# Emissions Cap or Emissions Tax?

A Multi-sector DSGE Analysis

Yazid Dissou[a,*]; Lilia Karnizova[b]

[a] University of Ottawa; [b] University of Ottawa

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**Abstract**

This paper compares a cap and a tax as instruments in controlling a reduction of greenhouse gas emissions using a multi-sector dynamic stochastic general equilibrium (DSGE) model. The model incorporates two types of fossils and takes into account stochastic variations in sectoral productivity shocks. We find that a cap dampens the volatility in the aggregate variables, relative to a tax. However, the tax policy is preferred from the welfare perspective when shocks to the production of fossils are taken into account. These shocks significantly affect the production of not only fossils, but also the other economic sectors. We further find that a cap constraint increases the sensitivity of fossils sectors to fluctuations in all types of productivity shocks.

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[*]Corresponding author: ydissou@uottawa.ca. The authors thank Qian Sun for excellent reserach assistance.

## 1. Introduction

Greenhouse gas emissions are rising both domestically and internationally. While there is a clear consensus in the scientific community that anthropogenic emissions are harmful and should be reduced, the debate on what policy scheme is optimal to restrain them is ongoing. This paper compares a carbon tax and a cap-and-trade. These policy instruments are two most appealing market-based policies by virtue of their simplicity and the relative ease of administrative implementation. Various forms of these two policies are already in effect in several jurisdictions. For instance, the European Union adopted Emission Trading Scheme in 2005, the United States launched a number of state-level programs such as Regional Greenhouse Gas Initiative and the province of British Columbia recently introduced revenue-neutral carbon tax to reduce emissions by 33 percent by 2020.

We evaluate the merits of the cap and tax from a perspective of a multi-sector real business cycle model. Our model has six production sectors, with distinct production technologies and productivity shocks. We model explicitly the production of the electricity and two fossils, coal and oil. The coal industry is more polluting, as measured by the amount of carbon dioxide emissions. The oil industry is less polluting. We separate goods producing industries into energy-intensive and energy non-intensive, and include services as a separate industry. We use the input-output tables and information on sectoral inputs and output to calibrate the model to the U.S. economy. Then we solve the model numerically and evaluate the implications of the emissions controls through simulations.

When assessing relative merits of either policy, it is important to gain clear insight into possible macroeconomic consequences of implementing carbon tax and cap-and-trade program respectively in the presence of uncertain future. Taking account of uncertainty is crucial for two reasons. First, uncertainty, as reflected in the level of output volatility for example, is costly to risk-averse individuals and, hence, should be made explicit in the cost-and-benefit analysis of each policy. Second, under uncertainty price-based and quantity-based policies are not equivalent and yield different unavoidable welfare losses depending on relative curvatures of marginal benefit (of abatement) and marginal cost functions (Weitzman (1974)). Therefore, the choice of an optimal policy instrument should not disregard how GDP and its principle components will react to unexpected shocks under the chosen climate policy.

The limited but growing literature concerned with modelling such macroeconomic outcomes in uncertain environments does not reach an agreement on how to rank the cap and the tax policy instruments. Only a limited number of publications (Angelopoulos et al. (2010);Fischer and Springborn (2011);Heutel (2012)) is concerned directly with relative assessment of climate change policies in dynamic stochastic general equilibrium (DSGE) framework.

Fischer and Springborn (2011) compare three climate change policies in the DSGE setting. They find that in the absence of uncertainty, the cap and tax policies have the same effects on the steady state levels of macroeconomic variables. During the transition, however, the welfare loss under the cap is higher than under the tax, so the tax is preferred to the cap. When productivity is stochastic, the cap reduces the volatility of aggregate variables. However, the tax policy is preferred from the welfare perspective when the transition period from no policy is taken into account.

Angelopoulos et al. (2010) distinguish between two types of uncertainty, economic and environmental, to welfare rank taxes, caps and intensity targets. Unlike the previous model without government, in this study public sector carries out abatement activities in cases where policies generate public revenues. Ability to generate revenues for abatement is essential for the policy comparison. If the environmental uncertainty is relatively high, intensity targets are preferred. If, on the other hand, the economic uncertainty is relatively more important, the tax is optimal.[1] Welfare is the lowest under the cap regime.

Unlike previous two studies, Heutel (2012) uses a DSGE framework to assess optimal

[1] Angelopoulos et al. (2010) consider two types of taxes: output tax (output is a polluting activity) and pollution tax. Output tax is preferred in the presence of high environmental uncertainty.

responses of dynamic carbon policies to TFP fluctuations. He estimates emissions to be procyclical and concludes that an optimal emissions policy should respond to business cycle fluctuations. The optimal policy can be implemented either through a tax or a quota if the regulator has the same information as private agents. The optimal should dampen emission procyclicality. Intensity targets are favoured over caps or taxes because they are more likely to soften procyclicality. However, the tax has a political advantage over the cap because the optimal policy should raise the tax during economic booms and lower it in recessions. In the similar vein, Hoel and Karp (2002) assess dynamic flexibility of policies in order to compare them in the context of uncertainty.[2] In their model a flexible tax dominates quotas. However, a partial equilibrium framework does not include the analysis of some key macroeconomic consequences such as output volatility.

All of the above studies aim to compare market-based carbon policies in a framework with uncertainty. There are a number of modelling differences and, unsurprisingly, policy ranking varies substantially from model to model.[3] Notwithstanding, singled-sectored closed economy is a common feature in these models' specifications. This paper follows the closed economy approach, but integrates the multi-sector analysis analogous to Kim and Kim (2006), in order to examine the potential role of productivity shock in policy adjustment across sectors.

Our key findings can summarized as follows. First, the volatility of macroeconomic aggregate is lower under the cap policy relative to the tax policy for all types of productivity shocks. Despite this finding, the cap is *not* preferred from the welfare perspective. The two policies are identical, from the welfare perspective, when productivity shocks originate in the non-energy related sectors. By contrast, the tax policy is clearly preferred to the cap if productivity shocks in the fossils production are taken into account.

[2] Here the source of uncertainty is the asymmetry of information between polluters and regulators.

[3] These studies differ in many modelling aspects, but most importantly in the way emissions and abatement activities are introduced.

## 2. The model

Our model is a multi-sector economy with industry-specific productivity shocks. Production and factor intensities vary by industries. We are interested in evaluating a climate policy as well as the effects of productivity shocks in an environment, in which firms have a choice between sources of energy. This section describes a possible market decentralization.

The model economy consists of three agents: a representative consumer, a representative firm, and the government. We begin with specifying the behaviour of the firm.

### *2.1. Production*

The firm produces products in six industries: coal industry, oil industry, electricity industry, an energy non-intensive goods producing industry, an energy-intensive goods producing industry and a services industry. Each of our six industries is in fact an index of a large number of industries in the real world. To avoid confusion, we will use "sector" to denote our six "industries" hereinafter.

We assume that the firm produces and sells a single distinct commodity in each sector. In the following context, we use the same abbreviations to denote both a sector and its corresponding commodity; that is, we use $COAL$ for both coal sector and coal commodity, $OIL$ for oil, $ELEC$ for electricity, $EIN$ for energy-intensive, $NEIN$ for energy non-intensive, and $SERV$ for services, and we will use subscript $i$ to denote the commodity, and $j$ for sector. Further, we classify the six sectors into two subsets, $EN$ and $NE$.

The subset $EN$=$\{COAL, OIL, ELEC\}$ denotes a subset of energy goods or commodities. In this subset, the two fossil fuels, coal and oil, are considered "dirty", and electricity is considered to be a clean energy. Moreover, we consider coal as dirtier energy (more polluting during production and consumption of this energy, as measured by the amount of carbon dioxide emissions) and oil cleaner (less polluting). Energy goods in the subset $EN$ are used for consumption. They are also used as energy input in the production of other sectors, which may include the sector that produces this energy good as well. Energy goods can also be used as investment good and add to capital stock, though traditional wisdom might tend to believe the otherwise.[4]

The subset $NE = \{EIN, NEIN, SERV\}$ denotes a subset of non-energy goods or commodities. Non-energy goods can be used for consumption. They can also be used as intermediate inputs in the production of other sectors, including their own sector. When used as intermediate input, they are assumed to be delivered and used within one period, and not add to the capital stock. In addition, they can also be used as investment good and built into the capital stock that the firm can use for production. The firm will in turn allocate capital to each sector accordingly. By virtue of the consumer ownership of capital, the firm's optimization behaviour is intratemporal, rather than intertemporal.

