Occasionally binding emission caps and real business cycles

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Abstract

Recent applications to the modeling of emission permit markets by means of stochastic dynamic general equilibrium models look into the relative merits of different policy mechanisms under uncertainty. It is always assumed the existence of a binding emission constraints (i.e. the emission cap is always smaller than what actual emissions would be in the absence of climate policy). Although this might seem a reasonable assumption, at first, the truth is that there are important instances where this assumption would be in sharp contrast with reality. A notable example would be the current status of the European Emission Trading Scheme. This paper explores the implications of adopting a technique that allows occasionally binding constraints and investigates the resulting effects on the relative merits of different policy choices under different macro-economic shocks.

Keywords: Dynamic Stochastic General Equilibrium model, emission trading, carbon tax, occasionally binding constraints.

JEL codes: Q58, Q54, E2.

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1 Introduction

The European Union Emissions Trading Scheme (EU-ETS) is the first, multi-regions large scale implementation of a pollution permit market. What is traded in this market are carbon emission permits and the initial allocation of such permits is a combination of long term nation-wide caps and within nations allocation. As in any market, the carbon price obviously reflects the equilibrium between emissions demand and supply of emissions. Current prices are around €4 a tonne of carbon dioxide and have been lower than this earlier this year, but the shock in prices have started much earlier, around 2008. The reason for such low prices is a combination of overallocation during the early phase of the scheme, the overlapping of policies favoring renewable technologies throughout Europe and the economics crisis. Since 2008 the EU-ETS has experienced a surplus of allowances and international credits compared to emissions, which have accumulated and rolled over in time. Figure 1 reports, on the left, data on total EU-ETS allowances and verified emission for the 2005-2012 period (spanning the first two “trading periods” of the scheme) published by the European Environment Agency (EEA), and, on the right, the *deficit* of allowances (for the sake of exposition), i.e. the difference between verified emission and allowances, and the industrial production gap for EU28 countries: there is an evident positive correlation between the allowance deficit and the business cycle, at least considering industrial production.[1]

The EEA *“Trends and projections in Europe 2013”* report[2] announces that: “Aggregated projections from Member States indicate that total EU 28 emissions will further decrease between 2012 and 2020. With the current set of national domestic measures in place, EU emissions are expected to reach a level in 2020 which is 21 % below 1990 levels (including emissions from international aviation). Implementing the additional measures at planning stage in Member States is expected to achieve a reduction of 24 % below 1990 levels in 2020.”

This is a clear and dramatic example of how, in reality, the assumption of binding caps can be far from what really turns out to be. It is thus important to model the possibility of non binding caps as otherwise the assessment of a cap system would tend to be biased unfavorably both in economic and in environmental terms.

[1]The industrial production gap in percentage terms is obtained by log-linearly detrending the 1975:III-2013:III quarterly index of industrial production for the EU28 countries published by the OECD. The annual figures are computed as averages of the quarterly ones.

[2]See `http://www.eea.europa.eu//publications/trends-and-projections-2013` for further details.

