Induced innovation in a decentralized model of climate change ⋆

Jérémy Laurent-Lucchetti [a] and Andrew J. Leach [b,*]

[a]HEC Montréal

[b]HEC Montréal, CIRANO, CIRPÉE

February, 2006

Abstract

We propose a model of climate change consistent with four principal stylized facts. First, the benefits and costs of climate change mitigation policies are not evenly distributed across generations. Second, capital accumulation is not determined jointly with emissions policy, but rather as a choice made by self-interested economic agents. Third, most research and development activity in the energy sector is undertaken by private firms. Fourth, significant imperfections exist in the market for technology. The model is calibrated to match global trends in GWP, energy production, and investment in research and development, and is used for the evaluation of policies including research and development subsidies and carbon taxes.

Key words: Alternative Energy Sources; Climate Change; Technological Change; Research and Development; Induced Innovation.

JEL Classification: Q42; Q54; O3.

⋆ Thanks to participants at the CIREQ Resource and Environmental Economics Workshop (2005), the Heartland Environmental and Resource Economics Conference (2005) and the *Journée Étudiante du CIRPÉE* (2005).

* Corresponding author. IEA-HEC Montréal, 3000 chemin de la Côte-Ste-Catherine, Montreal, QC, Canada. H3T 2A7. (514) 340-7001.

Email address: andrew.leach@hec.ca (Andrew J. Leach).

1 Introduction

The introduction of policies designed to reduce global carbon emissions is likely to greatly alter the returns to investment in research and development activities in the energy sector. Despite this, much of the economics literature on climate change has relied on exogenous time paths for technological change which are not related to policy choices. Recent papers by Goulder and Schneider (1999), Nordhaus (2002), Buonanno et al. (2003), and Popp (2004) have addressed the sensitivity of model results to the assumption that technological change is independent of policy. Further, papers by Popp (2004b), Gerlagh (2003), Gerlagh and van der Zwaan (2003), Gerlagh and Lise (2005), and Gerlagh (2006) have examined how the economy is likely to evolve in response to climate policy when there is competition between technologies.

Like the above-mentioned papers, we are interested in the economic transitions and technological change induced by climate policies. Through simulations of a calibrated economic model, we seek to evaluate the effects of proposed policies in terms of climate change mitigation, aggregate economic growth, changes in energy supply and technology, and cohort welfare. The model we propose is innovative in its consistency with the four stylized facts outlined below.

First, climate change policy and its ability to induce technological innovation represent potentially significant transfers of resources across generations. Agents alive today are expected to bear most of the costs of climate policy while the benefits in terms of climate change mitigation, technological innovation, and more abundant resources are passed on to future generations. Induced technological change not only affects the costs of meeting emissions targets, it may also alter the distribution of these costs across generations. In order to capture this important dimension, we follow the approach developed in Leach (2004) to characterize a decentralized economy comprised of overlapping generations of finite-lived agents. We do not solve explicitly for optimal policy, but rather examine the impact of climate policy on the welfare of cohorts of agents born both before and after policies are imposed. This is an important dimension of policy evaluation thus far absent from the literature on induced innovation.

Second, the supply of capital is not a pre-determined condition under which we can set environmental policy. Rather, domestic savings account for the majority of capital available for production and research and development, and this supply will be responsive to changes in interest rates. In our general equilibrium model, climate change policies jointly affect the accumulation of physical, environmental, and knowledge capital through changes in aggregate interest rates and sector-specific rates of return. In particular, a market is developed for capital, where supply is determined by the savings decisions of finite-lived agents as a function of rates of return, and capital is demanded both for production and research and development activities. This differentiates our model from optimal policy models in the tradition of Nordhaus and Boyer (2000) in which investment and emissions control policies are co-determined.

Third, although it may be financed by governments, most research and development activity in the energy sector is undertaken by private firms. In OECD member countries, we observe that research and development accounts for 2.26% of GDP, of which 62% is financed by the private sector. In World Energy Council (WEC) (2001), an average of 48.4% of US energy sector research and development investment between 1974 and 1999 is found to be from the private sector. Our model explicitly characterizes firms that rent investment capital in order to develop and sell energy technology in response to incentives provided by government subsidies. In the model we propose, energy production technology, the emissions intensities of output and energy production, and the share of alternative energy in total energy supply are each endogenous consequences of private rates of return and government policy.

Fourth, important imperfections exist in the market for research and development. Research and development activities are aimed at specific sectors of the energy market. The proceeds of these activities are, at best, weakly substitutable across energy sectors and other sectors of the economy, leading to important pecuniary externalities across sectors. We address this by explicitly modeling the competition between firms for research and development capital. It is also often the case that protection for inventors is limited, leading to dynamic inefficiencies. In our model, we capture this inefficiency since all inventions are assumed to become public domain after one period. This represents an important lower bound on the role of private incentives in driving research and development. Finally, the role of technological improvements in terms of climate change mitigation is assumed external to both the technology firms and production firms in the model.

We calibrate the model to match global data, and perform policy simulations. Among other results, we show that gross world product (GWP), emissions reduction, and alternative energy intensity may all be enhanced by a policy of carbon taxes recycled as alternative energy subsidies rather than as lump-sum transfers to agents. However, we find that agents prefer the lump-sum transfers to the subsidy recycling, and that agents alive when the policy is imposed prefer the status quo over any of the policies simulated. We find that research and development subsidies designed to reduce the carbon intensity of the economy increase emissions levels in the long run, while subsidies augmenting investment in alternative energy technology lead to increases in energy consumption but not emissions.

The decentralized nature of our model allows us to readily isolate the leverage of various features of the model on our results. First, we examine the importance of capital market structure. We find that capital demand for research and development may be less price elastic than the demand for physical capital. This is important for calibrating the costs of capital displaced by new research and development investment. Second, we examine the changes in results when investment is only possible in carbon-saving technology, as is the case in Popp (2004a) and Nordhaus (2002). Finally, we evaluate the sensitivity of results to assumptions on the functional form determining the ability of the economy to integrate new sources of alternative energy in production.

The remainder of the paper proceeds as follows. In Section 2, we present the model and the modifications for research and development. Sections 3 and 4 discuss the solution algorithm and calibration of the model. Section 5 presents the policy simulations and evaluation results. Section 6 discusses these results in the context of other papers in the literature. Section 7 concludes.

2 The economic environment

Below, we augment the decentralized, general equilibrium model proposed in Leach (2004) by adding sectors of the economy where existing technology stocks are enhanced by competitive firms through investment. We model the interaction of finite-lived agents and competitive firms in markets for capital, labour, carbon fuel, and technology. Agents own the capital stock and equal shares of a resource extraction firm. They rent capital and labour at competitive prices, and smooth their consumption through savings decisions. Capital supplied through agents' savings is used by firms for final production as well as for research and development activities. Final production uses carbon energy, which is supplied at competitive prices, and technology supplied by firms which develop carbon-reducing and alternative energy technology. Energy production technology is a market good, where firms invest to improve technology to meet profit maximization goals. The productive capacity of the economy is negatively affected by climate change induced by the use of carbon resources. Below, we present each sector of the model completely for clarity of notation.

2.1 Government

A government is assumed to possess only fiscal means of influencing emissions, through either emissions taxes, subsidies to research and development, or subsidies for alternative energy use. Specifically, the government may impose a well-head tax τ_t on carbon extraction, it may subsidize research and development by matching private investment, or it can directly subsidize the use of alternative energy in final production. All policies are implemented such that the budget is balanced in each time period by a lump-sum tax (subsidy) paid by (remitted to) agents.

