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Abatement Cost Uncertainty and Policy Instrument Selection under a Stringent Climate Policy. A Dynamic Analysis

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Summary

This paper investigates the relative economic and environmental outcomes of price versus quantity mechanisms to control GHG emissions when abatement costs are uncertain. In particular, we evaluate the impacts on policy costs, CO2 emissions and energy R&D for a stringent mitigation target of 550 ppmv CO2 equivalent (i.e. 450 for CO2 only) concentrations. The analysis is performed in an optimal growth framework via Monte Carlo simulations of the integrated assessment model WITCH (World Induced Technical Change Hybrid). Results indicate that the price instrument stochastically dominates the quantity instrument when a stringent stabilization policy is in place.

This paper has been awarded 2nd prize among all submitted papers to the 20th World Energy Congress held in Rome November 2007.

Keywords: Abatement Costs, Climate Policy

JEL Classification: H2, C6, Q5

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1. Introduction

The debate on price versus quantity instruments for tackling climate change has continued for decades. Although the introduction of a European emission trading scheme within the Kyoto framework could have represented a pragmatic resolution to this discussion, the need to engage the US and other large-emitters fast-growing countries, has led some economists to suggest a global carbon tax as a possible way around the impasse (see, for example, Stiglitz, 2006). For this reason, we elaborate upon existing work analysing climate change policy instruments under uncertainty. The problem was stated analytically by Weitzman, (1974); subsequently, numerical developments have been carried out in Pizer (1999), and Newell and Pizer, (2003).

In this paper, we study how uncertain abatement costs and uncertain climate sensitivity (which ultimately reflects on climate damages), jointly although independently, affect optimal choices when a stabilization target is imposed through a price instrument and compare it to the case when a quantity instrument is adopted. While the presence of uncertain abatement costs pushes risk adverse individuals to prefer the price instrument, the randomness of climate damages introduces an opposite bias towards the quantity instrument. We study how these two competing forces combine and we comment on the resulting optimal policy choices for a risk adverse individual.

For the purpose of our analysis we apply Monte Carlo simulations to WITCH (World Induced Technical Change Hybrid), an optimal growth integrated assessment model with a fairly detailed energy sector. First, the policy scenarios under examination – Cap & Trade and Carbon Tax – are analysed in a deterministic setting so as to verify consistency with the Weitzman result (1974) – i.e. that in the absence of uncertainty, price- and quantity-based market instruments are equivalent in their economic and environmental impacts. Subsequently, the analysis is reproduced for uncertain abatement costs and climate sensitivity. With a Monte Carlo simulation we evaluate the effect of uncertainty on endogenous GDP, consumption, CO_2 emissions, R&D investments in the energy sector and investment in clean electricity generation technologies, under price and quantity policy instruments.

Results show that uncertainty leads to GDP and consumption with higher means and lower variances under the price instrument than under the quantity instrument. The price instrument stochastically dominates the quantity instrument with respect to GDP and consumption and the presence of uncertainty on climate damages does not revert the preference for the quantity policy tool. Emissions on the other hand are constant under the Cap & Trade scenario, while they adjust to random differences in abatement costs under the Carbon Tax scenario, not necessarily satisfying the limits sought by a stabilization target. The explanation for this result lies in the fact that the effect of uncertain abatement costs is entirely reflected in economic growth in the Cap & Trade case, while under the Tax scenario, the carbon tax offers a safety valve in case of higher than expected abatement costs.

Thus while the tax option dominates with respect to GDP and consumption, it does less well with respect to achieving emissions reduction targets. The costs of not achieving the emissions targets, however, do not turn out to be that high: even in case of higher than expected climate damages, the penalty for non compliance to the environmental target is relatively small when carbon taxes are very high as in the stringent stabilization scenario considered here. This stems from the fact that one of results of greatly reducing carbon emissions is precisely that of hedging against worse than expected climate change consequences by keeping carbon concentrations under control. Intertemporal discounting further reduces the cost of slightly missing the environmental target. These issues, together, make the penalty rather small. Energy R&D investments appear to be higher under the Tax scenario (when productivity of R&D is higher than average, higher than average investments are induced by the carbon tax) but to display higher variance under the Cap & Trade scenario (notwithstanding the effectiveness of R&D, the target has to be achieved and at least some investments have to be undertaken). Finally, investments in renewables for electricity generation shows a higher mean and variance under the quantity instrument.

The paper is structured as follows. In the next section the model used for the analysis is described. This is followed by a description of the policy scenarios analysed and the assumptions behind them. Section 4 describes the way uncertainty is incorporated into the model, and Section 5 discusses results. In Section 6 we comment on risk aversion, and we conclude in Section 7.

