & Company, 3rd ed.

Walsh, C. (1995): "Optimal contracts for central bankers," *American Economic Review*, 85, 150–67.