2.2 Agents

A new cohort of agents is born in each period, and lives for $L = 60$ periods. Agents have an age-specific labour endowment, e_l, $\forall l \in 1..L$, which they supply inelastically. Denote the size of the birth cohort in each period t as $N_{1,t}$, and let the effective labour supply, N_t, in each period be defined as follows:

$$N_{1,t} = N_{1,0} \exp\left(\frac{\gamma_n}{\delta_n}(1 - e^{-\delta_n t})\right) \tag{2.1}$$

$$N_{l,t} = N_{l-1,t-1} \,\forall\, 1 \leq l \leq L \,\&\, 0 \leq t \leq \infty \tag{2.2}$$

$$N_t = \sum_{l=1}^{L} e_i N_{l,t}. \tag{2.3}$$

Agents are born with an initial endowment of assets, $a_{1,t}$, and seek to maximize their life-time utility through consumption and savings decisions. Denoting by $c_{l,t}$ the consumption by age l agents in model time period t, we can define the lifetime utility of an individual agent born in period t as:

$$\sum_{l=1}^{L} \beta^{l-1} U(c_{l,t+l-1}), \tag{2.4}$$

where $\beta \in (0,1)$ is a discount factor applied to the utility of future consumption. Suppose that utility takes constant relative risk aversion form with parameter σ as follows:

$$U(c_{l,t}) = \frac{c_{l,t}^{1-\sigma}}{1-\sigma} + \bar{u}. \tag{2.5}$$

Autonomous utility $\bar{u}$ is a constant which scales utility such that it is always positive, which ensures consistency when aggregating discounted utility in measures of welfare. In each period, agents receive income from their asset holdings $a_{l,t}$, from their supply of labour, and from a dividend paid by the resource extraction firm, d_t. They also receive a lump-sum repayment (deduction) of net taxes (subsidies), $\bar{\tau}_t$. Denote the gross rate of return on capital assets, comprised of rental rate ι and depreciation rate δ_k, by $r_t = (1 + \iota_t - \delta_k)$ and the wage rate by w_t.[1] The income of an age l agent at time t is thus given by:

$$y_{l,t} \equiv w_t e_l + r_t a_{l,t} + d_t + \bar{\tau}_t. \tag{2.6}$$

Agents must allocate this income between consumption and savings, so we can define the budget constraint in each period as:

$$a_{l+1,t+1} = y_{l,t} - c_{l,t}. \tag{2.7}$$

Each agent's problem is thus to maximize (2.4) by choosing a sequence of asset holdings subject to the budget constraint in (2.7) and sequences of prices w and r. The first order conditions for this problem yield $L-1$ Euler equations with the following form:

$$(y_{l,t} + r_t a_{l,t} - a_{l+1,t+1})^{-\sigma} = \beta r_{t+1} (y_{l+1,t+1} + r_{t+1} a_{l+1,t+1} - a_{l+2,t+2})^{-\sigma} \tag{2.8}$$

$\forall l = 1..L$, given $a_{l,t} = 0 \, \forall \, l > L, l <= 1$. The solution to these equations yields the utility-maximizing sequence of asset holdings. Asset holdings for all agents alive in any

[1] Here, we view agents as owning physical capital and thus they bear the costs of depreciation δ_k. Depending on the elasticity of capital supply and demand, some or all of this cost will be reflected in equilibrium price ι.

time period yields factor supply of capital:

$$K_t = \sum_{l=1}^{L} a_{l,t} * N_{l,t}. \tag{2.9}$$

2.3 Final production

The final production sector uses capital, labour, and energy services to produce a composite good using time-varying, Cobb-Douglas technology. Energy services, the implicit third factor of production, are produced using technologies $\phi_{c,t}$ and $\phi_{a,t}$ and carbon fuel, R. Carbon energy, $\phi_{c,t}R_t$, and alternative energy, $\phi_{a,t}$, are perfect substitutes in the production of energy services. The profit function for the representative firm is given by:

$$\Pi_t = Y_t - w_t N_t - \iota_t K_t - \zeta_{c,t}\phi_{c,t} - (\zeta_{a,t} - S_{e,t})\phi_{a,t} - \zeta_{r,t}R_t, \tag{2.10}$$

where production technology is defined as:

$$Y_t = F_t(K_t, N_t, \phi_{c,t}, \phi_{a,t}, R_t) = \Omega_t \, K_t^{\alpha} \, N_t^{1-\alpha-\theta_t} \left(\phi_{c,t}R_t + \phi_{a,t}\right)^{\theta_t}, \tag{2.11}$$

and the firm purchases inputs at competitive prices on factor markets. The rights to use technologies $\phi_{c,t}$ and $\phi_{a,t}$ are purchased from research and development firms at prices $\zeta_{c,t}$ and $\zeta_{a,t}$ and carbon fuel R_t is purchased at price $\zeta_{r,t}$. Labour and capital are paid rental rates w and ι respectively. Policy variable $S_{e,t}$ is a subsidy received for the use of alternative energy technology in final production.

The energy and labour shares of production vary with the law of motion for θ, given that we impose constant returns to scale in all time periods. The law of motion for θ is defined as:

$$\theta_t = \theta_0 \, \exp\left(\frac{\gamma_\theta}{\delta_\theta}(1 - e^{-\delta_\theta t})\right). \tag{2.12}$$

Total factor productivity is an endogenous outcome of economic activity driven by emissions-induced changes in global temperature, G:

$$\Omega_t = \frac{\overline{\Omega}_t}{(1 + b_1 * G_t + b_2 * G_t^2)}, \tag{2.13}$$

and is taken as given by the firm. The exogenous component of total factor productivity,

$\overline{\Omega}$, follows the law of motion:

$$\overline{\Omega}_t = \overline{\Omega}_0 \exp\left(\frac{\gamma_\Omega}{\delta_\Omega}(1 - e^{-\delta_\Omega t})\right). \tag{2.14}$$

Factor demands from the final production sector for capital, labour, carbon fuel, and technology are characterized by the solutions to the five first order conditions of the firm's profit maximization problem:

$$F_K = \iota_t \tag{2.15}$$

$$F_N = w_t \tag{2.16}$$

$$F_{\phi_a} = (\zeta_{a,t} - S_{e,t}) \tag{2.17}$$

$$F_{\phi_c} = \zeta_{c,t} \tag{2.18}$$

$$F_R = \zeta_{r,t} \tag{2.19}$$

2.4 Carbon Resource Extraction

The structure of the supply of carbon fuel, R, is taken from Nordhaus and Boyer (2000). Resources are supplied such that the marginal cost of extraction is equal to the price, and the cost of extraction is increasing and concave in cumulative extraction, X, which evolves as follows:

$$X_{t+1} = X_t + R_t. \tag{2.20}$$

While the supply of R is infinite, extraction costs tend to infinity in the long-run. Quantity supplied is given by the solution, given parameters ξ and price $\zeta_{r,t}$, to the following equation in unknown quantity R_t:

$$\zeta_{r,t} = \tau_t + \xi_1 + \xi_2 \left[\frac{X_t + R_t}{X^*}\right]^{\xi_3}. \tag{2.21}$$

The resource extraction firm faces increasing extraction cost per unit, and as such earns a surplus in each period, which is assumed to be returned to agents as a per-capita dividend, d_t.[2]

[2] The resource firm does not dynamically choose extraction to maximize rents. It merely extracts resources until the offered price equals its marginal extraction cost in each period.

2.5 Research and Development

Our model specifies two forms of knowledge which are substitutes in energy production. Firms in the research and development sector appropriate existing knowledge for one period and augment knowledge through investment. They then sell use of knowledge to final production firms. Two important market imperfections arise from this structure. First, the firms do not internalize the future benefit of accumulated knowledge, only the current period benefits. Second, through competition for capital, firms will impose pecuniary externalities on the competing sector.

The timing in the model of knowledge accumulation is as follows. At the end of a period, denote the stocks of technology for the production of energy by $\phi_{c,t-1}$ and $\phi_{a,t-1}$. Between time periods, some of the existing technology becomes obsolete, which we denote by depreciation factor δ_j for sector $j = a, c.$ [3] Denote the un-depreciated technology carried over from the previous period by:

$$H_{j,t} = (1 - \delta_j) * \phi_{j,t-1} \forall j = a, c. \tag{2.22}$$

This stock serves as an input to production of new technology, and is complemented by investment $I_{j,t}$. Technology production in both sectors is given by:

$$\phi_{j,t} = \mu_1 I_{j,t}^{\mu_2} H_{j,t}^{\mu_3} + H_{j,t} \forall j = a, c. \tag{2.23}$$

In order to enhance energy production technology in any period, firms must purchase investment capital at competitive price ι_t. The firm may benefit from a matching subsidy $S_{j,t}$ which defines the government contribution rate per dollar of private investment. Including subsidies, the profit functions for each of the research and development firms are given by:

$$\Pi_{j,t} = \zeta_{j,t} \left(\mu_{1j} \left(I_{j,t}(1 + S_{j,t}) \right)^{\mu_{2j}} H_{j,t}^{\mu_{3j}} + H_{j,t} \right) - \iota_t I_{j,t}. \tag{2.24}$$

The factor demands for investment capital, and thus the supply of technology, are determined such that the first order, necessary conditions for profit maximization are satisfied

[3] The literature is inconsistent in treatment of depreciation of knowledge. While we agree that one does not lose knowledge, it seems reasonable to suggest that some of our knowledge is no longer relevant to current production techniques. While our calibration reveals that depreciation rates of zero best fit the data, we retain the generality of the model here.

in each sector. The price of energy has a positive effect on the demand for capital, thus there will be growth and displacement effects of climate policy which propagate through the capital market. Price effects in the capital and energy markets will be analyzed in detail in the results below.

This parsimonious characterization of research and development allows us to maintain the transparency of the model and confront the model with global data to calibrate parameters. The energy technology stocks should respectively equate to the carbon energy-output ratio (ϕ_c) and the total production of alternative energy (ϕ_a). Thus, for equation (2.23), elements on both the right and left hand sides are observable in global, aggregate data.