The production technologies are distinct across the sectors, each requiring capital, labor, energy inputs and/or intermediate inputs. The output of sector $j$ is produced by combining an index of capital-labor-energy input, $KLE_{jt}$, an intermediate input produced by the energy non-intensive goods producing sector, $M_{EIN_{jt}}$, an intermediate input produced by the energy-intensive goods producing sector, $M_{NEIN_{jt}}$, and an intermediate input produced by the service sector, $M_{SERV_{jt}}$, in a production process that features Leontief technology:

$$Y_{jt} = \min\left\{\frac{KLE_{jt}}{a_{KLE_j}}, \frac{M_{EIN_{jt}}}{a_{M_{EINj}}}, \frac{M_{NEIN_{jt}}}{a_{M_{NEINj}}}, \frac{M_{SERV_{jt}}}{a_{M_{SERVj}}}\right\} \tag{1}$$

Eq. (1) is the first level of nest. In the second level of nest, the index of capital-labor-energy input for sector $j$ has a Cobb-Douglas form which implies a unitary elasticity of substitution between labor input and capital-energy composite input:

[4] Indeed, our squared benchmark input-output (IO) table confirm that coal and oil are not used for investment. However, the IO table shows that electricity used for investment purpose is not nil, though very small. We speculate this term as an option contract that firms sign with the electricity utility which allows firms to buy electricity from the utility at a predetermined price for a specified time period.

$$KLE_{jt} = AL_j YVA_{jt}^{\alpha_{L_j}+\alpha_{K_j}} E_{jt}^{1-\alpha_{L_j}-\alpha_{K_j}} \tag{2}$$

$$YVA_{jt} = \left[Z_{jt} KD_{jt}^{\alpha_{K_j}} LD_{jt}^{\alpha_{L_j}}\right]^{1/\left(\alpha_{K_j}+\alpha_{L_j}\right)} \tag{3}$$

where $\alpha_{L_j} \in (0,1)$, $\alpha_{K_j} \in (0,1)$, $LD_{jt}$ denotes the number of labor hours used by sector $j$ at period $t$, $KD_{jt}$ is capital used by sector $j$ at time $t$, and $E_{jt}$ is the index of energy input used by sector $j$ at time $t$.

In the third level of nest, the index of energy input $E_{jt}$ is a CES form of fossil energy (coal and oil) and electricity:

$$E_{jt} = AE_j \left[\alpha_{F_j} \left(FOS_{jt}\right)^{\frac{\sigma_{E_j}-1}{\sigma_{E_j}}} + \left(1-\alpha_{F_j}\right)\left(M_{ELEC_{jt}}\right)^{\frac{\sigma_{E_j}-1}{\sigma_{E_j}}}\right]^{\frac{\sigma_{E_j}}{\sigma_{E_j}-1}} \tag{4}$$

where $\alpha_{F_j} \in (0,1)$, $M_{ELEC_{jt}}$ is electricity input, and $FOS_{jt}$ is fossil energy input.

In the fourth (also the last) level of nest, the fossil energy input $FOS_{jt}$ is also a CES form index of coal and oil:

$$FOS_{jt} = AF_j \left[\alpha_{C_j} \left(M_{COAL_{jt}}\right)^{\frac{\sigma_{F_j}-1}{\sigma_{F_j}}} + \left(1-\alpha_{C_j}\right)\left(M_{OIL_{jt}}\right)^{\frac{\sigma_{F_j}-1}{\sigma_{F_j}}}\right]^{\frac{\sigma_{F_j}}{\sigma_{F_j}-1}} \tag{5}$$

where $\alpha_{C_j} \in (0,1)$, $M_{COAL_{jt}}$ is coal input, $M_{OIL_{jt}}$ is oil input.

The variables $AL_j$, $AE_j$ and $AF_j$ in Eqs. (2) to (5) are the levels of the industry-specific productivity. Multifactor productivity $Z_{jt}$ in each sector is subject to stochastic innovations which are not perfectly correlated across sectors. Similar to Horvath (2000) and Kim and Kim (2006), is is assumed that $Z_{jt}$ follows a stochastic process described by

$$\ln Z_{jt} = \rho_j \ln Z_{j,t-1} + \varepsilon_{j,t}. \tag{6}$$

The innovations $\varepsilon_{j,t}$ are assumed to be uncorrelated over time and follow $N(0,\Omega)$. The covariance matrix $\Omega$ is *not* restricted to be diagonal.

### *2.2. The consumer's problem*

We assume that the representative consumer owns capital stock. capital is rented to the firm, which will allocate it to each sector for production. The firm in turn pays the rental income $R_t$. The consumer makes investment decision to add to capital stock. The capital accumulation process is given by

$$K_{t+1} = (1-\delta) K_t + I_t$$

where $\delta \in (0,1)$ is a general depreciation rate, $K_t$ is overall capital stock at time $t$. Under the assumption that capital is perfectly mobile across sectors, rental price of capital is the same as $R_t$ for all sectors. The consumer uses some of the goods he buys from each sector as investment, denoted by $Dinv_{it}$. The total investment is an index of $Dinv_{it}$, taking a Cobb-Douglas form

$$I_t = I(Dinv_t) = AV \prod_{i=1}^{N} (Dinv_{it})^{\gamma_i}, \quad \sum_{i=1}^{N} \gamma_i = 1, \; AV > 0 \tag{7}$$

The relationship between $Dinv_{it}$ and its price $p_{it}$, and the indexed total investment and its price aggregator, is: $Dinv_{it} = \gamma_i \frac{Q_t I_t}{p_{it}}$, $i = 1, ..., N$, $Q_t = \frac{1}{AV} \prod_{i=1}^{N} \left(\frac{p_{it}}{\gamma_i}\right)^{\gamma_i}$, where $Q_t$ is the price of aggregate investment. Here the assumption is that the goods purchased for investment sell at the same price as for consumption. The aggregators ensure that

$$\sum_{j=1}^{N} p_{it} Dinv_{it} = Q_t I_t.$$

The representative consumer not only makes consumption-investment decision, but also makes work-leisure decision. He allocates labor hours to the various sectors. He seeks to maximize discounted expected utility subject to his budget constraint. We assume his discounted expected utility is given by

$$E_0 \sum_{t=0}^{\infty} \beta^t U\left(C_t, L_t\right), \ 0 < \beta < 1, \tag{8}$$

where $\beta$ is a discount factor, $C_t$ is an aggregate consumption index, $L_t$ is an aggregate leisure index at period $t$. The aggregate consumption index has a Cobb-Douglas form:

$$C_t = C\left(c_t\right) = AC \prod_{i=1}^{N} \left(c_{it}\right)^{\xi_i}, \ \sum_{i=1}^{N} \xi_i = 1, \ AC > 0 \tag{9}$$

where $\xi_j$ is the consumption expenditure share of sector $j$. The representative consumer is endowed with one unit of time in each period and the aggregate leisure index takes the following form:

$$L_t = 1 - LS_t = 1 - AH \left[ \sum_{j=1}^{N} \left( \alpha_{Hj} LS_{jt}^{\frac{\sigma_H + 1}{\sigma_H}} \right) \right]^{\frac{\sigma_H}{\sigma_H + 1}}, \ \sigma_H > 0, \ AH > 0, \ \sum_{j=1}^{N} \alpha_{Hj} = 1 \tag{10}$$

This form allows for constant elasticity of substitution between labor hours across sectors, implying restricted labour mobility, which means, consequently, that at the margin, all sectors do not pay the same hourly wage.

In addition, $U(\cdot)$ , the period utility function, is given by

$$U\left(C_t, L_t\right) = \ln C_t + \frac{\chi}{1-\eta} L_t^{1-\eta} \tag{11}$$

If $\eta = 0$, then $U\left(C_t, L_t\right) = \ln C_t + \chi L_t$. If $\eta = 1$, $U\left(C_t, L_t\right) = \ln C_t + \chi \ln L_t$.