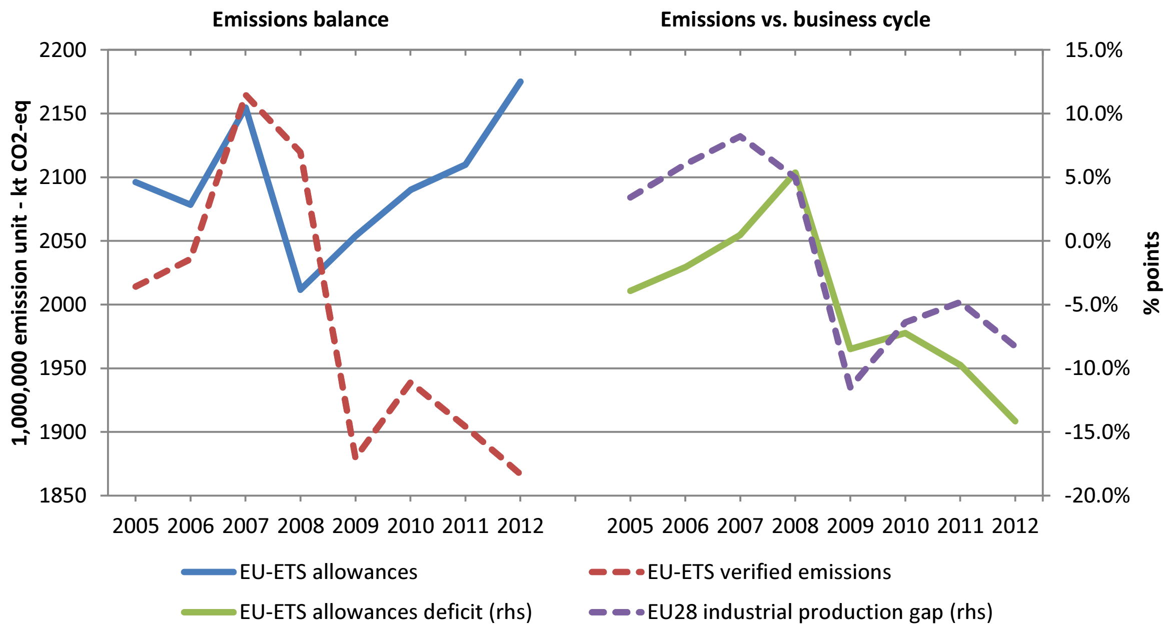

Figure 1: Emission gap vs. business cycles.

2 The model

Time is discrete, indexed by $t \in \{0, 1, ..., \infty\}$. There exists a continuum of *ex-ante* identical and infinitely lived households, with total mass equal to one. Households own both factors of production, capital and labor. Firms, directly owned by the households, produce a single homogenous final good competitively, via a constant-returns-to-scale production function, using capital, labor and energy. Energy is bought on the international market and firms are price takers. Depending on the scenario, the government can rise the price of energy through an environmental market based policy. The final good can be used for consumption and investment. Asset markets are complete. The next Sections will describe the model components more in detail.[3]

2.1 Households

Each household owns a single private firm. Firms employ labor and purchase intermediate goods in competitive markets but use the capital stock accumulated by the respective owner. The capital income of a generic household, excluding the non-depreciated capital stock installed in the firm, is given by the firm's earnings net of factor costs:

$$\pi_t = q_t - (1 + \tau_N)\, w_t n_t - (1 + \tau_E)\, p_t e_t, \tag{1}$$

[3]The model is a simplified representative-agent version of the framework developed in Valentina Bosetti and Marco Maffezzoli (2013), with a few twists.

where:

$$q_t \equiv \phi_t \left(k_t^{\alpha} n_t^{1-\alpha}\right)^{1-\gamma} e_t^{\gamma}, \tag{2}$$

denotes the firm's output, k_t the stock of capital in place at the beginning of period t, n_t the amount of labor hired, w_t the wage rate, p_t the price of energy, τ_E the carbon tax, when we assume a price mechanism is adopted, τ_N is the payroll tax, ϕ_t the level of aggregate productivity (common to all households), γ the share of energy in gross output, while α and $1-\alpha$ are respectively the share of capital and labor in value added. The aggregate productivity level and the international price of energy are subject to aggregate shocks: in particular, we assume that the logs of ϕ_t and the log of p_t follow stationary discrete Markov processes, characterized by transition matrices π_ϕ and π_p, and we assume $\mathbb{E}(\phi) = 1$ for normalization purposes. The aggregate shocks are realized at the beginning of period t, after capital is installed but before labor n_t and e_t are chosen.

We assume that emissions at the firm level are proportional to the use of energy, e_t, and units of emissions are chosen such that the quantity of emissions is equal to e_t. Firms face an emission constraint which requires that:

$$e_t \leq m_t, \tag{3}$$

where m_t is the stock of emissions permits purchased (or set aside when banking is allowed for) in the previous period and available for use at the beginning of period t.

2.1.1 The optimization problem

Household's preferences over stochastic consumption streams are given by:

$$u_t \equiv \mathbb{E}_t \left\{ \sum_{s=t}^{\infty} \beta^{s-t} \left[\frac{\left(c_s - \kappa \frac{l_s^{1+\eta}}{1+\eta}\right)^{1-\sigma} - 1}{1-\sigma} \right] \right\}, \tag{4}$$

where c_t is the consumption level, l_t the share of time devoted to labor, $\beta \in (0,1)$ the intertemporal discount factor, $\sigma > 0$ the reciprocal of the elasticity of intertemporal substitution, and $\eta > 0$ a parameter linked to the Frisch elasticity of labor supply.