2. The Analytical Framework

2.1 The WITCH Model

The analysis has been performed using the WITCH model – see Bosetti et al (2006) and Bosetti, Massetti and Tavoni (2007) for a detailed description of the model. WITCH is a regional integrated assessment model structured so as to provide normative information on the optimal responses of world economies to climate damages and to model the channels of transmission of climate policy to the economy. It is a hybrid model because it combines features of both top-down and bottom-up modelling: the top-down component consists of an inter-temporal optimal growth model in which the energy input of the aggregate production function has been expanded to give a bottom-up type of description of the energy sector. Countries are grouped in 12 regions that cover the world and that strategically interact following a game theoretic structure. A climate module and a damage function provide the feedback to the economy from carbon dioxide emissions into the atmosphere.[1]

Several features of the model allows us to investigate a number of issues in a greater detail than is usually done in the existing literature. First, although rather rich in its energy modelling and close in spirit to bottom-up energy models, WITCH is based on a top-down framework that guarantees a coherent, fully intertemporal allocation of investments under the assumption of perfect foresight. Second, the model can track all actions that have an impact on the level of mitigation – R&D expenditures, investment in carbon-free technologies, purchases of emission permits or expenditures for carbon taxes – and we can thus evaluate optimal responses stimulated by different policy tools. This leads to a transparent evaluation of abatement costs and to a clearer quantification of the uncertainties affecting them. Finally, the regional specification of the model and the presence of strategic interaction among regions – as for example through learning spillovers in Wind & Solar technologies – allows us to account for a very realistic issue, i.e. the incentives to free-ride in the choice of optimal investments.

Optimal growth models are normally very limited in terms of technological detail. This severely constrains any analysis of climate change issues, which are closely related to the evolution of energy sector technologies. In WITCH this sector is considerably more detailed than that of other optimal growth models (see Fig. 1 for a diagrammatic description) and allows a reasonable characterization of future energy and technological scenarios and an assessment of their compatibility with the goal of stabilizing greenhouse gases concentrations. Also, by endogenously modelling fuel prices, as well as the cost of storing the CO_2 captured, the model can be used to evaluate the implication of mitigation policies for the energy system and all its components.

A key feature of WITCH is that the interdependency of all countries' climate, energy and technology policies is accounted for by modeling the free-riding incentives on global externalities such as CO_2, exhaustible resources, international spillovers etc. Investment strategies are thus optimized by taking into account both economic and environmental externalities. The investment profile for each technology is the solution to an inter-temporal

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[1] The model is solved numerically in GAMS/CONOPT for 30 5-year periods, although only 20 are retained as we do not impose terminal conditions. Solution time for the Baseline scenario is approximately 30 minutes on a standard Pentium PC.

game between the 12 regions. More specifically, these 12 regions behave strategically with respect to all decision variables by playing an open-loop Nash game. From a top-down perspective, this enables us to analyze both the geographical dimension (e.g. rich vs. poor regions) and the time dimension (e.g. present vs. future generations) of climate policy.

In comparison to other optimal growth models, WITCH shares a game set-up similar to that in RICE (Nordhaus and Boyer, 2000), but departs from the stylized representation of the energy sector by featuring greater technological detail, technical change, natural resource depletion, etc. The MERGE model (Manne, Mendelsohn and Richels, 1995) links a simple top-down model to a bottom-up part that feeds in the cost of energy; in contrast, WITCH is a single model that represents the energy sector within the economy, and therefore enodogenizes the energy technology investment paths coherently with the optimal growth structure. Also, WITCH features a non-cooperative game among the regions.

Figure 1: The Production Nest and Assumed Elasticities of Substitution

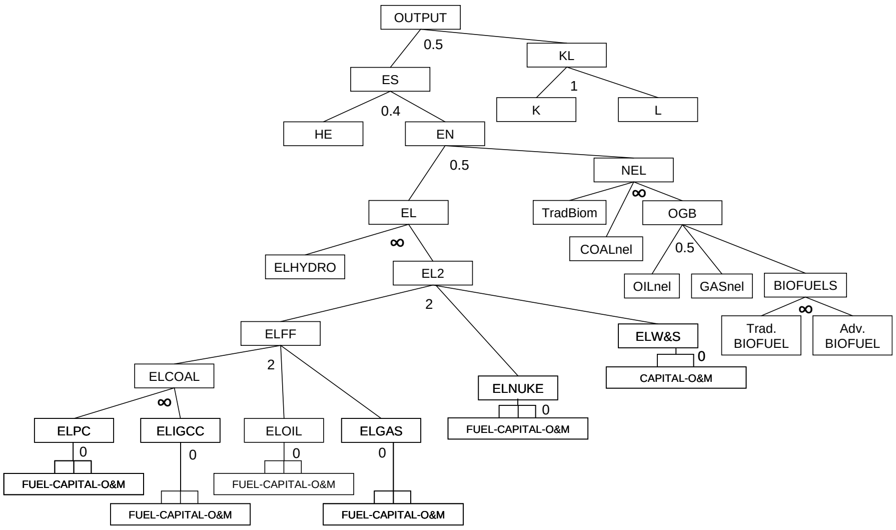

Figure 1.