The consumer's budget constraint is written as

$$\sum_{i=1}^{N} p_{it}c_{it} = (1-\tau_h)\sum_{j=1}^{N} w_{jt}H_{jt} - \sum_{i=1}^{N} p_{it}Dinv_{it} + (1-\tau_k)\, R_tK_t + T_t \tag{12}$$

where $\tau_h$ is the labour tax, and $\tau_k$ is the capital tax. This budget constraint can be rewritten, using the aggregate consumption price index, the aggregate consumption index, and the aggregate wage index, as

$$P_tC_t = (1-\tau_h)\, W_tH_t - Q_tI_t + (1-\tau_k)\, R_tK_t + T_t \tag{13}$$

where $P_t = \frac{1}{AC}\prod_{i=1}^{N}\left(\frac{P_{it}}{\xi_i}\right)^{\xi_i}$ is an aggregate consumption price index, which stems from (9) and with $c_{it} = \xi_i \frac{P_tC_t}{p_{it}},\ j = 1, ..., N$ ensures that $\sum_{j=1}^{N} p_{it}c_{it} = P_tC_t$, and $W_t = \frac{1}{AH}[\sum_{j=1}^{N}(\alpha_{Hj})^{-\sigma_H}(w_{jt})^{1+\sigma_H}]^{\frac{1}{1+\sigma_H}}$ is an aggregate hourly wage index, which stems from (10). Note that in general $P_t \neq Q_t$, even when the consumption and investment prices are the same for each commodity.

## *2.3. The government*

Lastly, the government collects four taxes: it levies a producer tax on the firm's products (the tax rate, $tx_j$, may vary across industries), taxes on labour and capital income, and a lump-sum tax $T_t$, as in Eq. (13). With the tax income it collects, the government purchase an exogenous amount of goods $G_{it}$ from each sector. We assume that the government cannot finance its expenditure by borrowing. Therefore, its budget must be balanced at each time $t$; that is:

$$T_t = \sum_{j=1}^{N} tx_jp_{jt}Y_{jt} + \tau_hW_tH_t + \tau_kR_tK_t - \sum_{i=1}^{N} p_{it}G_{it} \tag{14}$$

Note that $T_t$ can be either positive or negative. When it's negative, it's in fact a rebate or transfer to the consumer.

*2.4. Competitive equilibrium*

The competitive general equilibrium of the economy comprises the following conditions:

(1) firms minimizes its cost of producing in each sector subject to the sectoral production technology (1);[5]

(2) consumer maximize lifetime utility (8) subject to a sequence of budget constraint as in (13);

(3) labor markets and goods markets clear:

(a) total supply of goods is equal to total demand,

$$Y_{jt} = c_{it} + Dinv_{it} + \sum_{k \in EN \cup NE} M_{ikt} + G_{it}, i = j$$

(b) total supply of labour is equal to total demand,

$$LD_{jt} = LS_{jt},\ \ j = 1, ..., N,$$

(c) the demand for energy input of the three energy sectors is equal to the supply of each sector,

$$\sum_{j=1}^{N} M_{X,jt} = X_t,\ \ X_t \in EN,$$

(d) and the sum of each sector's capital stock is equal to the overall capital stock in the economy

$$\sum_{j=1}^{N} KD_{jt} = K_t.$$

[5] It is important to note that we are taking advantage of the fact that under constant return to scale, cost-minimizing input levels are identical to profit-maximizing input levels. Hence, we will focus our analysis on cost-minimization in this study.

*2.5. Modelling emissions policy*

We consider three types of environmental policy regimes: no policy, emissions cap and emissions taxes.

*No policy benchmark* As a benchmark case, we consider a model without an emissions policy. the case is denoted by 'No policy' in the paper. Without any regulation, the equilibrium price of commodities would be:

$$p_{jt} = (1 - tx_j)\, p_{it} = a_{KLE_j} p_{KLE_{jt}} + \sum_{k \in NE} a_{M_{kjt}} p_{kt}$$

where

$$p_{KLE_{jt}} = \frac{1}{AL_j} \left(\frac{w_{jt}}{\alpha_{L_j}}\right)^{\alpha_{L_j}} \left(\frac{R_t}{\alpha_{K_j}}\right)^{\alpha_{K_j}} \left(\frac{p_{E_j}}{1 - \alpha_{L_j} - \alpha_{K_j}}\right)^{1-\alpha_{L_j}-\alpha_{K_j}}$$

$$p_{E_j} = \frac{1}{A_{E_j}} \left[\alpha_{F_j}^{\sigma_{E_j}} \left(p_{FOS_{jt}}\right)^{1-\sigma_{E_j}} + \left(1 - \alpha_{F_j}\right)^{\sigma_{E_j}} \left(p_{ELEC_{jt}}\right)^{1-\sigma_{E_j}}\right]^{\frac{1}{1-\sigma_{E_j}}}$$

$$p_{FOS_j} = \frac{1}{A_{F_j}} \left[\alpha_{C_j}^{\sigma_{F_j}} \left(p_{COAL_{jt}}\right)^{1-\sigma_{F_j}} + \left(1 - \alpha_{C_j}\right)^{\sigma_{F_j}} \left(p_{OIL_{jt}}\right)^{1-\sigma_{F_j}}\right]^{\frac{1}{1-\sigma_{F_j}}}$$

There are two polluting inputs in our model, COAL and OIL. $CO_2$ emissions are linked in fixed proportions to the use of fossil fuels, with $CO_2$ coefficients differentiated by the specific carbon content of fuels. Restrictions to the use of $CO_2$ emissions in production and consumption are typically implemented through $CO_2$ taxes or exogenous emissions constraints that keep $CO_2$ emissions to a specified limit. Out of the two, COAL is more polluting. We denote $em_{coal}$ and $em_{oil}$ the emission factors. The total level of emissions is defined by the use of oil and coal, which in turn are equal to the gross output in the model,

$$EMISS_t = em_{coal} Y_{COAL,t} + em_{oil} Y_{OIL,t}. \tag{15}$$

In the case of No Policy, the level of emissions is allowed to vary freely.

*cap policy* The cap policy imposes a constraint on the level of emissions. In particular,

$EMISS_t \leq \overline{EMISS}$, where $\overline{EMISS}$ is the target level of emissions. The definition of emissions in (15) shows that the constraint on the emissions imposes a constraint on the production of coal and oil. The targeted level of emissions is achieved through a variable price of permit, $p_{e,t}$. The implied user prices for COAL and OIL are adjusted by the amount of the permit price. In particular, the market prices of the fossils are increased by $em_{coal}$ $p_{e,t}$ and $em_{oil}$ $p_{e,t}$. Since $em_{coal} > em_{oil}$, the use of coal is discouraged by more.

*tax policy* In the case of the tax, the carbon tax is fixed at the level that allows to achieve the targeted level of emissions in the deterministic case. The level of emissions is allowed to vary freely.

## 3. Deterministic environment

The model is solved numerically using a stochastic version of the extended deterministic path. The method has an advantage of being more accurate relative to linearization techniques. Further, it is more suitable than the first order approximation for analyzing the effects of large shocks.

### *3.1. Parameter calibration*

The model is calibrated to the U.S. economy, and the pollutant considered is carbon dioxide, the leading greenhouse gas. The sources for the calibration of the model fall into three main groups: macroeconomic parameters are taken from the real business cycle literature, parameters related to emissions are taken from Blasing et al. (2004) estimates,[6] and the parameters related to the composition of value added, GDP and gross output are estimated

[6] Available at: http://cdiac.esd.ornl.gov/trends/emis_mon/emis_mon_co2.html. These estimates offuel-specific $CO_2$ emissions are based on reported fuel consumption from the Energy Information Administration (EIA) in the Monthly Energy Review for several types of fossil fuels, each multiplied by their respective thermal conversion factors (given in Appendix A of each issue of Monthly Energy Review), then multiplied by their respective carbon dioxide emission factors given by U. S. Environmental Protection Agency (EPA 2003, Tables A-15-17).

from data published by U.S. Bureau of Economic Analysis (BEA).[7]

The macroeconomic parameters include a functional form and parameterization for the production function and the utility function, the process governing the productivity shocks, the capital decay rate, and the discount factor. The rate of capital depreciation is 10% per year, $\delta = 0.10$. The consumption-leisure trade-off in the steady state determines the value of $\chi$. The steady state value of labour hours is $H^* = 0.20$, which means twenty percent of the available time is devoted to work (King and Rebelo (1999)).

The elasticity of substitution between fossil fuel and electricity $\sigma_E$, is equal to 1, and $\sigma_F$, the elasticity of substitution between coal and oil, is equal to 0.5, referring to Beckman and Hertel (2009).We use two industry-level data sets to calibrate the rest of the parameters. The first is the Jorgenson's data set, which contains annual series for U.S. industry-level inputs and output for the period 1960-2005. The second is the input-output tables of the Bureau of Economic Analysis (BEA). Table 1 presents our categorization of the U.S. industries from both data sets into the six sectors of the model. We use the BEA classifications of the service industries, and the U.S. Department of Energy classification of energy intensive industries.