2.6 Climate and Emissions

The climate and emissions sectors are comparable to those presented in Nordhaus and Boyer (2000), with the important difference being that the ratio of emissions to output and the ratio of emissions to energy supply are endogenously determined along the transition path.

Emissions are generated by the use of carbon fuel for energy production. We assume that there are no technologies available for the sequestration of carbon resources used by the energy sector, so emissions in any period are equal to the quantity of carbon extracted.

Emissions augment a slowly decaying stock of atmospheric carbon, denoted by m_t, according to:

$$m_t = m_b + R_{t-1} + \delta_m(m_{t-1} - m_b), \tag{2.25}$$

where m_b is the pre-industrial level of carbon in the atmosphere, and δ_m is the sink rate for carbon above pre-industrial levels present in the atmosphere at the beginning of the year. Atmospheric carbon affects global surface temperature, G, and ocean temperature, O, through the following two-equation system:

$$G_t = \lambda_1 G_{t-1} + \eta \ln \frac{m_t}{m_b} + \omega O_{t-1}, \tag{2.26}$$

$$O_t = \lambda_2 O_{t-1} + (1 - \lambda_2) G_{t-1}. \tag{2.27}$$

These laws of motion allow us to define the standard benchmark in the literature of the long-run temperature change from a doubling of atmospheric carbon as $G_{2\times \mathrm{CO}_2} = \frac{\eta}{1-\lambda_1-\omega}$. Recall that it is the value G that has a negative effect on total factor productivity through equation (2.13).[4]

3 Solution

The solution to the model is defined by a sequence of prices $\{\iota, \mathbf{w}, \zeta_{\mathbf{r}}, \zeta_{\mathbf{c}}, \zeta_{\mathbf{a}}\}_{t=1}^{\infty}$ which generate equilibria in each of the factor markets described above across all periods. We solve a truncated version of this infinite horizon economy as follows. Denoting by $1..T$ the periods over which we solve the equilibrium of the economy, we must account for the life-cycle savings of agents born before period 1 and agents who live beyond period T. To accomplish this, we distribute an initial stock of capital to agents alive at period 1, and have them live shorter lives. The initial capital distribution across these agents is calibrated to approximately match the profile of asset holdings over ages for the cohort born in period 50.[5] For agents still alive at period T, we solve their entire sequence of asset holdings assuming that prices remain constant at $T-1$ values for all future periods. We then drop the first 20 and last 60 periods from the solution to obtain the analysis sample. These assumptions allow for minimal sensitivity to terminal and initial conditions as the consumption smoothing motives of all agents should be consistent. The model is solved by iteration on the vector of prices through a Tatonnement process until excess demand is zero for all commodities in all periods. For a complete characterization of the solution algorithm, see Leach (2004).

4 Calibration

We make use of a highly aggregated, global model, thus we must recognize that we may not fully capture the effects of policies. However, while the model may not generate precise predictions of the transition path of the global economy, the transparency of the model

[4] We use G rather than T for temperature to avoid confusion between time and temperature.
[5] This ensures that the distribution of capital among initial holders represents as close to an optimal choice for those agents, to minimize the model's sensitivity to initial conditions. Agents may be endowed with debt.

allows us to gain a sense of the propagation mechanisms which determine these paths. In order to ensure that our predictions are as consistent as possible, the model is calibrated to match short-run global trends in GWP, energy production, and investment in research and development as well as to future projections commonly adopted in the literature.

We have assembled data from four principle sources. International Energy Agency (IEA) (2004) data characterize gross world product, total primary energy supply by energy sector, and carbon emissions. We have assembled parallel data from OECD (2004) which characterize the same measures for OECD and IEA member countries. Research and development expenditure data consist of observations on the US economy, collected in World Energy Council (2001). Finally, global population data are obtained from United Nations (UN) (2004).

Calibration of the model proceeds as follows. First, we use OECD and US data to parameterize the relationship between investment and technological progress in the energy sector. Second, we calibrate the economy taking energy-sector investment as given. Finally, we calibrate a benchmark, subsidy policy such that investment rates, and thus endogenous technology, in the decentralized economy match investment rates observed in the data.

The values assigned to model parameters are shown in Table A.1, while transition paths generated through model simulations are compared to the data in Figures A.1-A.4. The calibration fits the data very well, with the exception of the use of alternative energy in production. The IEA (2004) data characterize an important decline in the rate of alternative energy adoption after 2010 which our model cannot replicate without additional assumptions. As such, we focus on the period of 1970-2010 for our calibrations of this trend. The error resulting from this approximation is evident in Figures A.3 and A.4. We discuss potential remedies for this inconsistency in Section 6. Below, we discuss in more detail the data and procedures that lead to fixing key parameters.

4.1 Energy Research and Development

To establish the empirical relationship between investment and technological change, we must establish the following values:

- μ_{1a}, μ_{2a}, μ_{3a}, μ_{1c}, μ_{2c}, and μ_{3c} - the parameters of the technology production function for both carbon-based and alternative technologies

- δ_c and δ_a - the rate of technology obsolescence in each sector
- $H_{c,0}$ and $H_{a,0}$ - the starting values for technology stocks in each sector

In order to calibrate these parameters, we have assembled data from WEC (2001) and OECD (2004), with omissions corrected using linear interpolation, describing GWP, research and development investment, emissions intensities, and energy shares by fuel for 1960-2002. We begin with OECD data, and classify energy production which does not make direct use of fossil fuels as alternative energy and calculate empirical emissions intensity of carbon energy (ϕ_c) and alternative energy production (ϕ_a). We then use the observed rates of investment in renewable and non-renewable energy in WEC data as representative of OECD rates over the same time period.[6] Due to limited observations and potential confounding factors in the data, we do not attempt to fully estimate the empirical relationship implied in (2.23), and rather we proceed as follows. For the carbon sector, we fix the relative share of investment, μ_{2c}, and existing technology, μ_{3c}, in (2.24) to the values used in Popp (2004a), and for the alternative energy technology, we fix the investment share, μ_{2a}. We then estimate scaling factors μ_{1j}, and obsolescence factors δ_j for each sector, as well as the existing technology share for alternative energy, μ_{3a}, using simulated least squares.[7] Identifying with a bar parameters for which values are fixed, and with a hat parameters for which values are estimated, we estimate the following equations:

$$\phi_{c,t} = \hat{\mu}_{1c}(I_{c,t})^{\bar{\mu}_{2c}}((1-\hat{\delta}_c)\phi_{c,t-1})^{\bar{\mu}_{3c}} + (1-\hat{\delta}_c)\phi_{c,t-1} \tag{4.1}$$

and

$$\phi_{a,t} = \hat{\mu}_{1a}(I_{a,t})^{\bar{\mu}_{2a}}((1-\hat{\delta}_a)\phi_{a,t-1})^{\hat{\mu}_{3a}} + (1-\hat{\delta}_a)\phi_{a,t-1}. \tag{4.2}$$

We report estimation results in Table 1.

[6] The WEC (2001) data give aggregate energy research and development investment from public and private sources. We assume that the average shares of 12% of public funding and 70% of private funding going to the fossil fuel sector remain constant through the sample period.

[7] For the estimation, we use data for the 1960-2002 time period, hence N=42.

Table 1
Simulated Least Squares results for research and development sector calibration.

	Carbon Energy	Alternative Energy
$\mu_{1,j}$	0.0057055	0.085543
$\mu_{2,j}$	0.22*	.22*
$\mu_{3,j}$	0.55*	0.49998
δ_j	0	0
N	42	42

(*) indicates a fixed parameter

4.2 The Climate Model and the Carbon Cycle

The climate model maintains the same parameter values as Leach (2004).[8] The set of parameters implies a half-life of atmospheric carbon of 44 years, which is slightly on the high side of statements by the IPCC (2001) that 40-60% of emissions are removed from the atmosphere within 30 years.[9] We calibrate temperature change to a long-run 3^oC warming for a doubling of atmospheric CO_2. The supply of carbon fuel is defined by the Nordhaus and Boyer (2000) parameters.

4.3 Other Economic Sectors

The number of parameters in the economic model far exceeds the identification capacity of our global data, so we must fix certain parameters and then choose the values of others to replicate desired trends. As such, we proceed iteratively as follows.

Parameters for population growth are chosen to match data from United Nations (2004). Agents are assumed to live from 16-76 years old, and the productivity profile which defines e_l for each age l is calibrated to the average deviations of earnings from mean earnings by age in the Labour Force Survey (Statistics Canada, 2004). The parameters governing the agents' asset accumulation problems are those for which we have the least data to guide our calibration. We fix the depreciation rate of capital to 5% per year, the agents' discount

[8] Readers familiar with the Nordhaus and Boyer (2000) models will note significant differences as a result of using an annual time interval rather than the 10 year interval used in Nordhaus and Boyer. For a comparable model using an annual time interval, see Pizer (1999).