The stock of physical capital evolves over time according to the following accumulation equation:

$$k_{t+1} = (1-\delta_K) k_t + d_t - z_t [x_t - \chi(k_t)] - c_t, \tag{5}$$

where $d_t \equiv (1-\tau_Y)(\pi_t + w_t l_t) + G_t$ denotes disposable income; note that τ_Y represents a proportional tax rate on income, $G_t \geq 0$ the per-capita government lump-sum transfers, $\delta_K \in [0,1]$ a physical depreciation rate, z_t the price of emissions permits, x_t the total number of emission permits withhold in period t, and $\chi(k_t)$ the number of permits obtained through grandfathering, that possibly depend on the size of the firm (hence,

$x_t - \chi_t$ represents the number of permits purchased, or sold, in the period). The stock of emission permits evolves according to:

$$m_{t+1} = (1 - \delta_M)(m_t - e_t) + x_t. \tag{6}$$

The parameter δ_M determines whether banking of permits is allowed: if $\delta_M = 1$, then no banking is allowed, and the emission constraint reduces to $e_{t+1} \leq x_t$; if $\delta_M = 0$, then banking is allowed, and permits can be set aside forever; finally, if $\delta_M \in (0,1)$, then banking is still allowed, but permits have a finite half-life.

We can now put all the elements together; for given sequences of factor prices, the dynamic optimization problem of a generic household is as follows:

$$\begin{aligned}
\max_{\{c_s, l_s, n_s, e_s, k_{s+1}, m_{s+1}\}_{s=t}^{\infty}} \quad & \mathbb{E}_t \left\{ \sum_{s=t}^{\infty} \beta^{s-t} \left[\frac{\left(c_s - \kappa \frac{l_s^{1+\eta}}{1+\eta}\right)^{1-\sigma} - 1}{1-\sigma} \right] \right\}, \\
\text{s.t.} \quad & k_{t+1} = (1 - \delta_K) k_t + d_t - z_t (x_t - \chi_t) - c_t, \\
& m_{t+1} = (1 - \delta_M)(m_t - e_t) + x_t, \\
& e_t \leq m_t.
\end{aligned} \tag{7}$$

2.2 Aggregate variables

2.2.1 The Government

The government might choose a price or a quantity instrument to regulate carbon emissions. In the first case, the government sets a carbon tax which acts effectively as a sales tax on energy imports. In the second case, the government sets the initial number of emission permits, M_0, and allocate them to the households for free according to a preferred rule (permits can obviously be auctioned and we do analyze the implication of alternative ways of allocating permits in Valentina Bosetti and Marco Maffezzoli, 2013). At the beginning of each period, the government issues X_t new emission permits and sells $(X_t - \chi_t) \geq 0$ of them on the secondary market at the price z_t. Apart from this, the government plays a minimalist role, collecting tax revenues, selling permits, and paying everything back to the households via lump-sum sum transfers[4] (capital letters denote aggregate variables):

$$G_t = \tau_Y Y_t + \tau_Y w_t (L_t - N_t) + (1 - \tau_Y)(\tau_N w_t N_t + \tau_E p_t E_t) + z_t (X_t - \chi_t), \tag{8}$$

where $Y_t = Q_t - p_t E_t$ denotes GDP.

[4]More complex ways of redistributing the revenues from the carbon policy and their implications are discussed in Valentina Bosetti and Marco Maffezzoli (2013).

2.2.2 Energy

Energy is imported from abroad, at a given international price p_t, and its supply is perfectly elastic. In other words, our economy can be characterized as a small open economy in the international market for energy; however, recall that households do not have access to international financial markets, and can only invest in physical capital. This implies that trade is balanced by assumption: energy imports are financed via final good exports.