Table 2 provides gives an implied input-output breakdown of the U.S. economy for the six sectors of the model. The construction of this table is explained in the Appendix. Annual series for labour input, capital input, energy input, value-added output and the KLE-output at the sectoral level are calculated based on the series from the Jorgenson's data set. The industry-level data are aggregated into our sectors using the Tornquist aggregation index. The sectoral indices are used to construct the implied series for total factor productivity at the VA level of output.

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[7] The data we use for calibration and simulation is drawn from "Annual_IOUse_Before_Redefinitions_1998-2009", available on http://www.bea.gov/industry/io_annual.htm, or downloadable from http://www.bea.gov/industry/xls/Annual_IOUse_Before_Redefinitions_1998-2009.xls, and from "GDPbyInd_VA_NAICS_1998-2010.xls", available on http://www.bea.gov/industry/gdpbyind_data.htm, or downloadable from http://www.bea.gov/industry/xls/GDPbyInd_VA_NAICS_1998-2010.xls

The parameters of the production functions and all relevant shares are calibrated to match the historical averages of the similar statistics in the U.S. data. <The table with the parameters values is to be completed>

*3.2. Emissions policy effects in the absence of uncertainty*

This subsection examines the properties of the model in the absence of productivity shocks. The emissions tax is chosen to achieve the same path of the price of emissions permit under the cap. Thus, in the absence of uncertainty, the two policy regimes imply exactly the same prices and quantities.

In the absence of uncertainty, an emissions reduction permanently lowers the deterministic steady state values of all aggregate variables. Table 3 and 4 report the effects of a twenty percent emissions reduction on the deterministic steady state values of the model. In addition, panel A of Table 4 reports the change in the sectoral output and inputs in the period when the emissions policy is introduced.

Implementation of any of the two policies leads to a reduction of all macroeconomic aggregates. With respect to the sectoral analysis, the largest reductions come from fossil fuel sectors. Unsurprisingly, of the two fossil fuel sectors, the coal sector exhibits larger reductions in every variable than the oil sector. The emission control policies have larger impact on the "dirtier" energy sector. Also it is not surprising that the policies affect energy-intensive sectors more than energy non-intensive sectors in energy demand because the higher dependence of energy-intensive sector on energy renders it more vulnerable to policies that would affect fossil fuel prices.

## 4. Stochastic environment: no emissions policy

### *4.1. Estimation of the productivity parameters*

The are six productivity series in our model. We estimate the parameters of the productivity shocks as follows. First, we construct the Solow residuals for empirical analogues of our theoretical sectors from the sectoral value-added output. In particular, we use the definition of the production function (3), the historical shares of labour and capital input in sectoral value added, and the data series on value added output, capital and labour input.

$$\ln SR_{jt} = \left(\alpha_{K_j} + \alpha_{L_j}\right) \ln YVA_{jt} - \alpha_{K_j} \ln KD_{jt} - \alpha_{L_j} \ln LD_{jt} \tag{16}$$

The resulting Solow residuals $\ln SR_{jt}$ have time series trends. We take the HP-filter cycle (the value of 100 is used as a weight in the HP-filter) of $\ln SR_{jt}$ as a measure of the sectoral TFP shocks, $\ln Z_{j,t}$. The coefficients of persistence are estimated from the individual regressions (6). The covariance matrix is computed based on the estimated residuals. The resulting parameters are reported in Table 5. The estimated are used to generate artificial economies.

### *4.2. Numerical solution and simulation method*

The results for the stochastic economy are based on a series of numerical simulations. In particular, we first evaluate the ability of the model with stochastic productivity shocks to replicate aggregate and sectoral business cycle statistics. Based on the TFP estimates, we ran Monte Carlo simulations for three regimes: "No policy", "cap" and "tax".

We further examine the implications of the model related to different sources of productivity shocks. "All" shocks specification corresponds to the case in which productivity shocks in all six sectors are stochastic. Then we examine the effects of productivity shocks originating in the energy sectors (COAL, OIL and ELEC). In this case, the shocks in the other three sectors (EIN, NEIN and SERV) are shut down. Then we do a reverse exercise in shutting down energy-related productivity shocks and examine the implications for non-energy productivity shocks.

For each regime, we compute the model-implied moments numerically. In particular, we ran 500 simulations, each with a duration of 100 periods. Each time, the model starts with the steady state of a no policy regime. The solution method was not successful in all simulations. The most restrictive scenarios, when the model could not be solved, were related to the scenarios that involved productivity shocks in the energy sectors. To ensure the comparability of the statistics across all the simulations, we used exactly the same replications for which the solution was successful for all types of shocks and all policy scenarios. The total number of successful solutions was 365. We compute different moments implied by the model numerically, by taking the averages across the 365 simulations.

### *4.3. Business cycle statistics*

This section illustrates that the model has relatively good business cycle properties in the absence of environmental regulations. In particular, we focus on the ability of the model to match business cycle characteristics regarding volatilities and comovement.

Table 6 report standard deviations and standard deviations relative to output for consumption, investment, labour input, capital services and value-added output for the U.S. economy and for the simulated model. The value added in the model is computed from the sectoral value added using the Tornquist aggregation. Consumption is measured by total private consumption expenditures for the U.S. economy and by the consumption aggregator in the model. Investment is total U.S. investment and the investment aggregator. Labour input is the Tornquist aggregate in the data from the Jorgenson's data set, and the hours aggregator in the model.

The model reproduces the property that consumption and capital are less volatile than output, while investment is more volatile. The model is having some difficulty to capture the relative volatility of labour input. However, this is a well known problem in the business cycle literature. The model does much better for the volatility of employment than the model of Fischer and Springborn (2011). Table 6 also report the correlation of the macroeconomic quantities with output. The model replicates the procyclicality of the aggregates.

## 5. Stochastic environment: emissions policy evaluation

### *5.1. Numerical solution and simulation method*

In the stochastic simulations, the tax rate is kept at the values obtained in the absence of productivity shocks (in the deterministic case). Thus, once the new steady state is reached, after the introduction of emissions controls, the tax remains constant. In this sense, the policy is "static", as described by Heutel (2012).

The long run effects of the emissions policy correspond to the effects on business cycle statistics *after* the economy completely adjusted to the specific emissions policy. Thus, the results of the simulations compare one economy in which emissions are controlled through a cap policy with another economy in which emissions are controlled through the tax. For these simulations, the statistics are computed for percentage deviations of each variable from a steady state under no-policy regime. We truncate the first 54 periods, to eliminate the dependence on the initial conditions (ref). The statistics are based on 46 period, which is the empirical sample in the Jorgenson's dataset.

### *5.2. Implications for aggregate volatility*

We start the comparison of the cap and tax emissions policies by examining their implications for the volatility of aggregate variables. Table 7 reports the standard deviations of consumption, investment, aggregate labour input and capital. All statistics are expressed relative to the standard deviation of the same variables in the No policy case and the same productivity shocks. Thus, the reported moments are comparable across the simulations for the specific types of productivity shocks, and with the statistics in the No policy case. It should be noted, however, that the statistics are not directly comparable across the simulations that use different types of shocks. In the No Policy case, simulations with productivity shocks to all sectors are the results of responses to individual shocks. When the emissions control is imposed, this constraint is required to be maintained either in every period (under the cap) or on average (under tax). Even though the realizations of the productivity shocks are exactly the same in the All shocks scenario, the simulated variables cannot be decomposed into the sums corresponding to the simulations with individual types of shocks. The columns for individual shocks answer the following question: "If the specific type of productivity shocks, say TFP shocks to the production of oil, are the only source of uncertainty in the economy, how would the volatility of the aggregate variables change in the presence of emissions control under the cap and tax policies?"

The standard deviations in Table 7 imply that the volatility of all aggregate variables under all simulations is uniformly lower under the cap policy relative to the tax policy. Table 7 also reports the median values of the differences between standard deviations of variables under the tax and cap policy. All the median values are positive. The statistical significance of the differences in standard deviations is evaluated with the sign test and the Wilcoxon signed rank tests. Both tests evaluate the hypothesis that the data come from an arbitrary continuous distribution whose median is zero. The Wilcoxon signed rank is valid for only symmetric distributions. The skewness test applied to the differences in standard deviations cannot reject the null of symmetry.

### *5.3. Welfare comparison*

Consumers in our model are risk averse, and dislike consumption fluctuations. Despite the lower volatility of the aggregates, the cap is *not* a preferred policy from the welfare perspective.