[9] Our parameter value implies that 62% of emissions would be removed within 30 years.

factor to β=.96, and the coefficient of relative risk aversion to $\sigma = 1.2213$, which are the values used in Pizer (1999).[10] We also adopt the Nordhaus and Boyer (2000) value for the capital share parameter α, equal to .3.

We also need, at this point, a first estimate of the benchmark subsidy values for alternative and fossil fuel investment. In WEC (2001), we find that ratios of public to private financing are approximately 3.08:1 in the alternative sector and .19:1 in the fossil fuel sector. We use these rates below, and calibrate the aggregate trends in the model such that the total primary energy supply matches the global aggregate trends. We will then adjust these rates to match the combination of fossil fuel and alternative energy in the data.

We calibrate the trends for the energy share and total factor productivity and the initial capital endowment using simulations of the model. Agents' initial capital endowment is defined such that the capital stock in 1970, the first period in the analysis sample, is equal to the value used in Nordhaus (1994), converted to \$1997 US. The energy share parameter θ is time varying. We fix the initial value to be .37, and set parameters $\gamma_\theta = -.0185$ such that the energy share of final production matches observed data. Finally, we also adjust parameters determining the exogenous evolution of total factor productivity to ensure that economic growth and energy supply follow IEA (2004) medium-term projections.

4.4 Benchmark Policy

The calibration exercise to this point has focussed only on the total primary energy supply. We now adjust the subsidy rates used in the calibration such that the mix of alternative and fossil fuel energy supply matches the data. Carbon taxes and alternative energy subsidies are set to zero in these simulations. We find that when the rate of government subsidy is 1.45:1 (.25:1) in the alternative (carbon) sector, the fuel mix in the simulations matches the data over the 1970-2010 period. The alternative fuel share is lower than that

[10] In Pizer (1999), the CRRA coefficient is a parameter in a social welfare function which is maximized by a social planner under uncertainty over parameter values in the climate model. The literature is by no means consistent on an approximate value for this parameter. Previous IAM studies have tended to use logarithmic utility, $\lim_{\sigma\to 1}$, while values in the macroeconomics literature vary substantially. For a complete discussion of the role of the CRRA, see Kocherlakota (1996). Compared to a logarithmic utility model, our parameterization will imply smoother utility paths for agents.

observed in the data. It is likely that our characterization of all funding being paid out as a complement and not a substitute to private investment leads to lower government funding rates by increasing the marginal return to private investment.

4.5 Future projections

Given the time scale over which climate change policies must be evaluated, the parameter values determining the future evolution of the economy will hold great leverage on the results. Specifically, the long-run growth rates of the energy share parameter θ and the value of exogenous factor productivity, $\overline{\Omega}$, will have the largest effects. For comparability, we adopt assumptions on these values which are consistent with Nordhaus and Boyer (2000).

The energy share of production is assumed to decline exogenously in Equation (2.12). An initial rate of decline of 1.8% per year in this parameter allows us match energy share data over the calibration period. We assume that the second derivative of the energy share with respect to time is determined by $\delta_\theta = .007$, which is consistent with Nordhaus and Boyer's assumption that this parameter lies between 6% and 10% per decade for the regions in RICE-99.

The exogenous trend for factor productivity is set such that its second derivative with respect to time is near zero over the model period. This is consistent with global assumptions in the DICE-99 model in Nordhaus and Boyer (2000).

5 Climate Change Policy Evaluation

The policy evaluation results are intended to illuminate the propagation mechanisms which lead to the long-run outcomes of climate policy. We examine the effects of two policy mechanisms available to governments: carbon taxes and direct funding of research into alternative energy and carbon-reducing technologies. We further examine the implications of recycling the revenues from a carbon tax as a subsidy to alternative energy use rather than as a lump-sum transfer to agents. Below, we discuss the measures of policy performance and the evaluation results for each type of policy.

In order to evaluate policies aimed at reducing society's reliance on carbon emissions through the stimulation of research and development, we may use both positive and normative metrics. Natural positive metrics are GWP, total emissions, energy intensity, emissions intensity, and global surface temperature. It is more difficult to develop the appropriate normative metric of social welfare, which is where the overlapping generations model becomes an important tool. For an individual agent, the sum of indirect utilities discounted at the private rate of time preference provides a positive measure of their welfare. The aggregation of the utility measures of individual agents within and across time periods is purely normative, and the model is structured such that the choice of aggregation and social discounting will have no impact on the outcome of the economy, only on how we value a particular transition path over another, *ex post.*[11] We abstract from this discussion, and report only the private evaluation of welfare: for each time period, our measure of welfare is simply the sum of discounted, indirect utility for agents born in that period.

5.1 Carbon Taxes and Alternative Energy Subsidies

We impose a $50/ton carbon tax and examine the implication of recycling the revenues from this tax to agents directly on a per-capita basis (denoted by Carbon Tax - LS), or applying these revenues as a subsidy to alternative energy use in final production (denoted by Carbon Tax - EAS).

The carbon tax has a large, immediate impact on production regardless of the means of recycling, shown in Figure A.5. GWP drops by almost 1% as a result of limited short-term substitution for carbon energy. The first 80 years after the policies are implemented show virtually no difference in GWP across the recycling methods, however, when the carbon tax is diverted for alternative energy subsidies, GWP recovers and eventually rises to a level 4.85% above benchmark values, while the maximum impact is 4.15% with the recycling to agents.

Many of the long-run growth effects of policies come from induced innovation. Figures A.6 and A.7 show the effects of the tax policies in terms of induced investment. The

[11] Agent responses to equilibrium prices determine consumption. Agents make decisions which are privately optimal, and do not consider how society values their consumption path.

carbon tax recycled to agents generates an immediate 60% increase in private investment in alternative energy, and investment levels remain above the benchmark for roughly 200 years and then are slightly below the benchmark thereafter. The recycling of tax revenues in the form of a subsidy to alternative energy use magnifies this to more than 200%. The increases in alternative energy capacity are shown in Figure A.8. Were the private rate of return to alternative energy investment large enough to justify investing all of the proceeds of the carbon tax in alternative energy technology, the results of the two policies would be equivalent. However, agents choose to consume some of the proceeds of the tax, while allocating some to capital accumulation which drives innovation.

We see some potential evidence of displacement effects as a results of the carbon tax. Investment in carbon-reducing technology is lowered by 15% immediately with further reductions in the near term under both policies, but recovers in later stages, again as carbon resources become relatively less expensive. This is however the combined result of two effects. The primary effect is that, with an increase in resource prices, the value of carbon-reducing technology decreases. The second is a medium-term crowding out effect, where the increase in alternative energy capacity further reduces the rate of return to carbon-reducing technology investment. We attempt to isolate these effects in the next section and in the sensitivity analysis.

As a result of induced innovation and factor substitution, the carbon tax reduces energy use dramatically in the short term, however long-term energy use is greater than the benchmark case, as shown in Figure A.9. The reduction in emissions relative to the benchmark is also not permanent, as shown in Figure A.10. As the benchmark carbon price eventually rises to levels higher than those under the carbon tax, carbon resources become cheaper under the tax than at the same period of time under the benchmark, again as a result of reduced cumulative extraction. As such, while emissions decrease rapidly by almost 40% after the imposition of the tax, they eventually rebound to be above benchmark levels.[12]

[12] Specifically, we observe higher emissions under the carbon tax (LS) policy after 2205, and after 2210 for the carbon tax (EAS) policy. Cumulative emissions are everywhere lower under the tax regardless of recycling. After 100 years, cumulative extraction levels are 1305, 794, and 745 GtC respectively under the benchmark, the carbon tax, and the carbon tax with alternative energy subsidy.

The energy intensity and carbon intensity of production follow paths similar to emissions and energy levels as shown in Figures A.11 and A.12; initially decreasing, but surpassing the benchmark case marginally after 150 years. The carbon resource conservation is again at the heart of this result. The eventual increase in emissions over benchmark levels as well as increases in emissions and energy intensity are of particular interest since papers published in the literature with only carbon-saving technology will not show this characteristic. In the sensitivity analysis section below, we further examine this result.

The aggregate growth results above are due in part to climate change effects, since the carbon tax reduces cumulative emissions by almost 50% over the first 100 years. However, the induced temperature difference of approximately 1^{o}C after 100 years increases total factor productivity by only .34%. While this difference is small, the evolution of the economy is such that, while being marginally more productive as a result of reduced climate change damages, it also develops expanded capacity for producing alternative energy relative to the benchmark. Combined with the fact that the relative price of carbon resources is kept lower through reduced cumulative extraction, the economy is able to recover to higher levels than under the benchmark scenario. Since the energy-production capacity is higher with the alternative energy subsidy than under the lump-sum recycling, we see some additional improvements.