2.3 Equilibrium

In equilibrium, the demand and supply of labor coincide: $N_t = L_t$. In the Appendix we describe the equilibrium conditions in detail. It seems useful to highlight here that, thanks to the "Cobb-Douglas" form of the production function, we can easily solve for energy and hours as functions of the capital stock. We start by expressing hours as a function of capital and energy:

$$N_t = \left(\frac{1-\tau_Y}{1+\tau_N} \frac{s_N}{\kappa} \phi_t K_t^{s_K} E_t^{\gamma} \right)^{\frac{1}{\eta+1-s_N}} . \tag{9}$$

Then, we can express energy as a function of the capital stock alone:

$$E_t = \min \left\{ \left[\frac{\gamma \left(\phi_t K_t^{s_K} \right)^{\xi} \left(\frac{1+\tau_N}{1-\tau_Y} \frac{\kappa}{s_N} \right)^{1-\xi}}{(1+\tau_E)\, p_t + \frac{z_t(1-\delta_M)}{1-\tau_Y}} \right]^{\frac{1}{1-\gamma\xi}}, M_t \right\}, \tag{10}$$

where $\xi \equiv (\eta+1) / (\eta+1-s_N)$.

3 Calibration

The parameters that characterize household's preferences are selected in the following way: the intertemporal discount factor and the reciprocal of the elasticity of intertemporal substitution are set to standard values in the literature, $\beta = 0.985$ and $\mu = 2$. There is still no general consensus on how to parametrize the elasticity of labor supply in macro models, due to the somehow conflicting empirical evidence at the macro (where large estimates are typically obtained) and micro level (where the estimates tend to be much lower). However, Felix Reichling and Charles Whalen (2012) report that the Congressional Budget Office incorporates into its analysis an estimate of the Frisch elasticity of labor supply that ranges from 0.27 to 0.53. **?** perform a large-scale international comparison of labor supply elasticities for 17 European countries and the US, and report own-wage elasticities that range from 0 to 0.65 for women and single men, and from 0 to 0.2 for married men. Jäntti et al. (2013) obtain broadly comparable results with a different methodology and

Parameter	*Value*	Parameter	*Value*	Parameter	*Value*
β	0.985	α	0.33	ρ_ϕ	0.95
σ	2	γ	8.26%	σ_ϕ	0.070
η	1.9	τ_N	19%	ρ_p	0.73
ξ	5.293	τ_Y	27%	σ_p	0.124
δ	0.025	$\bar{p}$	0.73		

Table 1: Summary of the benchmark parametrization.

sample, and show that macro estimates on the same data are not far from the micro ones. The previously cited studies suggest that elasticities higher than unity are unlikely, in particular for many European countries. Therefore, we set $\eta = 1.9$ in order to make the model reproduce a Frisch elasticity equal to 0.53, the upper limit in the CBO estimated range. OECD (2009) considers 18 OECD countries and reports the 24-hour breakdown of time spent in main activities for individuals aged 15 and over: on average, those individuals devote 67% of their time to leisure and personal care. Hence, we calibrate ξ so that the average number of hours worked, in absence of climate policies, correspond to 33% of the time endowment.

The depreciation rate is set to $\delta = 0.025$, while the share of capital in value added, α, is assumed to be 0.33: both values are standard in the literature. The share of energy in gross output, γ, is calibrated in order to make the model reproduce, in absence of climate policies, a share of total energy expenditure in GDP equal to 9%, a figure in line with the empirical evidence for EU countries.

Using data for 27 EU countries in 2012 provided in James Rogers and Cécile Philippe (2012), we compute the cross-country average Social Security payroll tax rate and the average income tax rate, equal respectively to $\tau_N = 19\%$ and $\tau_Y = 27\%$.

As far as the supply of emission permits is concerned, we assume that:

$$X_t = \bar{X} + \upsilon_1 K_t, \tag{11}$$

$$\chi_t = \upsilon_2 X_t. \tag{12}$$

In our benchmark parameterization, we assume that permits are fully auctioned, and set $\upsilon_1 = 0$, $\upsilon_2 = 0$, and $\bar{X}$ equal to the desired level of aggregate emissions.