Legenda: KL= capital-labour aggregate; K = capital invested in the production of final good; L= Labour; ES = Energy services[2]; HE = Energy R&D capital; EN = Energy; EL = Electric energy use; NEL = Non-electric energy use; OGB = Oil, Gas and Biofuel nest; ELFF = Fossil fuel electricity nest; W&S= Wind and Solar; ELj = Electricity generated with the technology j; TradBiom= Traditional Biomass; Kj = Capital for generation of electricity with technology j; O&Mj = Operation and Maintenance costs for generation of electricity with technology j.

2.2 Endogenous Technical Change (ETC) in the WITCH model

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[2] Energy services ES, combines energy with a variable, HE, that represents technological advances stemming from investment in energy R&D for improvements in energy efficiency. An increase in energy R&D efforts improves the efficiency with which energy, EN, is translated into energy services, ES.

Technical change in WITCH is endogenous and can be induced by climate policy, international spillovers and other economic effects. The hybrid nature of WITCH allows it to model endogenous technological change (both in its bottom-up and top-down dimensions) as driven both by Learning-by-Doing (LbD) and by energy R&D investments. These two sources of technological improvements act through two different channels: LbD is specific to power-generation costs, while R&D affects the non-electric sector and the overall system energy efficiency. We focus on the latter, as this will be the source of uncertainty in our modelling exercise.

Investments in energy R&D increase energy efficiency. Following Popp (2004), technological advances are captured by a stock of knowledge, combined with energy, in a constant elasticity of substitution (CES) function that produces energy efficiency improvements:

$$ES(n,t) = \left[\alpha_H HE(n,t)^{\rho} + \alpha_{EN} EN(n,t)^{\rho}\right]^{1/\rho} . \qquad (1)$$

Where the variables are as defined in Figure 1. The stock of knowledge $HE(n,t)$ is derived from energy R&D investments in each region through an innovation possibility frontier characterized by diminishing returns to research. This formulation is proposed by Jones (1995) and empirically supported by Popp (2002) for energy related innovations:

$$HE(n,t+1) \ = \ a(n) I_{R\&D}(n,t)^{b} HE(n,t)^{c} + HE(n,t)(1-\delta_{R\&D}) , \qquad (2)$$

where $\delta_{R\&D}$ is the depreciation rate of knowledge and $I_{R\&D}$ is……...

Social returns to R&D are understood to be higher than private returns. Hence, the positive externality of knowledge creation is accounted for by assuming that the return on energy R&D investment is four times higher than the return on investment in physical capital. This way to capture market failure in innovation was proposed by Nordhaus (2003). At the same time, the opportunity cost attributed to the crowding out of other forms of R&D is captured by subtracting four dollars of private investment from the physical capital stock for each dollar of R&D crowded out by new energy R&D. We further assume new energy R&D crowds out half the amount of other R&D, as in Popp (2004).

2.3 Climate Module and the Cost of Global Warming.

In WITCH a climate module, adapted from Nordhaus and Boyer (2000), governs the cycle of CO_2 emissions into the atmosphere. Climate sensitivity (*CS*) enters explicitly in the equation that governs the temperature (T) and it is thus easy to impose on it a random pattern:

$$T(t+1) = T(t) + \sigma_1 \left\{ F(t) - \frac{4.1}{CS} T(t) - \sigma_2 \left[T(t) - T_{LO}(t) \right] \right\} \tag{3}$$

where $T_{LO}(t)$ is temperature of deep oceans (deg C above preindustrial), $F(t)$ is radiative forcing (W per meter squared) and CS is defined as the global mean climatological temperature change resulting from a doubling of atmospheric CO_2 content (in deg C). What is generally recognised within this strand of climate literature is that the climate sensitivity parameter is extremely uncertain, it is known perhaps only to a factor of three or less; at the same time it plays a key role in determining final temperature changes.