Finally, in terms of welfare, an additional result sheds light on the political economy of climate policy. Regardless of the chosen method of tax recycling, agents alive when the policy is implemented are uniformly worse off. Where the tax revenues are recycled to agents as a lump-sum payment, agents are partially compensated for their drop in consumption, but they are still constrained by the drop in production and the marginal products of labour and capital.[13] Younger agents are quickly found to be better off under the carbon tax than they would be in the benchmark case. They can borrow against future productivity, and since agents receive a progressive, per-capita share, not an income-based share, they are better off under the carbon tax. The alternative energy subsidy funded by the carbon tax has a longer payback period in terms of welfare because agents are not compensated directly for their drop in consumption, but rather in the long-run by lower energy costs and by climate change mitigation. Specifically, the first cohort of agents who

[13] Policies are imposed with perfect foresight, so agents will increase savings before the policy goes into effect to smooth their utility streams.

would be better off under the carbon tax policy with lump-sum recycling are born 16 years after the policy is implemented. The first cohort made better off by the energy subsidy relative to the benchmark are born 40 years after the policy is imposed, but these agents still prefer the lump-sum recycling to the energy subsidy. The first agents who prefer the alternative energy subsidy to the per-capita payment as the means of recycling proceeds from the carbon tax are those born 100 years after the policies are imposed.

5.2 Research financing

We model government subsidies to research and development imposed as complements to private investment. The benchmark values for the rates at which governments match private research expenditure are 1.45:1 in the alternative sector and .25:1 in the carbon sector. We examine the effect doubling the government subsidy rate in one sector, holding the subsidy rate in the other sector constant. There may be both direct and indirect effects of these increases. Specifically, we are interested in changes in the cross-sector crowding out of research and development arising from technology competition. This policy differs from the carbon taxes discussed above because the policy induces an increase in capital demand which is not accompanied by an aggregate economic slowdown.

Popp (2004a, 2004b) and Nordhaus (2002) each account for the external cost of research and development in the energy sector. [14] Specifically, Popp (2004a) contends that spending on energy research and development crowds out other investment at a rate implying that 50% of new investment comes at the expense of investment in other research and development. This crowding out rate has important leverage on the optimal policy results since it determines the social cost of new innovations.

Our model differs from Popp (2004a) in two ways important to this discussion. First, agents' savings decisions determine the supply of capital, so the price of capital will reflect the private rates of return to investment. The rates of return will be equalized across all investment avenues, and equal to the private marginal product of capital in research

[14] Popp (2004a) assumes that the social cost of research and development is captured by the constraint $K_{t+1} = (I_t - 4 * crowdout * R_{E,t}) + (1 - \delta_K)K_t$, such that each unit of new research and development investment, $R_{E,t}$, crowds out some of its value from other research and development activities, assumed to have a social cost equivalent to 4 units of physical capital, K.

and development and final production. The difference between the social and private rates of return to research and development is determined by the choice of a welfare function, from which we largely abstract in this paper. However, in our decentralized model, crowding out is an endogenous consequence of climate policies: an increase in the rate of return in one research and development sector will increase the demand for capital, thus increasing aggregate interest rates and/or reducing quantities of capital used for both final production and investment in competing technologies. However, since research and development outside the energy sector is not considered in our model, we may not capture fully the crowding out effect of energy research and development on other technological progress. For the results reported in this paper, we look only at crowding out within the energy sector.

We can see from Figures A.6 and A.7 that the effects on private investment of increasing subsidies to a particular sector are qualitatively as we would expect, however the magnitudes of these effects are surprising. Own-sector effects are show a maximum increase in alternative sector investment of 24% and a maximum increase in carbon sector investment of 5.3%. The displacement effects are smaller than suggested by Popp (2004a). The maximum reduction in private investment in carbon energy induced by increasing funding to alternative energy is 14%, while in the alternative sector, carbon subsidies reduce investment by a maximum of only 1.3%. Some difference across sectors is expected due to the structure of carbon sector technology as being a complement to resources in energy production, and the difference in benchmark subsidy rates.

Displacement effects within the research and development sectors are more muted than the 50% suggested by Popp (2004a). Below, we explore the characteristics of the capital market and agent investment and find that supply and final production demand are both sufficiently locally elastic to absorb some of the increase in demand from the subsidized sector without leading to a large decrease in investment by other research and development sectors. This suggests that optimal policy models may have over-estimated the social-cost of research and development, and thus under-estimated its role in determining the social costs of climate policy.

In terms of aggregate economic effects, these policies are not significant to the same degree as the \$50/ton carbon tax. However, an interesting result from our welfare calculations allows us to again shed light on the political economy of climate policy. We find that the increased carbon subsidy would be welfare-preferred to the increase in alternative energy sector subsidies or to the status quo by agents born through the year 2036.

6 Discussion

In this section, we attempt to identify the components of the model which may have important leverage on the results. In particular, we examine the importance of the decentralized capital market, the role of technology competition, and the effect of altering the structure of the energy production function.

6.1 The role of the capital market

Above, we discuss the role of the capital market in propagating displacement effects. Here, we attempt to isolate this effect directly. In models proposed by Popp (2004a) and Nordhaus (2002), investment and environmental policy are co-determined. In this context, crowding out costs are assumed to constrain the net benefits of emissions control policy. While these policies increase our environmental capital, they come at a productivity cost, and may also attract investment away from sectors with high social rates of return. An over-estimate of this last effect will lead a planner to choose lower levels of emissions control at the margin, or to choose policies which induce less innovation where that is an option.

In our general equilibrium model, crowding out is an endogenous consequence of increasing capital demand leading to increased interest rates. Carbon tax policies imposed in an unrestricted model will induce simultaneous decreases in the supply of capital by agents and in the demand for capital in final production and increases in demand for research capital.

How much variation is actually induced in the supply of capital and the interest rate? In Figure A.13, it is clear that the savings decisions of agents are elastic to the interest rate changes induced by the policies. For the carbon tax with lump-sum recycling, there is some dis-saving before the policies go into effect, since young agents are anticipating their tax revenues in coming years. With the alternative energy subsidy, the reverse occurs, as agents accumulate capital to insulate themselves from the economic slowdown. In the long-term, the more productive economy leads to increased capital accumulation.[15] For the alternative technology subsidy alone, we see the effect of increased capital demand leading to increased capital formation in the long-term.

Crowding out will occur where the supply of capital is not sufficiently price-elastic to satisfy new demand induced by policy changes without significant increases in interest rates. Given the decentralized structure of our model, we can isolate these capital market effects by taking the benchmark capital supply as given, re-solving the model, and comparing the transition paths. Recalculating the results from the alternative energy technology subsidy, we find that the impacts of assuming a fixed capital stock are small and mostly felt in the long term. As reduced emissions render the economy more productive, the production sector begins demanding more capital than in the benchmark and begins to crowd out other investment. In the short term, the demand for capital in final production is sufficiently locally price elastic so that displaced investment in technology is only increased marginally by the inelastic capital market, and most of the capital for induced innovation is obtained at the expense of physical capital. We replicate these calculations for the Nordhaus (2002) assumption that capital is available in infinite quantity at benchmark interest rates. We find that this leads to small increases in capital accumulation and investment.

We cannot refute the contention that some capital for induced investment in energy technology crowds out other investment rather than generating new investment. In fact, earlier results of the crowding out rate increase only slightly when we impose a fixed capital market. However, we find that much of the new investment in research and development comes at the expense of physical capital used in final production, not other research and development. As such, if our model correctly captures the elasticity of savings decisions, an assumption that 50% of induced investment is likely to be acquired from other research and development opportunities with a high social rate of return may be an overestimate.

[15] Here, we cannot use the values to directly compute elasticities since we only observe the change in equilibrium capital supply for a change in the equilibrium price, and the policies affect both the supply and demand for capital.

6.2 The role of technology competition

In Popp (2004a) and Nordhaus (2002), investment is only possible in carbon-reducing technology, and not directly in carbon-free technology, while other papers such as Gerlagh (2003) emphasize the role of competing technologies.

Our model allows investment in both alternative and carbon energy technologies, modeled as substitutes in final production. Where only a single technology is present, the effect of any price policy (a carbon tax or a carbon reduction subsidy) will be to increase investment in carbon-reducing technology. Where two technologies exist, the impact of the price policy on the carbon-reducing technology is not known *ex ante*, but rather depends on the marginal knowledge product of investment in each of the sectors as well as the respective marginal energy products of knowledge. In our calibrated model, these values are such that a carbon tax will lead to a reduction in investment in the carbon-reducing technology. Below, we examine a subset of results under the assumption that investment in alternative energy technology is autonomous, set at levels observed in the benchmark simulation of the model. This proxies for a single sector model, and allows us to test the sensitivity of results to technology competition.