The log of the aggregate productivity level is assumed to follow an AR(1) process of the form:

$$\begin{aligned} \ln \phi_{t+1} &= \rho_\phi \ln \phi_t + \epsilon_{\phi,t+1}, \\ \epsilon_{\phi,t} &\sim N\left(0, \sigma_\phi^2\right). \end{aligned} \tag{13}$$

Following Thomas F. Cooley and Edward C. Prescott (1995), we set we set $\rho_\phi = 0.95$ and

$\sigma_\phi = 0.07$. Similarly, the log of the international price of energy follows:

$$\ln p_{t+1} = \ln(\bar{p}) + \rho_p \ln p_t + \epsilon_{p,t+1}, \qquad (14)$$
$$\epsilon_{p,t} \sim N\left(0, \sigma_p^2\right).$$

We take the quarterly average imported crude oil price for the 1974:I-2013:II period, as published by the U.S. Energy Information Administration (EIA) in its *Short-Term Energy Outlook*, as a proxy for the overall price of energy p_t: we apply the Hodrick-Prescott filter (with the smoothing parameter equal to 1600) to the time series and estimate (14) on the cyclical component. The estimated parameters values are $\rho_p = 0.73$ and $\sigma_p = 0.124$. Both stochastic processes are then approximated with a 5-state discrete Markov chain computed using Rouwenhorst's method, as suggested in Karen Kopecky and Richard Suen (2010).

Finally, the average price $\bar{p}$ is calibrated to make the model reproduce in steady state, again in absence of climate policies, the average energy intensity of GDP at constant purchasing power parities (expressed in koe/\$2005p) for EU countries over the 2002-12 period, equal to 0.128, computed using data from the *Global Energy Statistical Yearbook* 2013 published by *Enerdata*. The parameter constellation is summarized in Table 1.

The model is solved using fully non-linear methods: the policy functions are computed using the Euler equation approach discussed in Pontus Rendhal (2013), while the ergodic distribution of the endogenous state variables is obtained with the binning approach discussed in Young (2010) and extended to the bivariate case in Marco Maffezzoli (2011).[5]

4 Results

In order to evaluate the implication of alternative carbon policies under uncertainty in the representative household productivity, we discuss six scenarios. All of them, but the no policy case, are calibrated in order to have the same environmental effect on average, that is a 10% reduction in emissions with respect to the no policy case. The European Commission claimed that the EU-ETS managed to reduce overall emission by 8.3% over the 2005-10 period.[6] This is a rather modest target when compared to the more challenging targets that were advocated for at the Copenhagen Climate Change Conference of Parties in 2009; Still it is more aggressive mitigation action than most nations of the world are currently doing or planning to do. A 10% reduction vis a vis the no policy case in 2011 translates into a 23% (27%) cut with respect to 1990 emissions if

[5]We use a grid of 1000 nodes for capital and 200 nodes for the stock of permits: further increasing the density of the grid has no significant impact on the results. The policy functions are approximated via multivariate linear interpolation.

[6]See `http://ec.europa.eu/clima/publications/docs/factsheet_ets_emissions_en.pdf` for further details.

we account for the fact that greenhouse gasses emissions have been decreasing by 15% (18%) in the EU15 (EU27) in 2011 with respect to 1990. This is actually more than the 2020 goal for the European Union that is to reduce emissions by 20% with respect to 1990 emission levels.

An important caveat the reader should bear in mind when looking at the welfare performance of each scenario we discuss below is that we are entirely neglecting the welfare implications of climate change. This would be inappropriate if we were to compare the no policy case with the climate policy scenarios. However, we are mainly interested in comparing costs and volatility implications of alternative climate policy scenarios which, by construction, are going to be by and large similar in environmental terms.

The six scenarios discussed in the next sections are the following:

1. **NoPolicy:** this is the benchmark model where no climate policies are in place, i.e. $\tau_E = 0$ and $M_t = \infty$.

2. **Tax:** the government uses a price instrument to limit emissions, thus $M_t = \infty$ and no market for emission permits is in place. The carbon tax is calibrated in order to achieve a 10% decrease in emissions in steady state (the resulting tax is $\tau_E = 0.0915$). Revenues are rebated through a lump-sum transfer to the household.

3. **Quantity - Cap (*fully auctioned permits*):** the government chooses a cap to limit emissions in line with previous scenarios, in average, but now the constraint on emissions, $E_t \geq M_t$, is *not necessarily* binding in equilibrium. Banking of unused permits is not allowed, i.e. $\delta_M = 0$. Again, the calibrated level of M_t is constant over time and equal to 0.0653. Permits are fully auctioned.