Temperature enters a quadratic damage function that affects output. The damage function, as estimated in Nordhaus and Boyer (2000), includes a whole set of climate impacts, ranging from impacts on agriculture to coastal vulnerability, to health and other catastrophic events, etc. The non-linearity of the damage function implies that changes of climate sensitivity at high ranges of temperature have a higher impact on output than the same changes have at low levels of temperature:

$$\Omega(n,t) = \frac{1}{1 + \left(\theta_{1,n} T(t) + \theta_{2,n} T(t)^2 \right)}. \tag{4}$$

3. Policy Scenarios analyzed

The numerical analysis described in this paper has been performed for a given global climate target. For its recognized scientific relevance, the climate target that we have selected is the stabilisation of atmospheric concentration of Greenhouse Gases (GHG), at 450 parts of CO_2 per million by volume (ppmv) by 2100.[3] Given the regional structure of the model, some assumption on the distribution of the necessary effort to reach such a global target had to be made. The abatement burden in the following exercises has been allocated on the basis of a Rawlsian principle of entitlement to equal per-capita emissions. A different allocation choice would affect the welfare distribution but not the general nature of the results with respect to GDP, consumption, R&D investment and investment in renewables.

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[3] This is roughly equivalent to a stabilization of all greenhouse gases at 550 ppmv. Other major GHG are: methane, nitrous oxide. Temperature increases as a result of a higher radiative forcing, induced by higher concentrations of GHG in the atmosphere. By selecting a time path of emissions so to stabilize the concentrations of GHG it is possible to stabilize the increase of world average temperature at "safe levels".

We consider two different policies:

S1) *Cap & Trade*. We use as policy tool a world carbon market that equalizes marginal abatement costs worldwide. Each model region is assigned an entitlement in terms of emissions rights that it can either use or trade in the market. The total amount of emission allowances produces a global emission path through time which entails the stabilization of concentrations below the target (550 ppmv CO_2 equivalent).

S2) *Global Carbon Tax*. Each model region receives an entitlement of emissions rights. The total amount of emission rights produces a global emission path through time that entails the stabilization of concentration below the target (550 ppmv CO_2 equivalent). Emissions above and below the regional level of emission rights are taxed or subsidised, respectively. In particular, those regions emitting above their permitted regional level contribute to an international redistribution agency which provides payments of a carbon credit for those regions emitting below their permitted regional level. The carbon tax is set equal to the price of emission permits, i.e. to the price of carbon, derived from scenario *S1*.

4. Uncertainty and Monte Carlo Simulation

4.1 Abatement costs

Given the technological disaggregation of the WITCH model, uncertainty about abatement costs could be modelled in a number of different ways. For example, there could be uncertainty about the future costs of Carbon Capture and Sequestration or about the full cost of Nuclear Power, to mirror the potential social opposition to such possible options. Alternatively it could be represented as uncertainty concerning the future cost of renewable technologies; or as uncertainty about the potential for energy savings. In the present exercise, given the focus on energy R&D, uncertainty has been modelled as concerning the effectiveness of energy knowledge investments. In particular, we have concentrated on the parameter accounting for the productivity of investments in energy R&D, i.e. on $a(n)$ in equation (2).

It is very hard to find an adequate probability distribution estimate in the literature for anything related to uncertainty about abatement costs. We have assumed that the productivity parameter is multiplied by a log-normal variable with unit mean and 0.3 standard deviation. This ensures that the productivity of new R&D investments varies by roughly 50% for a 95% confidence interval.

4.2 Climate Sensitivity

We have fitted the distribution of the climate sensitivity parameter on data available from Hegerl et al (2006). The distribution of the log of the parameter CS is assumed to be N(0.96, 0.485). Such a distribution corresponds to a mean climate sensitivity of 2.9, the base value normally fed into the WITCH model.

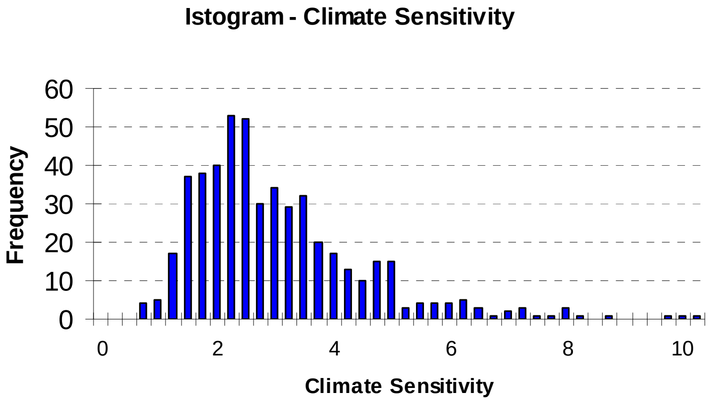

Figure 2. Assumed distribution for the Climate Sensitivity parameter

5. Simulation Results

5.1 Deterministic analysis

In this section, we present a deterministic analysis of each of the two policy scenarios for the central case value.