Table 8 reports the welfare costs of emissions control and productivity shocks. Before discussing the combined effects of the emissions policy and productivity shocks, it is worth examining the two effects separately. Panel C of the table focuses on the welfare costs of business cycles under No policy. The entries report the percentage change in consumption from the deterministic steady state, per year, needed to achieve the same level of utility as the expected level of utility in the stochastic environment, holding labour constant. We focus on the costs of consumption volatility for two reasons. First, we want to compare our welfare costs with other existing studies. Second, we not be believe that the model provides a good characterization of the costs of leisure volatility.

The costs of business cycles implied by our model are small, less than 0.02% of the consumption. In the aggregate, they are about 2.5 larger than the estimates of 0.008% of Lucas.

By construction, the cap and tax policies are identical in the deterministic case. The welfare cost for the infinite horizon, including the transition period is 0.33% of consumption reduction. The cost is consistent with CGE multi-sector models <to be confirmed>.

Panels A and B of Table 8 report the welfare costs of the emissions policy in the stochastic environment. The values $\phi$ indicate the percentage reduction in consumption from the deterministic steady state with No policy needed to replicate the expected utility level under each policy instrument (holding labour fixed). To calculate the expected utilities, we follow the approach of Otrok (2001). We compute the utility levels for given realizations of productivity shocks, combined with the emissions control policy over the first 30 and 100 years. Thus, our utility measures include the period of transition after the introduction of emissions controls. The ax-ante expected level of the utility is the average across our Monte-Carlo simulations. The entries labeled U(tax)-U(cap) give the median differences between the utility levels for a specified time horizon. The stars in the Table indicate that the difference is significant at less than 1 percent confidence level, according to the sign rank test.

Two results regarding the policy comparison stands out. First, the sources of the shocks matter. The cap and tax policies are equivalent, from the welfare perspective, when the shocks originated in the non-energy sectors are considered. The sign rank test cannot reject the equivalence of the medians in the utility levels. Moreover, the Kolmogorov-Smirnov test cannot reject the hypothesis that the utility levels are generated by the same distribution. By contrast, the cap and tax policies produce rather distinct welfare costs. Notably, the effects of energy-related shocks are not washed out when all shocks are considered jointly, and the welfare costs are different from the case of all shocks.

Second, the cap policy is more costly than the tax policy. This result seems puzzling, if one focuses on the volatility measures alone. The reason is that the emissions control alter in a significant way how the economy responds to energy-related shocks, and more specifically to productivity shocks of the fossils sectors. The ability to adjusts to the shocks becomes rather distinct under the cap and tax policies. As a result, not only the standard deviation, but the whole shape of the distribution changes.

Figure 2 plots the probability densities of the percentage changes in consumption in different simulations. We focus on consumption, because this series determines our welfare calculations. It should be noted, however, that the cap or tax policies introduce important differences in the behaviour of other aggregates. To compile Figure 2, we aggregate observations from periods 55 to 100 of the simulations across *all* 365 replications. The total number of observations is 16790. This aggregation provides a better illustration of the distributional differences. In our model, it is not only the sign (positive or negative shocks), but also the magnitude of the shocks matters. Combining the series across all replications allows us to consider a more diverse sample of productivity shocks. The welfare measures take the transition period into account. This is not the case for consumption distribution on Figure

2. Consistent with the welfare results, we cannot reject that the consumption distribution is the same across the cap and tax policies for the shocks unrelated to the energy sectors. By contrast, the distributions are quite distinct when productivity shocks to fossil production are taken into account.

Table 9 complements Figure 2 by providing formal statistics. Panel A of the table reports the asymptotic probability values for the Kolmogorov-Smirnov test that the distribution of consumption is the same under the cap and tax. Asymptotic p-values are rather accurate for the combined replication sample. The low p-value implies that the null hypothesis of the distributional equivalence can be rejected. The other panels of Table 9 provide summary statistics of the empirical distribution, computed for the total replication sample.

Fischer and Springborn (2011) obtain similar welfare ranking between the cap and the tax policies. Examining the effects of the aggregate productivity shock, they find that adopting the cap policy leads to the lower volatility. In the stochastic steady state, they cannot reject the equivalence between the two policies from the expected PVU perspective. Accounting for the transition path, either in the deterministic case (in the absence of the productivity shocks) or in the stochastic environment, the tax is less costly. Fischer and Springborn (2011) attribute the difference to the effects of the transitional dynamics. The linearization techniques by construction excludes any possible asymmetries in the responses of the economy to productivity shocks.

Our modelling strategy ensures that the deterministic paths to the introduction of the emissions controls are identical under the cap and the tax. The differences in the welfare costs that we get are thus attributed to the effects of the productivity shocks.

### *5.4. Implications for sectoral variables*

Analysis of the aggregate variables hides important variations across sectors. Table 10 focuses on the volatility of sectoral output. The table reports standard deviations of value-added output relative to the aggregate value added in the No Policy case for the simulations with the same types of shocks. Several findings emerge from the Table.

First, emissions control increases the sensitivity of fossil sectors to productivity shocks. For all types of shocks, the propagation of productivity shocks in the fossil sectors changes substantially relative to the No Policy case, and differ across the policy instruments.

Second, the economy becomes more sensitive to the productivity shocks originating in the fossil sectors. Our analysis shows that the responses of *all* sectors to oil shocks are substantially modified relative to the No Policy case. Further, they are quite distinct for all sectors under the cap and the tax policies.

Third, emissions constraint under the cap policy is a constraint on the joint production of coal and oil. In the presence of this constraint, the correlation of gross outputs of the two sectors changes from highly positive in the case of No policy to essentially -1 in the case of the cap. As a result, the volatility of coal is greater under the cap policy. An exceptions is the case of the simulations with the productivity shocks in non-energy-intensive and service sectors. It should be noted that services do not use any coal as intermediate input.

Table 11 provides additional information on the distribution of sectoral value added output. Panel A reports the p-values for the Kolmogorov-Smirnov tests that sectoral output series under the cap and the tax come from the same distribution. The other two panels of the table report the statistics for median, skewness and kurtosis.

## 6. Concluding remarks

To achieve the dramatic reductions required to stabilize greenhouse gas concentrations in the atmosphere at the lowest cost, one should make informed choice among policies both by their expected cost-effectiveness and by their response to unexpected events along the path. We find that although a cap-and-trade policy and a carbon tax produce equivalent outcomes in expectation, a cap reduces economic volatility, compared to tax policy and no policy, and a tax enhances volatility. Despite this result, the tax policy is preferable from the welfare perspective. Emissions control change the economy's ability to respond to productivity shocks in the fossil sectors.

Regarding future studies, our study provides a few highlights. First, it is important to note that any policy aimed at reducing emissions, whether it is a tax or a quota, ceteris paribus imposes disproportionately higher costs on energy-intensive sectors (Metcalf, 2009; Bukowski and Kowal, 2010).[8] Therefore, heterogeneity in production technology across the economy can have potentially large consequence on theses policies' respective welfare outcomes. Second, environmental damages from emissions are transnational in nature and any meaningful progress to lower emissions with market-based policies cannot be achieved by an isolated economy. Moreover, sources of productivity shocks are never entirely domestic. Therefore, a more appropriate framework would reflect sensitivity to foreign factors that ultimately affects performance and ranking of climate change policies.

Furthermore, allowing for trade openness in model specification can be particularly insightful for the case of a small open economy such as Canada. Namely, this extension allows for a small open economy to experience shocks in its terms of trade. Another important issue that is international in scope concerns shifting of pollution-intensive goods producing from countries that adopt and enforce carbon policies to those countries that are lax in their environmental regulations (Metcalf, 2009). If such is indeed the case and if the main goal is to reduce global emissions, we must answer the question that if adoption of either tax or cap would be immaterial to the general progress. Will domestic carbon policy have a dramatic effect on employment in energy-sector domestically and abroad which, in turn, has an impact on welfare? Open economy model can provide insights into welfare consequences of either policy. In short, the choice of modelling tools that carefully considers sectoral representation and trade openness may significantly contribute to the analysis in question.

[8] In his overview of carbon policies Metcalf (2009) notes that economists have reached a consensus: taxes or quota should be implemented as far upstream in the production process as possible.