4. **Quantity - Banking (*fully auctioned permits*)**: the government adopts a quantity instrument to limit emissions in line with previous scenarios, in average; this times banking of unused permits is allowed, with (arbitrarily) $\delta_M = 0.25$. As in the previous scenarios, the calibrated level of M_t is constant and equal to 0.0660. Permits are fully auctioned.

5. **Quantity - Cap (*output-based allocated permits*):** the government chooses a cap to limit emissions in line with previous scenarios, in average, but now the constraint on emissions, $E_t \geq M_t$, is *not necessarily* binding in equilibrium. Banking of unused permits is not allowed, i.e. $\delta_M = 0$. Currently, in the EU-ETS only 5% of permits are auctioned, hence we set$\upsilon_2 = 0.95$; the remaining permits are allocated following an output-based rule, i.e. in our case proportionally to the installed capital stock. We calibrate the proportionality parameter υ_1 in order to make the model replicate the desired long-run level of emissions: the calibrated value is 0.01999.

6. **Quantity - Banking (*output-based allocated permits*)**: the government adopts a quantity instrument to limit emissions in line with previous scenarios, in average; this times banking of unused permits is allowed, with (arbitrarily) $\delta_M = 0.25$. As in the previous scenarios, we set$\upsilon_2 = 0.95$; the proportionality parameter υ_1 is set to 0.02023.

4.1 Long-run properties

A summary of results is presented in Tables 2 and 3, where each policy scenario corresponds to a separate column and each row represents an aggregate macro economic variable (we report both absolute values and % distance from the No Policy case). In particular, we report the unconditional means of the variables (i.e. their "steady-state" values) in Table 2 and their volatilities, as measured by the standard deviation, in Table 3.[7] Furthermore we report in Table 2 the steady-state welfare level,[8] computed as the unconditional mean of the representative household's value function, and the probability of the emission constraint being binding, computed from the ergodic distribution of the model.

All policy simulations imply a decrease in welfare, hence no evidence of strong double dividend effect can be found.[9] The policy simulations imply welfare costs in the order of 0.6-0.8%, within the bounds of the EMF22 assessment for the EU 20/20/2020 policy costs done with a suite of CGE models (a welfare loss of 0.5–2.0% by 2020 as in Christoph Böhringer et al., 2009) and of estimates in Fischer and Springborn (2011). A cap and trade system with banking and a non binding constraint set-up outperforms the tax in welfare cost terms. If we look into hours of work implications, which is another obvious performance indicator, we see that, although differences are small, all the cap systems again outperform the carbon tax.

What is more relevant to our analysis is that the choice of the solution method, whether we assume the cap is always binding, FIXED, or we allow for an occasionally binding constraint, CAP, is indeed a very relevant one in assessing macro economic implications of the same policy, namely a cap on emissions. By looking at the last row of Table 2 we can see that the cap turns out to be binding approximately half of the time, as in the other half of simulations economic performance is such that emissions are lower than the cap. When adopting an approach that requires an always binding cap, welfare costs are overestimated. There are two components to the difference in welfare. The first is

[7]The statistics are computed directly from the model's ergodic distribution: hence, the small-sample bias problem that affects alternative solution procedures is absent here.

[8]Being the welfare levels negative, because of the form of the utility function, in order to compute percentage variations we adopt the following usual convention: $\Delta x\% = (x' - x) / |x| \cdot 100$.

[9]Interestingly, Valentina Bosetti and Marco Maffezzoli (2013) do find a double dividend effect when policies are evaluated using an heterogenous agents model set up as opposed to the representative agent model.