Here, we focus on the change in the effects of the carbon tax with lump-sum revenue recycling. Figure A.14 shows the change in carbon-reducing technology investment which occurs as a result of fixing the transition path for alternative energy technology. The results show that, as expected, the amount of carbon-reducing investment increases where alternative energy capacity is taken as given. However, despite the increased investment in carbon-reducing technology, the model predicts less emissions reduction, and welfare reductions due to the imposition of the constraint on alternative energy investment.

This implies that an optimal policy model solved with induced innovation only for carbon-reducing technology is likely underestimate the optimal emissions reduction relative to a case where the transitions of both carbon-free and carbon-reducing technologies are affected by policy decisions. These results echo the comparisons presented in Popp (2004b), which show the effect of a backstop technology introduced in the model proposed in Popp (2004a). However, as acknowledged in Popp (2004b), these results may confound the welfare effects of introducing a backstop technology with those of technology competition. Here, we begin with a two-sector model, and show the effects of competition versus a model where innovation is constrained to benchmark values in one sector. We can thus separate the welfare effect of placing the constraint on alternative sector investment and find that it reduces welfare by .1-.2%.

6.3 The role of the energy aggregation function

The model used in the simulations to this point uses a parsimonious final production structure where alternative and carbon energy services are aggregated linearly. This structure is such that the model cannot be well calibrated to fit IEA (2004) data which show a decline in the rate of alternative technology adoption in medium-term projections. Here, we re-examine the results under differing assumptions for the elasticity of energy services with respect to changes in alternative energy technology. This analysis allows us to capture the elasticities of substitution discussed in Gerlagh and Lise (2005), while maintaining our parsimonious structure.[16] Specifically, we recast the final production function as:

$$F_t(K_t, N_t, \phi_{c,t}, \phi_{a,t}, R_t) = \Omega_t \, K_t^{\alpha} \, N_t^{1-\alpha-\theta_t} \left(\phi_{c,t} R_t + (\phi_{a,t})^{\rho}\right)^{\theta_t}, \tag{6.1}$$

such that ρ determines the marginal energy services provided to final production by additional alternative energy capacity. Figure A.15 shows this relationship for alternative values of $\rho = .5$, $\rho = .8$, and for $\rho = 1$, the linear aggregation case used throughout the paper. We re-calculate the policy simulation results for the carbon tax with revenue recycled as an alternative energy subsidy for each of these cases.

The following expected effects occur by construction. Since a decrease (increase) in ρ reduces (increases) the marginal energy product of new alternative sector investment holding technology in the carbon-reducing sector constant, we expect to see a less (more) asymmetric response in investment as ρ decreases (increases), with additional carbon-reducing investment complementing alternative sector investment. In the benchmark case, we see substantial increases in investment in alternative energy technology, combined with a decrease in investment in carbon technology. This induced innovation in alternative capacity for the case of perfect substitutes ($\rho = 1$) exceeds that for $\rho = .8$ ($\rho = .5$) by increasing factors of 5-10% (10-15%).

[16] We do not re-calibrate any other parameters in the model in order to perform these simulations.

The economy's ability to compensate for carbon taxes with increased alternative energy use is reduced by the decreasing elasticity. As a result, we see dramatic increases in the use of carbon-reducing technology to offset the effects of the carbon tax. As shown in Figure A.16, the reliance on carbon energy is greatly increased under reductions of parameter ρ. This is very important for interpreting our results, since the value of this parameter for future sources of alternative energy is largely unknown.

7 Conclusion

We develop a model in which induced innovation occurs in a decentralized environment which is consistent with the following stylized facts. First, the benefits and costs of climate policy are distributed unequally across cohorts of finite-lived agents. Second, the supply of capital is not jointly determined with emissions policy, but rather by the self-interested decisions of economic agents. Third, research and development activities are undertaken by profit-maximizing firms, and firms in the economy must compete to acquire capital as they do other factors of production. Finally, the government employs fiscal means to influence the decisions of agents and firms in an imperfect market.

We show that the capital market provides an important propagation mechanism for induced innovation. Specifically, we show that many policies may simultaneously reduce the demand for capital and reduce its supply such that interest rate effects will be limited. This will not be the case uniformly across all policy choices. We also show that, given our calibration, the demand for final production capital is more locally price elastic than the demand for research and development capital. As such, much of the investment displaced by induced innovation may be physical and not knowledge capital, implying a lower social cost of induced innovation than previously specified in the literature.

We show that the inclusion of sectors offering carbon-reducing and carbon-free technologies influences policy analysis results. Where carbon-reducing technologies are the only option available, induced innovation reduces emissions and energy intensity in the long-run, while the same may not be true under technology competition. Where there are also opportunities to develop carbon-free technology, global resource use will be deferred to future periods. This effect is very important for consideration of long-term climate change mitigation, since it may imply that policies may achieve only a delay in the onset of effects rather than a solution to the problem.

We also describe welfare effects and address political economy considerations of induced innovation. We show that while agents prefer lump-sum recycling of carbon taxes or carbon reducing subsidies in the short-term, aggregate economic performance and long-term emissions reduction are maximized through recycling of tax revenues to alternative energy subsidies or through direct subsidies to backstop technology development.

The results of this paper in terms of the absolute effects of climate policy must be taken with caution. Research and development proceeds generally follow a stochastic process, and are not directly and predictably correlated with investment as they are in this paper. However, if we are able to capture the expected returns to investment in sector-specific research, we are able to better evaluate the impacts of climate policies than we would be able to in a model of exogenous technological change. The introduction of a stochastic innovation process in the presence of risk-averse agents, an analog to the model we propose, would likely be intractable. As such, it is important to interpret the results presented with the caveat that, in the best case scenario, we are limited to describing the welfare of agents and the evolution of the economy under the expected consequences of climate policies.

References

Buonanno, P., C. Carraro, and M. Galeotti (2003): "Endogenous Induced Technical Change and the Cost of Kyoto," *Resource and Energy Economics*, 25, 11–34.

Gerlagh, R. (2003): "Induced Technological Change under Technology Competition," *Fondazione Eni Enrico Mattei, Nota di Lavoro 5.2003*.

——— (2006): "A Climate-Change Policy Induced Shift from Innovations in Carbon-Energy Production to Carbon-Energy Savings," *Energy Economics*, Cited from resubmitted revisions.

Gerlagh, R., and W. Lise (2005): "Carbon taxes: a drop in the ocean, or a drop that erodes the stone? The effect of carbon taxes on technological change," *Ecological Economics*, 54, 241–260.

Gerlagh, R., and B. van der Zwaan (2003): "Gross World Product and Consumption in a Global Warming Model with Endogenous Technical Change," *Resource and Energy Economics*, 25, 35–57.

Goulder, L. H., and S. H. Shneider (1999): "Induced Technological Change and the Attractiveness of CO2 Abatment policy ," *Resource and Energy Economics*, 21, 211–253.

International Energy Agency (2004): *World Energy Outlook: 2004*. IEA Publications, Paris.

Kocherlakota, N. R. (1996): "The Equity Premium: It's Still a Puzzle," *Journal of Economic Literature*, 34(1), 42–71.

Leach, A. (2004): "The Welfare Implications of Climate Change Policy," Submitted Manuscript.

Nordhaus, W. D. (2002): *Modeling Induced Innovation in Climate-Change Policy*chap. Modeling Induced Innovation in Climate-Change Policy. Resources for the Future Press.

Nordhaus, W. D., and J. Boyer (2000): *Warming the World*. MIT Press, Cambridge, Mass.

Organization for Economic Co-operation and Development (2004): "Annual National Accounts - Comparative tables based on exchange rates and PPPs.," SourceOECD National Accounts Statistics.

Pizer, W. A. (1999): "The optimal choice of climate change policy in the presence of uncertainty," *Resource and Energy Economics*, 21, 255–87.

Popp, D. (2004a): "ENTICE : Endogenous Technological Change in the DICE model of Global Warming ," *Journal of Environmental Economics and Management*, 48(1), 742–768.

——— (2004b): "ENTICE-BR: The Effects of Backstop Technology R&D on Climate Policy Models," *NBER Working paper*, 10285, Forthcoming in *Energy Economics*.

Statistics Canada (2004): "Labour Force Survey (LFS)," CANSIM Database.

United Nations Population Division (2004): *World Population Prospects Population Database*. United Nations, New York, USA.

World Energy Council (2001): *Energy Technologies for the Twenty-First Century*. World Energy Council, London.