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Table 1: Classification of U.S. industries into the sectors of the model

| Industry from the Jorgenson's data set (industry number) | Industry from the BEA tables (NAICS industry code) |
|---|---|
| COAL: Coal sector in the model | |
| Coal mining (3) | Coal mining (212100) part of Mining, except oil and gas (212) |
| OIL: Oil and gas sector in the model | |
| Crude oil and gas extraction (4) | Oil and gas extraction (211) |
| Petroleum refining (16) | Petroleum and coal products (324) |
| Gas utilities (31) | Natural gas distribution (221200) part of Utilities (22) |
| ELEC: Electricity sector in the model | |
| Electric utilities (30) | Electric power generation, transmission, and distribution (221100) part of Utilities (22) |
| EIN: Energy intensive producers | |
| Metal mining (2) | Mining, except oil and gas (212) |
| Non-metallic mineral mining (5) | less Coal mining (212100 ) |
| Lumber and wood products (11) | Wood products (321) |
| Paper and allied products (13) | Paper products (322) |
| Chemicals and allied products (15) | Chemical products (325) |
| Rubber and plastic products (17) | Plastics and rubber products (326) |
| Stone, clay and glass products (19) | Nonmetallic mineral products (327) |
| Primary metals (20) | Primary metals (331 ) |
| NEIN: Non-energy intensive producers | |
| Agriculture, forestry, fisheries (1) , | Farms (111CA) |
| Food and kindred products (7) | Forestry, fishing, and related activities (113FF) |
| Tobacco manufactures (8) | Food and beverage and tobacco products (311FT) |
| Textile mill products (9) | Textile mills and textile product mills (313TT) |
| Apparel and other textile products (10) | Apparel and leather and allied products (321) |
| Furniture and fixtures (12 ) | Furniture and related products (337) |
| Printing and publishing (14) | Printing and related support activities (323) |
| Leather and leather products (18) | Fabricated metal products (332) |
| Fabricated metal products (21) | Computer and electronic products (334) |
| Non-electrical machinery (22) | Machinery (333) |
| Electrical machinery (23) | |
| Motor vehicles (24) | Motor vehicles, bodies and trailers, and parts (3361MV) |
| Other transportation equipment (25) | Other transportation equipment (3364OT) |
| Instruments (26) | Electrical equipment, appliances, and components (335) |
| Miscellaneous manufacturing (27) | Miscellaneous manufacturing (339) |
| SERV: Services | |
| Construction (6) | Construction (23) |
| Wholesale and retail trade (32) | Wholesale trade (42) Retail trade (44RT) |
| Transportation and warehousing (28) | Transportation and warehousing (48TW) |
| Communications (29) | Information (51) |
| Finance, insurance and real estate (33) | Finance, insurance, real estate, rental, and leasing (FIRE) |
| Personal and business services (34) | Professional and business services (PROF) |
| Government enterprises (35) | Educational services, health care, and social assistance (6) |
| | Government (G)Support activities for mining (213) |
| | Water, sewage and other systems (221300) part of Utilities (22) |

Table 2: Input-output table for the six sectors of the model, based on historical U.S. averages and a GDP value of 1,000 USD

| | COAL | OIL | ELEC | EIN | NEIN | SERV | C | I | G |
|---|---|---|---|---|---|---|---|---|---|
| COAL | 0.73 | 0.01 | 4.47 | 1.25 | 0.13 | 0.00 | 0.00 | 0.00 | 0.00 |
| OIL | 0.11 | 43.00 | 4.50 | 5.14 | 3.10 | 15.68 | 15.48 | 0.27 | 0.00 |
| ELEC | 0.11 | 1.26 | 0.63 | 6.62 | 5.17 | 18.21 | 11.84 | 0.00 | 0.00 |
| EIN | 0.20 | 6.23 | 1.35 | 60.16 | 47.25 | 52.56 | 19.55 | 0.45 | 0.00 |
| NEIN | 0.53 | 1.42 | 1.37 | 15.40 | 192.80 | 107.00 | 104.27 | 61.02 | 9.78 |
| SERV | 0.37 | 4.71 | 3.48 | 23.47 | 44.76 | 209.82 | 624.26 | 126.01 | 27.06 |
| WAGES | 2.19 | 8.08 | 7.37 | 46.40 | 137.61 | 410.62 | 0.00 | 0.00 | 0.00 |
| IND. TAXES | 0.82 | 3.67 | 5.19 | 2.39 | 4.75 | 57.27 | 0.00 | 0.00 | 0.00 |
| PROFITS | 1.52 | 18.87 | 15.50 | 26.93 | 58.03 | 192.78 | 0.00 | 0.00 | 0.00 |

Table 3: Effects of a twenty percent emission reduction on the deterministic steady state: aggregate variables (percentage change relative to the steady state under No Policy)

| | C | I | L | K | GDP |
|---|---|---|---|---|---|
| Own calculations | -1.08 | -1.89 | -0.55 | -1.89 | -1.18 |
| FS (2011) | -1.10 | – | -0.43 | -3.30 | -3.30 |

Table 4: Effects of a twenty percent emission reduction on the deterministic steady state: sectoral variables (percentage change relative to the steady state under No Policy)

| | COAL | OIL | ELEC | EIN | NEIN | SERV |
|---|---|---|---|---|---|---|
| A. Impact effects | | | | | | |
| Y(j) | -27.79 | -16.07 | -5.94 | -1.77 | -1.23 | -0.75 |
| L(j) | -16.26 | -6.03 | -0.59 | -0.80 | -1.27 | -0.87 |
| K(j) | -28.64 | -9.60 | 1.47 | 1.03 | 0.05 | 0.89 |
| E(j) | -47.59 | -20.35 | -20.22 | -10.52 | -8.95 | -8.28 |
| PE(j) | 33.48 | 11.28 | 24.70 | 10.71 | 7.74 | 7.84 |
| B. Long-run effects | | | | | | |
| Y(j) | -27.34 | -16.30 | -6.69 | -2.08 | -1.25 | -1.09 |
| L(j) | -15.34 | -5.33 | -0.12 | -0.24 | -0.61 | -0.40 |
| K(j) | -29.18 | -10.92 | -0.56 | -0.81 | -1.57 | -1.14 |
| E(j) | -46.65 | -20.31 | -20.10 | -10.80 | -9.17 | -8.86 |
| PE(j) | 32.31 | 11.41 | 24.05 | 10.83 | 8.01 | 8.12 |

Notes: Impact effects report a percentage change in each variable in the period of the policy shock. Long-run effects correspond to percentage changes of the steady state values.

Table 5: Parameters of the productivity shocks

A. Persistence of productivity shocks

| | COAL | OIL | ELEC | EIN | NEIN | SERV |
|---|---|---|---|---|---|---|
| $\rho_j$ | 0.549 | 0.658 | 0.652 | 0.488 | 0.490 | 0.636 |

B. Variance-covariance matrix, 100 x $\sqrt{\Omega}$

| | COAL | OIL | ELEC | EIN | NEIN | SERV |
|---|---|---|---|---|---|---|
| COAL | 5.649 | 0.129 | 0.513 | 0.388 | 0.213 | -0.116 |
| OIL | 0.129 | 17.441 | 0.658 | 1.192 | -0.183 | -0.066 |
| ELEC | 0.513 | 0.658 | 2.774 | 0.230 | 0.188 | 0.041 |
| EIN | 0.388 | 1.192 | 0.230 | 3.257 | 0.403 | 0.077 |
| NEIN | 0.213 | -0.183 | 0.188 | 0.403 | 1.936 | 0.130 |
| SERV | -0.116 | -0.066 | 0.041 | 0.077 | 0.130 | 0.932 |

Table 6: Business cycle properties of the 'No policy' model: aggregate volatilities and correlations

| | U.S. data | All | Energy | Oil | En.Int. | Other | FS |
|---|---|---|---|---|---|---|---|
| Standard deviation | | | | | | | |
| C | 1.71 | 1.89 | 1.61 | 1.57 | 0.26 | 0.83 | 2.50 |
| I | 7.84 | 11.54 | 7.92 | 7.70 | 2.38 | 7.19 | |
| L | 2.49 | 1.80 | 1.32 | 1.28 | 0.38 | 1.02 | 0.27 |
| K | 1.52 | 2.30 | 1.60 | 1.55 | 0.43 | 1.45 | 3.09 |
| Y | 2.31 | 2.42 | 1.49 | 1.44 | 0.55 | 1.65 | 3.32 |
| Standard deviation relative to standard deviation of output | | | | | | | |
| C | 0.74 | 0.78 | 1.08 | 1.09 | 0.47 | 0.50 | 0.75 |
| I | 3.39 | 4.76 | 5.30 | 5.34 | 4.34 | 4.36 | |
| L | 1.08 | 0.75 | 0.88 | 0.89 | 0.69 | 0.62 | 0.08 |
| K | 0.66 | 0.95 | 1.07 | 1.08 | 0.79 | 0.88 | 0.93 |
| Correlation with output | | | | | | | |
| C | 0.80 | 0.73 | 0.88 | 0.88 | 0.80 | 0.80 | 0.63 |
| I | 0.80 | 0.94 | 0.95 | 0.95 | 0.96 | 0.96 | 0.93 |
| L | 0.86 | 0.90 | 0.92 | 0.92 | 0.94 | 0.94 | 0.88 |
| K | 0.44 | 0.67 | 0.68 | 0.68 | 0.64 | 0.64 | 0.68 |

Notes: Standard deviationsfor for U.S. data are computed as percentage deviations from the HP filtered trend (based on the weight of 100). Statistics of the model are for percentage deviations from the deterministic steady state, averaged over the numerical replications. Output is GDP for the column FS (2011), and aggregate value added constructed from sectoral value added for all other cases. FS denotes the simulation results from Fischer and Springborn (2011). For capital stock, correlations are between K(t+1) and Y(t).