Unconditional mean						
			FULLY AUCTIONED		GRANDFATHERED	
	NoPol.	*Tax*	*Cap*	*Bank.*	*Cap*	*Bank.*
Output (Q)	**0.572**	0.562	0.563	0.564	0.570	0.570
%Δ from NoPolicy		*-1.78%*	*-1.56%*	*-1.54%*	*-0.36%*	*-0.37%*
GDP (Y)	**0.525**	0.520	0.520	0.520	0.527	0.527
%Δ from NoPolicy		*-1.04%*	*-0.95%*	*-0.92%*	*0.34%*	*0.35%*
Cons. (C)	**0.446**	0.442	0.442	0.443	0.447	0.447
%Δ from NoPolicy		*-0.91%*	*-0.85%*	*-0.80%*	*0.12%*	*0.15%*
Investment	**0.079**	0.077	0.078	0.078	0.080	0.080
%Δ from NoPolicy		*-1.76%*	*-1.53%*	*-1.57%*	*1.60%*	*1.50%*
Gov. rev. (G)	**0.183**	0.183	0.183	0.183	0.183	0.183
%Δ from NoPolicy		*0.36%*	*0.16%*	*0.18%*	*0.26%*	*0.26%*
Capital (K)	**3.154**	3.098	3.106	3.108	3.204	3.204
%Δ from NoPolicy		*-1.77%*	*-1.53%*	*-1.48%*	*1.59%*	*1.58%*
Hours (N)	**0.330**	0.328	0.328	0.328	0.330	0.330
%Δ from NoPolicy		*-0.62%*	*-0.54%*	*-0.53%*	*-0.12%*	*-0.12%*
Energy (E)	**0.067**	0.061	0.061	0.061	0.061	0.061
%Δ from Bench.		*-10%*	*-10%*	*-10%*	*-10%*	*-10%*
Price of Per. (z)			0.035	0.034	0.042	0.040
Banked Per. (M)				0.082		0.077
Welfare	**-179.87**	-181.19	-181.13	-181.02	-179.45	-179.40
%Δ from NoPolicy		*-0.74%*	*-0.70%*	*-0.64%*	*0.23%*	*0.26%*
Prob. of the cap being binding			**50.3%**	**25.7%**	**67.0%**	**26.9%**

Table 2: Stochastic properties of the main variables I: unconditional means.

that forcing emissions to be higher than they would by means of a subsidy, in the FIXED case, is obviously sub-optimal and reduces welfare. But, in addition, the reduction in the volatility of consumption is exaggerated in the FIXED case, thus augmenting welfare.

Other differences are that the average price of permits is obviously underestimated (as we report the average price, half of the time the price will be negative rather than zero) and the mitigating effect on economic volatility, as mentioned, is inflated. Indeed, evaluated using the assumptions of the FIXED simulation, the carbon tax performs better than the cap system. This is no longer true when we are evaluating the cap system under the assumption as in the CAP simulation.

The Banking scenario, by providing intertemporal flexibility does outperform the other three policy instruments in welfare and GDP terms. The constraint on emissions, $E_t \geq M_t$, is now binding in only a quarter of simulations (again last row of Table 2), as the permits can be rolled over to subsequent periods and used up when more needed, partially relaxing the constraint.

Volatility (Std. Dev.)						
			Fully auctioned		Grandfathered	
	NoPol.	*Tax*	*Cap*	*Bank.*	*Cap*	*Bank.*
Output (Q)	**0.035**	0.034	0.030	0.030	0.032	0.032
%Δ from NoPolicy		*-1.58%*	*-13.15%*	*-13.01%*	*-7.40%*	*-7.08%*
GDP (Y)	**0.032**	0.032	0.030	0.030	0.031	0.031
%Δ from NoPolicy		*-0.85%*	*-6.53%*	*-6.65%*	*-4.08%*	*-3.61%*
Cons. (C)	**0.022**	0.022	0.021	0.021	0.021	0.021
%Δ from NoPolicy		*-0.59%*	*-4.94%*	*-5.80%*	*-2.56%*	*-2.38%*
Investment	**0.012**	0.012	0.011	0.011	0.011	0.012
%Δ from NoPolicy		*-1.23%*	*-9.13%*	*-8.31%*	*-6.09%*	*-4.93%*
Gov. rev. (G)	**0.011**	0.011	0.012	0.012	0.011	0.011
%Δ from NoPolicy		*0.54%*	*6.13%*	*5.68%*	*-4.69%*	*-4.24%*
Capital (K)	**0.234**	0.230	0.221	0.217	0.225	0.226
%Δ from NoPolicy		*-1.37%*	*-5.46%*	*-7.19%*	*-3.85%*	*-3.08%*
Hours (N)	**0.007**	0.007	0.006	0.006	0.006	0.006
%Δ from NoPolicy		*-0.43%*	*-11.98%*	*-11.83%*	*-7.07%*	*-6.78%*
Energy (E)	**0.014**	0.013	0.007	0.007	0.007	0.008
%Δ from Bench.		*-10.01%*	*-51.18%*	*-47.98%*	*-47.91%*	*-46.11%*
Price of Per. (z)			0.037	0.036	0.037	0.036
Banked Per. (M)				0.017		0.015

Table 3: Stochastic properties of the main variables II: standard deviations.