Under Cap & Trade, abatement costs are equalized across regions and world time path of carbon prices is reflected in emissions permit prices. The equal per capita burden sharing scheme implies sizeable trading of carbon between High Income and Low Income countries; especially in the first half of the century when the target is very binding for high personal emission countries, trade of more than 2GtC are reported between the two regions. In term of monetary transfers, the rapidly growing carbon prices necessary to attain the strong mitigation are such that transfers keep increasing despite the reduction in the quantity of carbon traded. The following Table1 reports the carbon market expenditures and revenues in 2030 and 2050, also expressed as a percentage of GDP.

Monetary transfers in the Carbon Market (values and shares of GDP)

	High Income	Low Income
2030	-0.6 (1.3%)	+0.6 (2.3%)
2050	-1.6 (2.7%)	+1.6 (2.9%)

* Trillions 1995 USD.

Table 1.

Countries with high initial per capita emissions are large permit buyers and undergo significant carbon expenditures, for example the US would have a cost equal to 2.1% and 4.2% of GDP in 2030 and 2050 respectively. Clearly, a different allocation scheme that favours High Income countries –such as a sovereignty[4] one- would imply flows in the opposite direction. Yet, as noted above, the allocation scheme has no effect on the global variables, as they are determined by world marginal abatement costs[5].

This set of carbon prices is used as the appropriate carbon tax in the Carbon Tax scenario. Regions pay the tax on carbon to an international redistribution agency on each ton of carbon in excess of their limit, while regions falling short of their of limit are entitled to a subsidy equal to the carbon value of their saved emissions.

Simulation results show that Cap & Trade and a global Carbon Tax yield the same outcome in terms of costs, GDP, consumption and emissions. This result confirms Weitzman (1974). To understand this outcome, it is important to stress the fact that each region ultimately experiences any climate policy as an intertemporal time path of carbon prices, or (what should be the same thing) the time path of world's equalized marginal abatement costs. That is, under certainty, two policies that produce the same time path of carbon prices are perceived as identical. Very minor differences across simulations are solely attributable to numerical approximations used by the optimization solver. The following Table 2 and Figures 3 and 4 report on the endogenous outcome variables under the three different scenarios.

Deterministic Outcome (sum over the period 2002-2102)

	GDP*	Consumption*	CO2 Emissions (GtC)
Trade	2288	1910	95
Tax	2288	1910	95

* Trillions 1995 USD.

Table 2.

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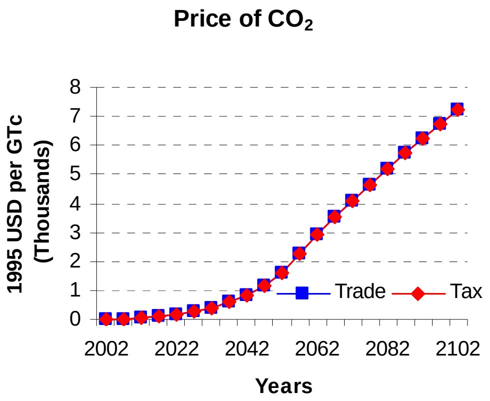
[4] The Sovereignty allocation scheme implies allowances are distributed to each region according to their base year share of total emissions.

[5] E.g. The Coase Theorem holds also in our framework.



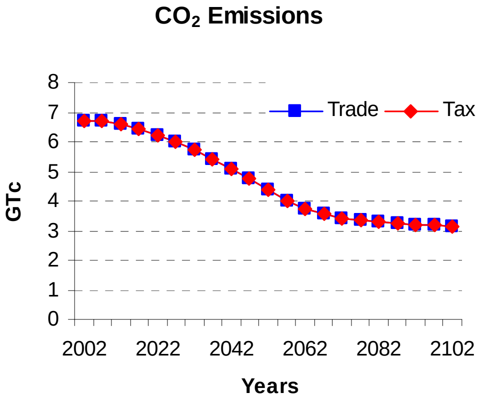


Figure 3.

Figure 4.

These results clearly show that Cap & Trade and Carbon Tax policies, in a deterministic context, yield the same results in economic and environmental terms.