Table 7: Impact of the emission policy on aggregate volatilities

| | Simulations by types of shocks | | | | | FS |
|---|---|---|---|---|---|---|
| | All | Energy | Oil | En.Int. | Other | Model |
| | A. Standard deviation: Cap | | | | | |
| C | 0.55 | 0.65 | 0.65 | 0.46 | 0.48 | 0.73 |
| I | 4.38 | 4.47 | 4.48 | 4.30 | 4.28 | |
| L | 0.62 | 0.61 | 0.61 | 0.69 | 0.61 | 0.07 |
| K | 0.85 | 0.88 | 0.88 | 0.76 | 0.84 | 0.86 |
| Y | 0.88 | 0.70 | 0.69 | 0.99 | 0.98 | 0.89 |
| | B. Standard deviation: Tax | | | | | |
| C | 0.72 | 0.98 | 0.99 | 0.47 | 0.50 | 0.76 |
| I | 4.66 | 5.09 | 5.13 | 4.34 | 4.32 | |
| L | 0.71 | 0.80 | 0.81 | 0.70 | 0.62 | 0.08 |
| K | 0.91 | 1.00 | 1.00 | 0.78 | 0.86 | 0.95 |
| Y | 0.96 | 0.90 | 0.89 | 1.00 | 1.00 | 1.02 |
| | C. Median of the difference between standard deviations under the Tax and Cap policies | | | | | |
| C | 0.17 | 0.33 | 0.34 | 0.01 | 0.02 | |
| I | 0.27 | 0.61 | 0.62 | 0.03 | 0.05 | |
| L | 0.09 | 0.19 | 0.20 | 0.01 | 0.01 | |
| K | 0.06 | 0.13 | 0.13 | 0.02 | 0.02 | |
| Y | 0.07 | 0.20 | 0.20 | 0.01 | 0.02 | |

Notes: Standard deviations of variables are reported relative to the standard deviation of aggregate value added output in the No policy case. The moments are the averages across the simulations. The statistics for the FS model are inferred from Table 6 of Fischer and Springborn (2011). See section ? for furher explanations.

Table 8: Welfare analysis

| | Simulations by types of shocks | | | | | |
|---|---|---|---|---|---|---|
| | None | All | Energy | Oil | En.Int. | Other |
| A. Welfare costs over the first 30 years | | | | | | |
| $\phi$(cap) | | 0.999 | 1.061 | 1.068 | 0.826 | 0.788 |
| $\phi$(tax) | | 0.808 | 0.876 | 0.885 | 0.826 | 0.786 |
| U(tax)-U(cap) | 0 | 0.025* | 0.025* | 0.025* | 0.000 | 0.000 |
| B. Welfare costs over the first 100 years | | | | | | |
| $\phi$(cap) | | 1.067 | 1.111 | 1.117 | 0.865 | 0.836 |
| $\phi$(tax) | | 0.877 | 0.925 | 0.933 | 0.865 | 0.834 |
| U(tax)-U(cap) | 0 | 0.028* | 0.028* | 0.028* | 0.000 | 0.000 |
| C. Costs of business cycles (no policy) | | | | | | |
| $\phi$(no policy) | | 0.019 | 0.014 | 0.013 | 0.000 | 0.004 |

Notes: The values of $\phi$ give the percentage reduction in consumption from the deterministic steady state with No policy needed to replicate the expected utility level under each policy instrument (holding labour fixed). U(tax)-U(cap) is the median difference between the utility levels for a specified time horizon, averaged across the simulations. The stars indicate that the difference is significant at less than 1 percent confidence level, according to the sign rank test.

Table 9: Impact of the emission policy on the distribution of consumption

| A. Kolmogorov-Smirnov test of the distributional equivalence (p-values) | | | | | |
|---|---|---|---|---|---|
| | All | Energy | Oil | En.Int. | Other |
| Cap vs. Tax | 0.00 | 0.00 | 0.00 | 0.78 | 0.25 |
| | mean | median | std | skewness | kurtosis |
| B. All productivity shocks | | | | | |
| No policy | -0.10 | -0.06 | 2.12 | -0.12 | -0.07 |
| Cap | -1.41 | -1.29 | 1.52 | -0.40 | 0.37 |
| Tax | -1.20 | -1.15 | 1.97 | -0.13 | -0.06 |
| C. Shocks to energy sectors | | | | | |
| No policy | -0.10 | -0.02 | 1.82 | -0.22 | -0.12 |
| Cap | -1.41 | -1.21 | 1.11 | -1.02 | 1.26 |
| Tax | -1.20 | -1.11 | 1.65 | -0.26 | -0.09 |
| D. Shocks to oil sector | | | | | |
| No policy | -0.10 | -0.02 | 1.77 | -0.22 | -0.11 |
| Cap | -1.41 | -1.21 | 1.06 | -1.07 | 1.37 |
| Tax | -1.20 | -1.11 | 1.60 | -0.27 | -0.08 |
| E. Shocks to energy-intensive sector | | | | | |
| No policy | -0.01 | -0.01 | 0.29 | -0.07 | 0.02 |
| Cap | -1.09 | -1.09 | 0.28 | -0.07 | 0.02 |
| Tax | -1.09 | -1.09 | 0.29 | -0.07 | 0.02 |
| F. Shocks to other sectors | | | | | |
| No policy | 0.01 | -0.00 | 0.97 | 0.02 | 0.01 |
| Cap | -1.08 | -1.08 | 0.93 | 0.02 | 0.01 |
| Tax | -1.08 | -1.09 | 0.97 | 0.02 | 0.01 |

Notes: Consumption is expressed in percentage deviations from the deterministic steady state in the No policy case. Moments are computed for the combined replication - simulation sample (16790 observations in total).

Table 10: Policy impact on the volatility of sectoral output

| | COAL | OIL | ELEC | EIN | NEIN | SERV |
|---|---|---|---|---|---|---|
| All productivity shocks | | | | | | |
| Cap | 0.80 | 0.36 | 1.01 | 0.95 | 0.93 | 0.95 |
| Tax | 0.70 | 0.74 | 1.00 | 0.95 | 0.97 | 0.98 |
| Shocks to energy sectors | | | | | | |
| Cap | 0.76 | 0.35 | 1.02 | 0.82 | 0.80 | 0.84 |
| Tax | 0.70 | 0.74 | 1.00 | 0.82 | 0.94 | 0.94 |
| Shocks to oil sector | | | | | | |
| Cap | 0.81 | 0.35 | 0.87 | 0.82 | 0.79 | 0.84 |
| Tax | 0.72 | 0.74 | 0.95 | 0.81 | 0.94 | 0.94 |
| Shocks to energy-intensive sector | | | | | | |
| Cap | 0.99 | 0.57 | 1.01 | 1.00 | 1.00 | 1.00 |
| Tax | 0.84 | 0.87 | 1.01 | 1.00 | 1.00 | 1.00 |
| Shocks to other sectors | | | | | | |
| Cap | 0.28 | 0.58 | 1.00 | 1.00 | 0.98 | 0.99 |
| Tax | 0.90 | 0.90 | 1.00 | 1.00 | 0.99 | 0.99 |

Note: entries report the standard deviation of sectoral value-added output relative to the standard deviation of the value added output in the No policy case for the same type of shocks.