Table A.1
Calibrated and Fixed Parameter Values

Parameter	Description	Value
Fixed Parameters, Research and Development Sector		
μ_{1a}	Scaling factor, alt. energy research	0.085543
μ_{2a}	Existing technology share, alt. energy research	0.49998
μ_{3a}	Investment Share, alt. energy research	.2
δ_a	Knowledge obsolescence, alt. energy	0
μ_{1c}	Scaling factor, carbon energy research	0.0057055
μ_{2c}	Existing technology share, carbon energy research	.55
μ_{3c}	Investment Share, carbon energy research	.2
δ_c	Knowledge obsolescence, carbon energy	0
Fixed Parameters, Economic Sector		
σ	Coefficient of Relative Risk Aversion	1.2213
β	Discount Rate	.96
δ_k	Capital Depreciation Rate	.05
α	Production Share of Capital	.3
ξ_1	Minimum extraction cost of carbon($)	113
ξ_2	Linear rate in extraction cost of carbon	700
ξ_3	Exponent in extraction cost of carbon	4
Calibrated Parameters, Economic Sector		
γ_θ	Growth of energy share of production	-0.0185
δ_θ	Decay rate of energy share of production	0.007
γ_ω	Growth rate of technical change	0.0117
δ_ω	Decay rate on γ_ω	5.2617×10^{-11}
γ_n	Growth rate of population	0.02
δ_n	Decay rate on γ_n	.03
Fixed Parameters, Climate Sector		
m_b	Preindustrial concentration of CO_2	590
δ_a	atmospheric retention of CO_2	.9846
δ_e	atmospheric retention of emissions	.987
λ_1	AR(1) parameter on temperature deviations	.9472
λ_2	Temperature sensitivity to CO_2 doubling	.341633
λ_3	Rate of mixing for ocean and surface temperature	0.009866
$G_{2\times CO_2}$	Implied temperature sensitivity to CO_2 doubling	3
λ_4	AR(1) parameter on ocean temperature deviations	0.02
b_1	Linear component in damages from temperature changes	-0.0045
b_2	Quadratic component in damages from temperature changes	0.0035

Table A.2
Initial Period (1970) Values

Variable	Description	Calibrated Value
K_0	Capital Stock, US$	$20.206 * 10^{12}$
N_0	Effective Labour Supply	$3669.8 * 10^{6}$
ω_0	Productivity	.019635
θ_0	Initial Energy Share of Production	.037
m_0	Atmospheric CO_2 levels, GtC	675
G_0	Surface temperature change, ^oC	0.05
O_0	Ocean temperature change, ^oC	0

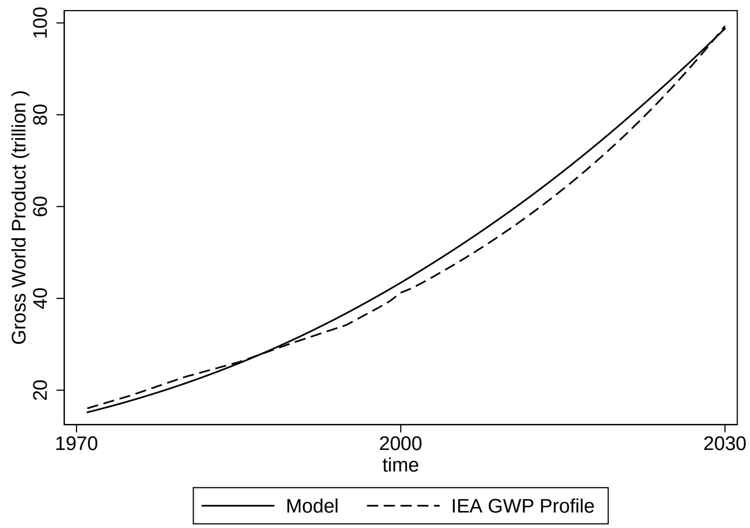

Fig. A.1. Gross World Product ($\$US{*}10^{12}$)

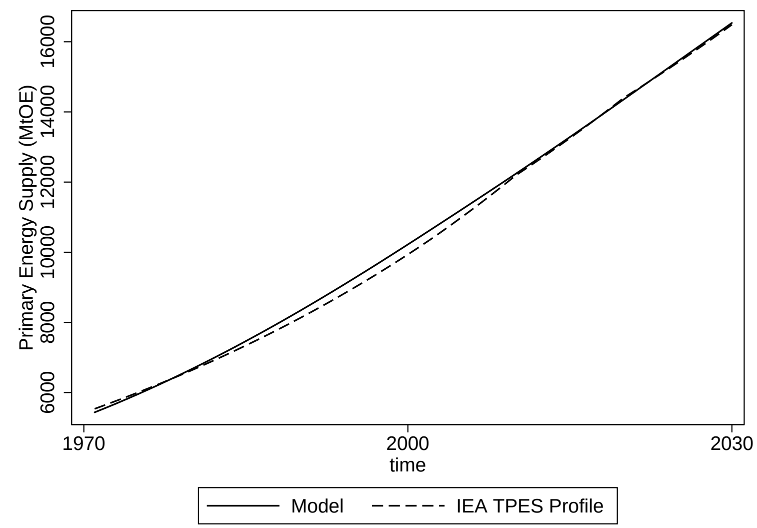

Fig. A.2. Total Primary Energy Supply (MtOE)

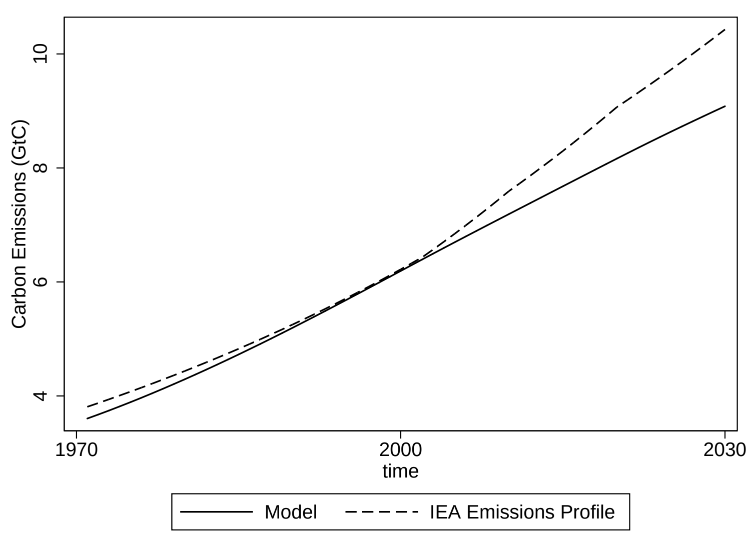

Fig. A.3. Carbon Emissions (GtC)

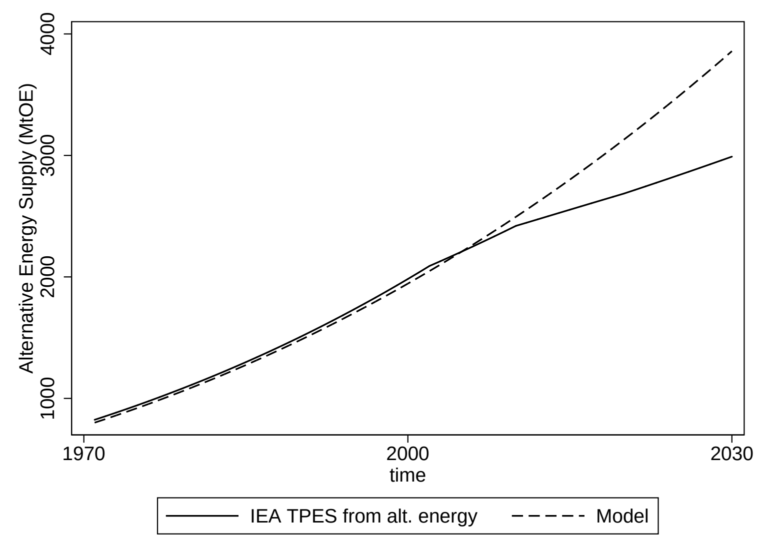

Fig. A.4. Alternative Energy Production (MtOE)

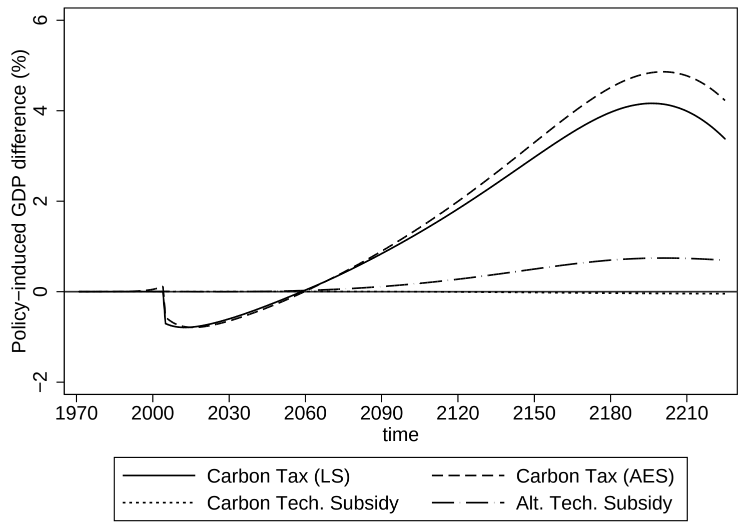

Fig. A.5. Policy-induced Differences in Gross World Product (%)