5.2 Monte Carlo analysis

In this Section, we show how the social planners' optimal behaviour changes in response to the joint, although independent, perturbation of the two world parameters under investigation. The present exercise aims to determine the magnitudes and distributions of the optimal choice variables (investments and consumption) in a response to random realizations of the energy R&D productivity parameter and the parameter that governs climate sensitivity under the Cap & Trade and under the Carbon Tax scenarios. We simulate the case of an advisor who uses the central value for the productivity parameter to advise a policy maker. The policy maker has the option to choose between Cap & Trade and a Carbon Tax (fixed once and forever) as a policy instrument. If the real world was deterministic, the Weitzman principle of equality between the two instruments would be valid, as we have shown above. Suppose, instead, that the policy maker knows that the world she faces is characterized by uncertainty on the realization of the productivity parameter and of the climate sensitivity. If she decides to adopt a Cap & Trade approach to contain carbon emissions, she has a flexible instrument that will automatically adjust carbon prices to match equalized marginal abatement costs under any random realization of the R&D productivity parameter. Policy costs might turn to be higher, but the time path of emissions remains unchanged. The presence of uncertainty on climate sensitivity does not neutralize the possibility to miss the environmental target. However, given the stringency of the climate policy, deviations from the optimal temperature path typically occur in a range in which the effect on the climate damage function is contained. If instead she implements the Carbon Tax, she will not be able to adjust the carbon price to match the random realization of marginal abatement costs. Thus policy costs will not exceed a maximum threshold, but the environmental target might not be met, even with fully deterministic climate dynamics. The randomness of the climate system further increases the variability of the final temperature outcome. With our Monte Carlo analysis we provide estimates of the distributions of key economic variables under both types of policies, as a function only of our assumptions about the distribution of R&D productivity.

5.2.1 Environmental and Economic Impacts

Let us start by considering the environmental impact of the two alternative policy scenarios – namely their effect on CO_2 concentrations. By construction, Cap & Trade emissions are fixed while emissions under the Carbon Tax scenario are not: unfavourable (favourable) realizations of marginal abatement costs lead to higher (lower) emissions.

RESULT 1: Under Cap & Trade, uncertainty about the random parameter is manifested in the costs (GDP and Consumption); under a Carbon Tax, it is transmitted via CO_2 emissions.

We report below the time paths of CO_2 emissions and of the carbon tax under the two scenarios. The heterogeneity results from variability in R&D productivity realizations.

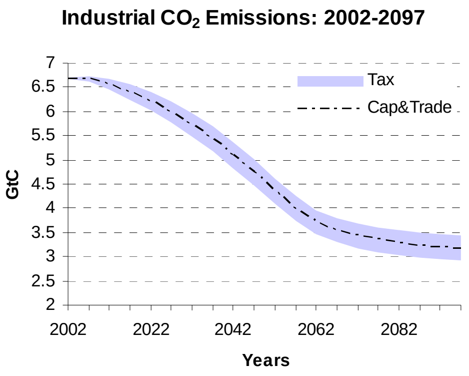


Figure 5.

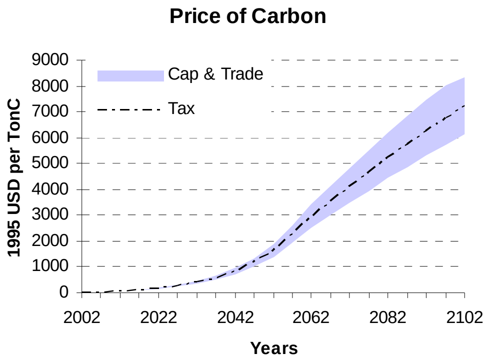


Figure 6.

Under the Cap & Trade policy, the time path of emissions is insensitive to random realizations of the productivity parameter. Under the Tax, however, the optimal abatement rate varies so as to adjust marginal abatement costs to equal marginal benefits in terms of avoided taxes. In Figure 5, the grey area contains all possible emissions time paths under the Tax policy and the dotted line represents the non-stochastic emissions cap imposed under the Cap & Trade policy. In Figure 6, the grey area contains all possible carbon price paths under Cap & Trade, while and the dotted line represents the non-stochastic carbon tax imposed under the Tax policy.

The final outcome on temperatures, and thus the final impact on the economy, depends on the realization of the parameter that governs climate sensitivity.