Table 11: Impact of the emissions policy on the distribution of sectoral output

| | COAL | OIL | ELEC | EIN | NEIN | SERV |
|---|---|---|---|---|---|---|
| A. The Kolmogorov-Smirnov test (p-values) | | | | | | |
| All | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 |
| Energy | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| Oil | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| En.int. | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Other | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| B. Simulations with shocks to oil sector | | | | | | |
| NP, median | 0.24 | 0.17 | 0.03 | 0.08 | 0.07 | 0.01 |
| Cap, median | -22.06 | -10.57 | -0.52 | -0.49 | -0.92 | -0.71 |
| Tax, median | -21.14 | -9.16 | -0.41 | -0.39 | -0.84 | -0.64 |
| NP, skewness | -0.18 | -0.46 | -0.05 | 0.43 | -0.21 | -0.12 |
| Cap, skewness | 0.03 | -2.25 | -0.14 | 0.03 | -0.44 | -0.22 |
| Tax, skewness | -0.25 | -0.62 | -0.03 | 0.27 | -0.25 | -0.14 |
| NP, kurtosis | 2.77 | 2.89 | 3.23 | 3.12 | 2.94 | 2.92 |
| Cap, kurtosis | 1.87 | 9.69 | 3.35 | 2.99 | 3.43 | 3.19 |
| Tax, kurtosis | 2.81 | 3.14 | 3.28 | 3.11 | 2.99 | 2.96 |
| B. Simulations with shocks to energy intensive sector | | | | | | |
| NP, median | 0.24 | 0.17 | 0.03 | 0.08 | 0.07 | 0.01 |
| Cap, median | -22.06 | -10.57 | -0.52 | -0.49 | -0.92 | -0.71 |
| Tax, median | -21.14 | -9.16 | -0.41 | -0.39 | -0.84 | -0.64 |
| NP, skewness | 0.05 | -0.13 | -0.03 | -0.01 | -0.12 | -0.13 |
| Cap, skewness | 0.11 | -0.13 | -0.03 | -0.01 | -0.12 | -0.13 |
| Tax, skewness | 0.06 | -0.14 | -0.02 | -0.01 | -0.12 | -0.13 |
| NP, kurtosis | 2.77 | 2.89 | 3.23 | 3.12 | 2.94 | 2.92 |
| Cap, kurtosis | 1.87 | 9.69 | 3.35 | 2.99 | 3.43 | 3.19 |
| Tax, kurtosis | 2.81 | 3.14 | 3.28 | 3.11 | 2.99 | 2.96 |

Notes: Value added output is expressed in percentage changes from the deterministic steady state in the No policy case. Moments are computed for the combined replication-simulation sample.

## 7. Figures

**Figure 1** Response to a twenty percent emissions reduction in the deterministic case

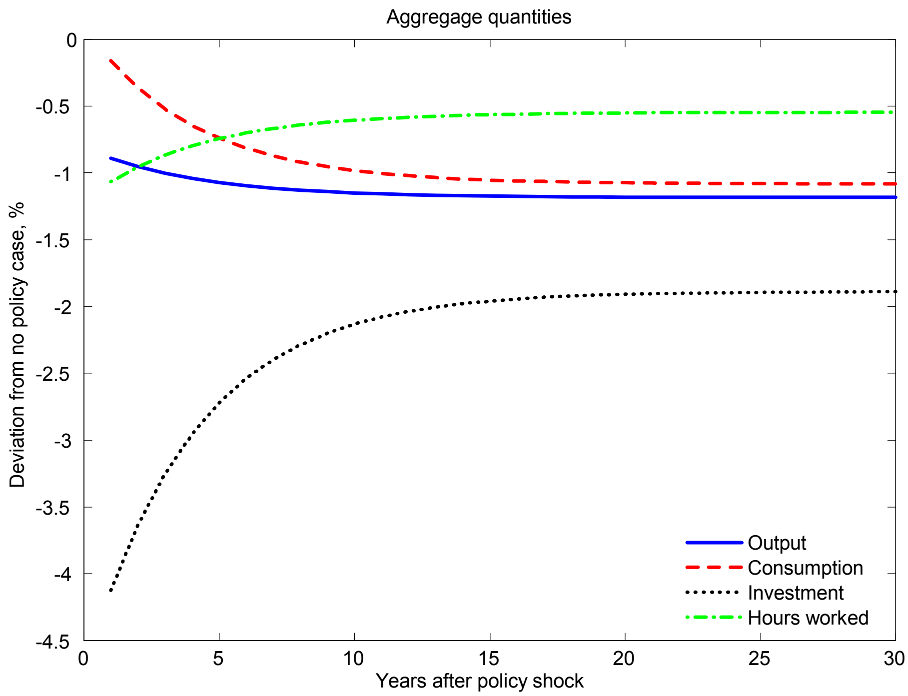
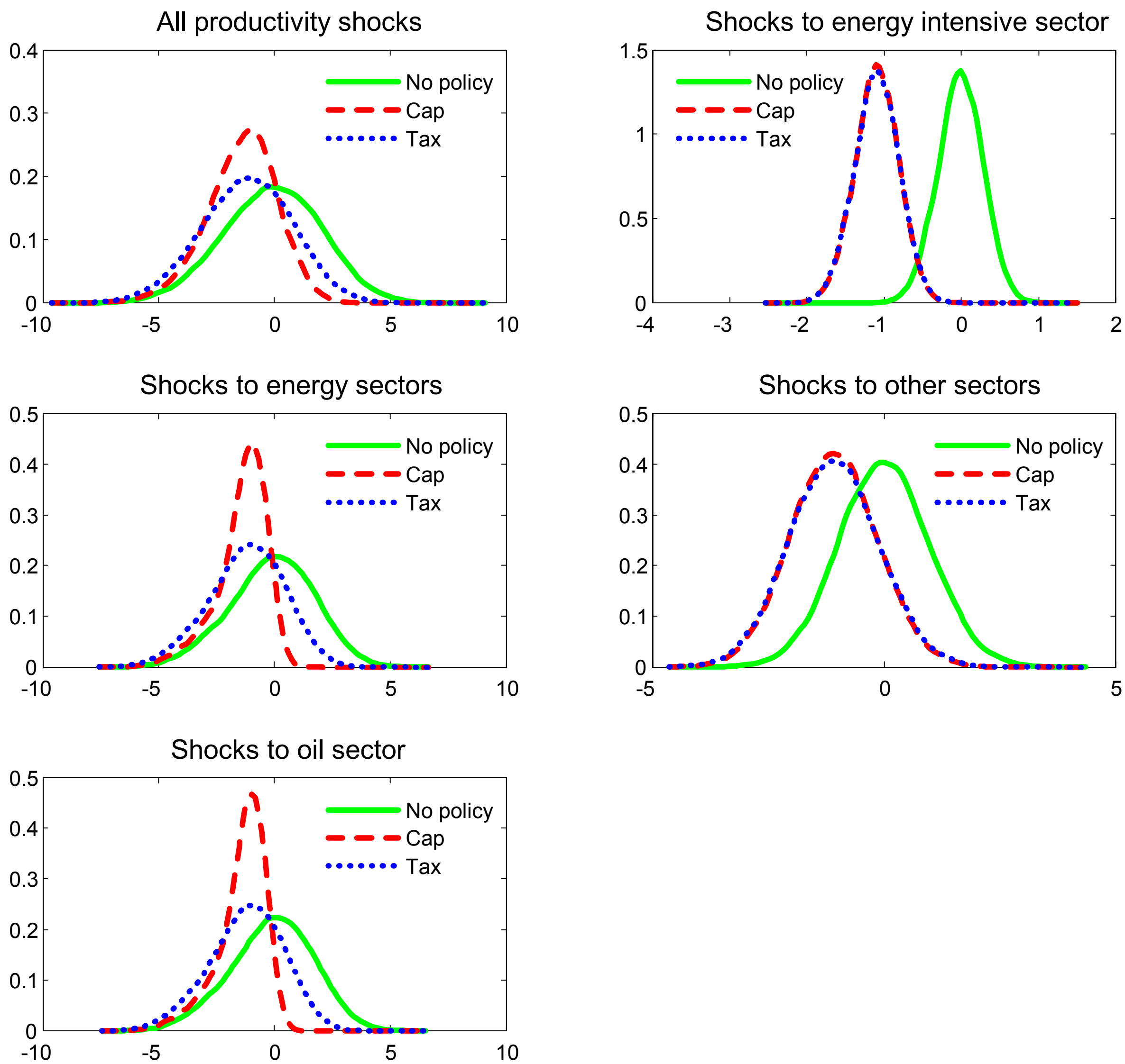


**Figure 2** Probability density functions of percentage changes in consumption




Notes: The percentage change in consumption is expressed relative to the deterministic steady state in the No Policy case and plotted for all simulations (16790 observations in total). Each density is estimated based on a normal kernel function, 100 points and an optimal bandwidth.