5 Conclusions

If we impose a fixed cap (FIXED), as it has been done in the literature so far, rather than allowing for the constraint to be occasionally binding (CAP) we do overestimate policy costs. We also underestimate the average value of emission permits as well as overestimate their volatility.

Emission volatility, thus being notably lower than in the TAX case (where it fluctuates with productivity shocks), is far from being null, as would be estimated in the FIXED case, and comparable in both the CAP and BANKING case.

The price of permits function as a stabilizer, reducing economic volatility in the case of an emission cap. However, if the emission cap constraint is allowed to be non binding its shadow price, namely the price of permits, will not run from positive to negative values but it will be zero in the case of unexpected economic cooling. Thus the stabilizing effect on economic volatility is less than in the work presented by S-F.

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A Appendix

Being in equilibrium $L_t = N_t$, the equilibrium conditions can be combined and summarized as:

$$V_t = \left(C_t - \kappa \frac{N_t^{1+\eta}}{1+\eta}\right)^{-\sigma} \tag{15}$$

$$\kappa N_t^{\eta+1} = \frac{1-\tau_Y}{1+\tau_N} s_N Q_t, \tag{16}$$

$$\gamma \frac{Q_t}{E_t} = (1+\tau_E)\, p_t + \frac{z_t\,(1-\delta_M) + \tilde{\mu}_t}{1-\tau_Y}, \tag{17}$$

$$V_t = \beta \mathbb{E}_t \left\{ V_{t+1} \left[1 - \delta_K + (1-\tau_Y)\, s_K \frac{Q_{t+1}}{K_{t+1}} + z_{t+1} \chi'_{t+1} \right] \right\}, \tag{18}$$

$$z_t = \beta \mathbb{E}_t \left\{ \frac{V_{t+1}}{V_t} \left[z_{t+1}\,(1-\delta_M) + \tilde{\mu}_{t+1} \right] \right\}, \tag{19}$$

$$K_{t+1} = (1-\delta)\, K_t + Y_t - C_t, \tag{20}$$

$$M_{t+1} = (1-\delta_M)\,(M_t - E_t) + X_t, \tag{21}$$

$$\tilde{\mu}_t\,(E_t - M_t) = 0 \tag{22}$$

$$E_t \leq M_t \tag{23}$$

$$\tilde{\mu} \geq 0 \tag{24}$$

where $s_N \equiv (1-\alpha)(1-\gamma)$, $s_K \equiv \alpha(1-\gamma)$ and $\tilde{\mu}_t \equiv \mu_t / \upsilon_t$.

Note that (16) can be solved for N_t:

$$N_t = \left(\frac{1-\tau_Y}{1+\tau_N} \frac{s_N}{\kappa} \phi_t K_t^{s_K} E_t^{\gamma} \right)^{\frac{1}{\eta+1-s_N}}. \tag{25}$$

Imposing $\tilde{\mu}_t = 0$, we can combine (16) and (17) in order to get:

$$\tilde{E}_t = \left[\frac{\gamma\,(\phi_t K_t^{s_K})^{\xi} \left(\frac{1+\tau_N}{1-\tau_Y} \frac{\kappa}{s_N} \right)^{1-\xi}}{(1+\tau_E)\, p_t + \frac{z_t (1-\delta_M)}{1-\tau_Y}} \right]^{\frac{1}{1-\gamma\xi}}, \tag{26}$$

where $\xi \equiv (\eta+1)/(\eta+1-s_N)$. If $\tilde{E}_t < M_t$, then $E_t = \tilde{E}_t$ and $\tilde{\mu}_t = 0$; otherwise, $E_t = M_t$ and:

$$\tilde{\mu}_t = (1-\tau_Y) \left[\gamma \frac{Q_t}{E_t} - (1+\tau_E)\, p_t \right] - z_t\,(1-\delta_M). \tag{27}$$