We can now analyze the economic consequences of uncertainty for the two policy instruments. As shown in Tables 3 and 4 and in Figures 7 and 8, The Tax policy produces slightly higher GDP and consumption values and a lower variance relative to Cap & Trade. This result is explained by a twofold argument:

1. First The Cap & Trade approach is more sensitive to abatement cost realizations: whenever R&D is found to be less productive than anticipated, economic policy costs, in terms of lower GDP and consumption, are higher with the quantity instrument than with the price instrument. This is likely to be offset by the fact that the Cap & Trade scenario implies strict compliance with the environmental target, while the Tax scenario means that the economy incurs an environmental penalty for not complying with the environmental target whenever abatement cost are higher than expected.
2. Second, environmental penalty that arises when, under the Tax policy instrument, emissions are higher than expected due to high abatement costs, does not counterbalance greater policy costs. Even if there might be combinations of high abatement costs and high climate sensitivity. This derives from the stock nature of the CO_2 externality (temperature and damages react very slowly to increase in emissions flows) and from the limited impact of variations of the world temperature when a stringent environmental target is implemented.

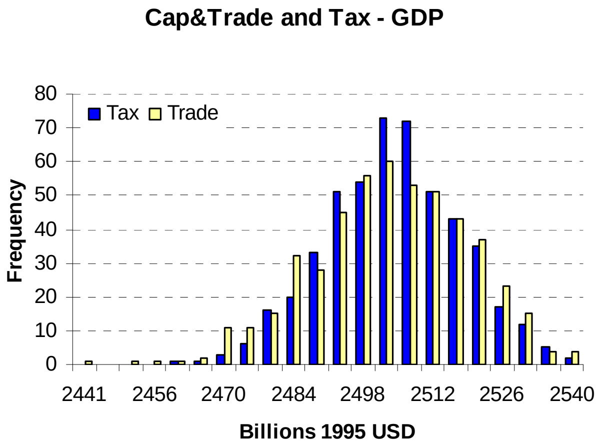


Figure 7.

GDP - Descriptive Statistics

	Trade	*Tax*
Mean	2500.880	2501.686
Standard Dev.	16.221	13.726

Table 3.

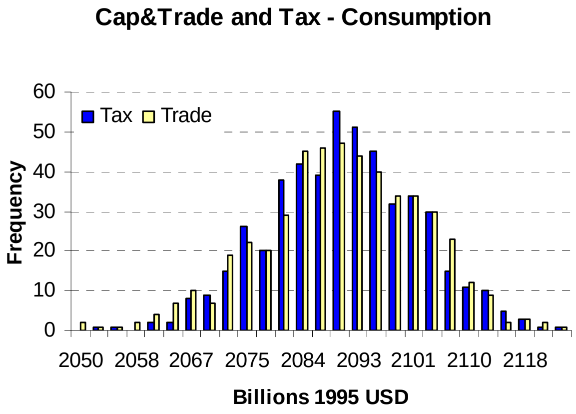


Figure 8.

Consumption
Descriptive Statistics

	Trade	*Tax*
Mean	2088.579	2089.124
Standard Dev.	12.624	11.587

Table 4.

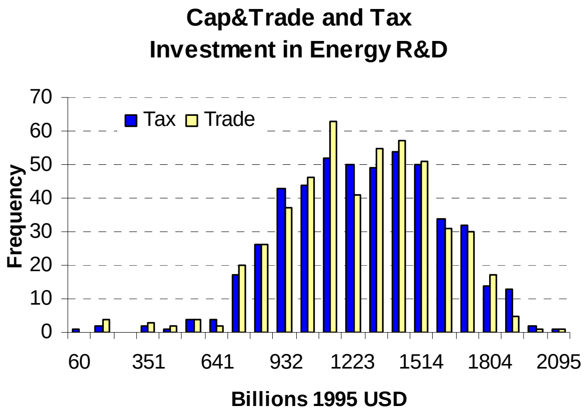
We can thus state the second result:

RESULT 2: GDP and Consumption are higher in the Tax case; they have higher variance under the Cap & Trade policy as opposed to the Carbon Tax policy.

5.2.1 Innovation Impacts

Considering the impacts of the two different policies on innovation activities, such as R&D investments, we find a larger mean investment in energy R&D under the Carbon Tax than under Cap & Trade. Variance also in this case is higher under the Cap & Trade scenario than under the Carbon Tax. These results are shown in Figure 9 and Table 5.

Differences in the productivity of R&D have asymmetric effects under the Carbon Tax and Cap & Trade policies. The higher variance of the investments in R&D under Cap & Trade is due to the fact that with a quantity instrument, the objective is, quite trivially, to meet the cap. This requirement binds when energy R&D productivity is low (i.e. some investment has to be made anyway) but also when R&D productivity is high (i.e. enough investment has to be done to meet the target). This is the reason for the higher variance. Concerning the mean, there is no incentive with a quantity instrument to invest beyond what has to be done to meet the cap. However, such an incentive does exist when considering a price instrument. We can summarize this in the following result:



Investment in Energy R&D
Descriptive Statistics

	Trade	*Tax*
Mean	1170.617	1226.190
Standard Dev.	336.195	333.338

Figure 9.

Table 5.

RESULT 3: The distribution of investments in energy efficiency R&D is higher under the Tax policy, while the variance is higher under Cap & Trade.

In Figure 9 below we provide additional evidence about the different impacts upon innovation activities under Cap & Trade *vs* Carbon Tax policies by looking at investments in renewable electricity generation. Investments in renewables have higher variance and higher mean under Cap & Trade (by the same line of reasoning offered for investments in energy R&D, the cap on emission being the main driving force). However, the higher investments that are necessary to reach the target under a low realization for the productivity of energy R&D investments, are so large in the Cap & Trade case that they more than compensate investment stimulated by the carbon tax when abatement costs are lower than expected (the right tail of the distribution in Figure 9). Effects on investments in renewables grow larger due to the learning effects (i.e. the greater the installed capacity in wind and solar technologies in this model, the lower the investment costs for new plants, as a result of a learning-by-doing). This leads to result four:

RESULT 4: The distribution of investments in Wind&Solar electricity generation technologies is higher under the Cape&Trade policy. Also the variance is higher under the Cap&Trade Policy compared to the Tax policy instrument.

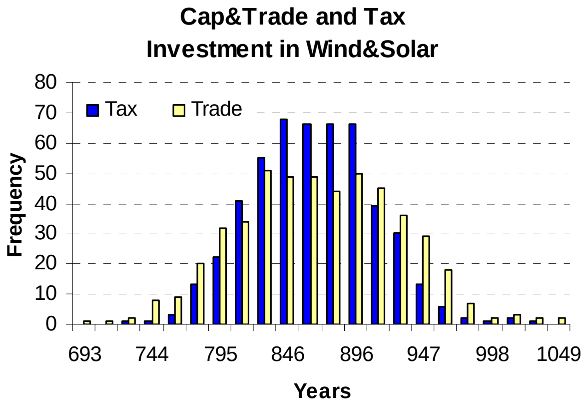


Figure 10.

Investment in Wind&Solar
Descriptive Statistics

	Trade	*Tax*
Mean	857.45115	855.8505
Standard Dev.	57.764551	44.628811

Table 6.

7. Final remarks.

In the present paper, we have analyzed the impact of uncertainty in abatement costs and in climate sensitivity for quantity versus price policy instruments. For this purpose we have used the integrated assessment WITCH model to perform Monte Carlo analyses on the realization of the energy R&D productivity parameter and the sensitivity parameter which governs temperature increases. This is just one way in which abatement cost uncertainty might be represented in this model. Results indicate that uncertainty about abatement costs leads to GDP and consumption profiles with slightly higher means and considerably lower variance under the price instrument (Carbon Tax). Emissions are constant under the Cap & Trade scenario, while they adjust in response to random abatement costs under the Carbon Tax scenario (not necessarily satisfying the limits required by a stabilization target)**.** The effect of uncertainty on energy R&D productivity produces higher values for energy R&D investments under the price instrument.

The presence of uncertainty on climate sensitivity does not revert the standard result shown in Pizer (1999). This is due to the fact that at low levels of temperature increases, as it is the case when a stringent climate target is adopted, deviations from the optimal path are relatively mild when a quadratic damage function is adopted.

Implementing either a global trading scheme or a tax scheme could involve huge transfers of resources between countries. We have shown how large these transfers can be in the case where the initial allocations were made on a per capita basis. It is reasonable to question the practicality of such large transfers. In this context we note that a different allocation of initial allocations can reduce the size of the transfers. Moreover it is also important to note that the size of the transfers is not a function of the choice of taxes or permits. In both cases a given initial allocation implies the same magnitude of transfers. The major difference is that with a tax a central authority is needed to act as a 'clearing house' for the transfers, whereas with permits such transfers can be made in a more decentralized manner.

For future work, we identify the following important candidate tasks: first, to repeat the exercise for different stabilization targets which will imply different carbon prices, second, to run analogous experiments which incorporate uncertainty on parameters which affect abatement costs directly, rather than via efficiency only. For example, consider uncertain realizations of Carbon Capture and Sequestration of CO_2 and uncertainty in the external costs of nuclear power. This would increase the scope of the results and provide an interesting and up–to-date policy relevant results. Finally it is important to investigate further the issue of transfers between countries and how they can be managed and kept at an acceptable level, while recognizing the need to respect the goals of inter and intra- generational equity.

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