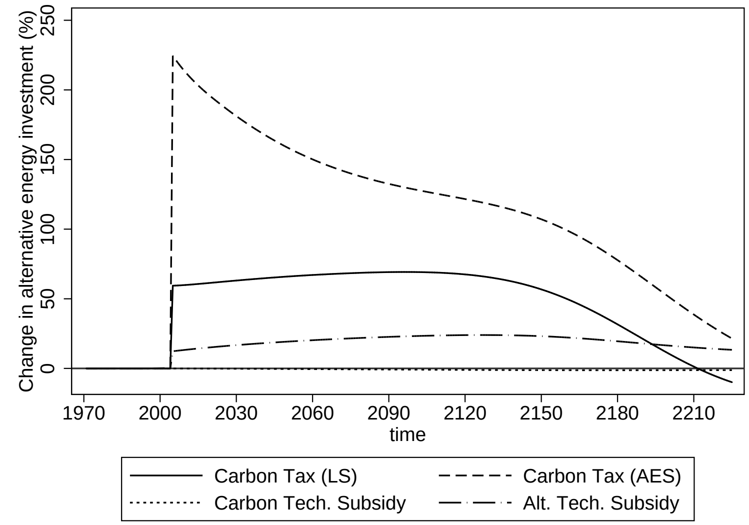

Fig. A.6. Policy-induced Changes in Alternative Energy Investment (%)

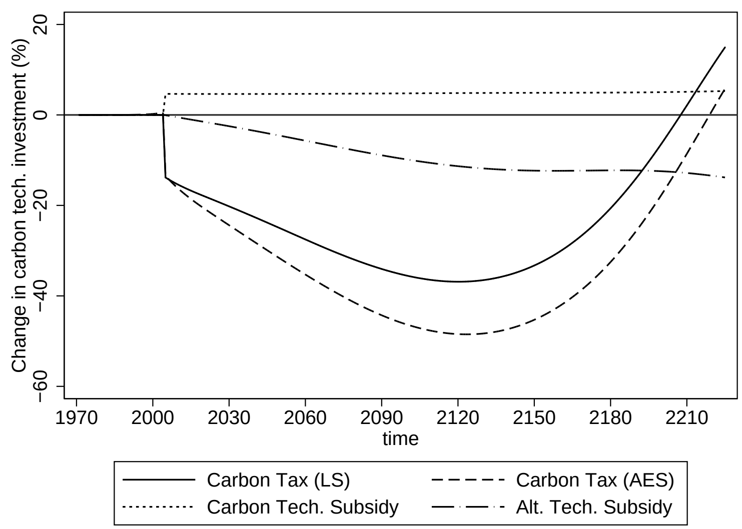

Fig. A.7. Policy-induced Changes in Carbon-reducing Technology Investment (%)

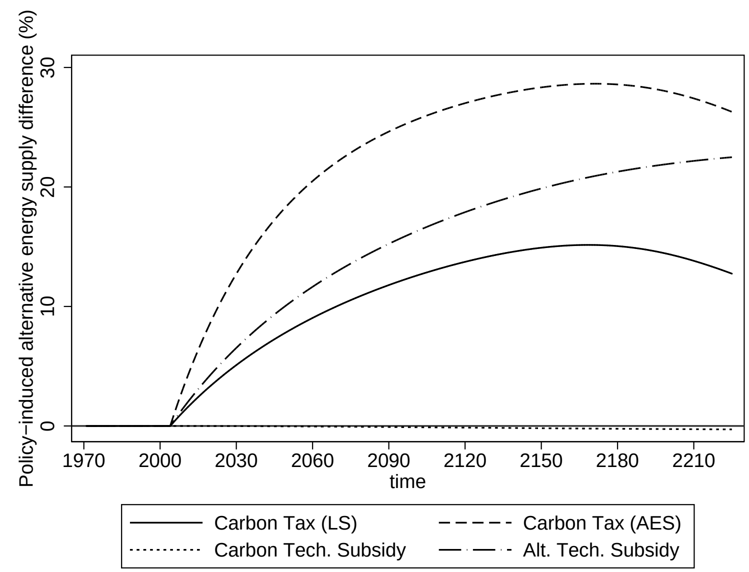

Fig. A.8. Policy-induced Changes in Alternative Energy Production (%)

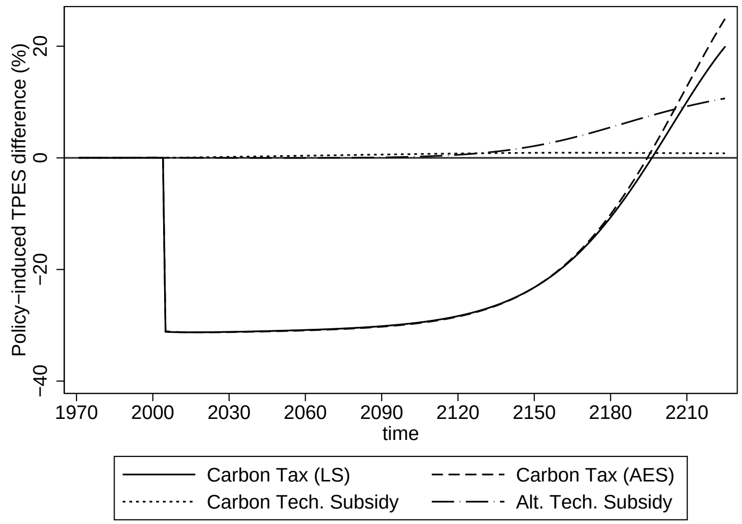

Fig. A.9. Policy-induced Deviations in Total Primary Energy Supply (%)

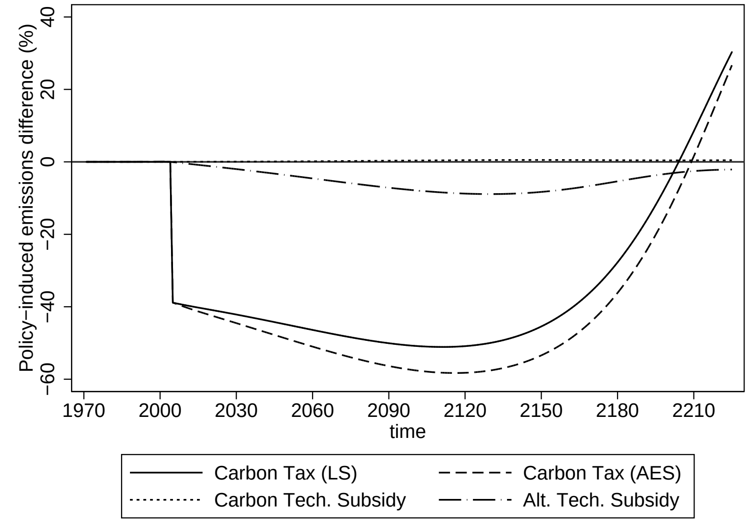

Fig. A.10. Policy-induced Reduction in Carbon Emissions (%)

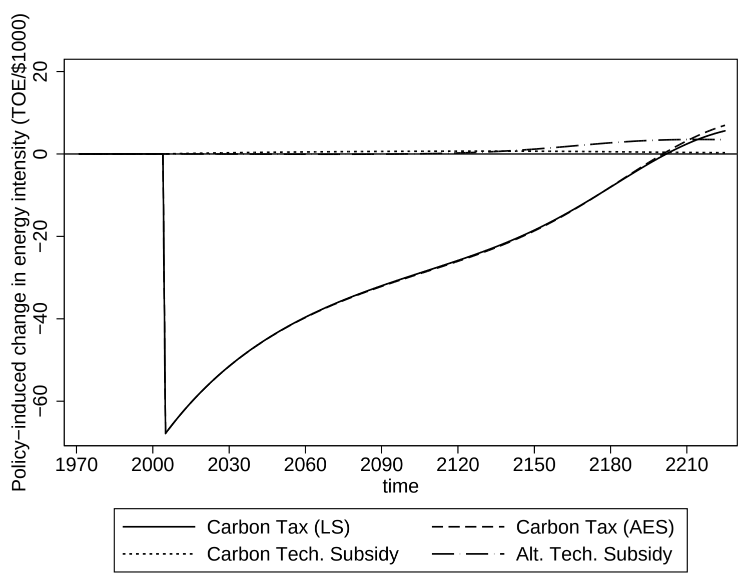

Fig. A.11. Policy-induced Reductions in Energy Intensity (%)

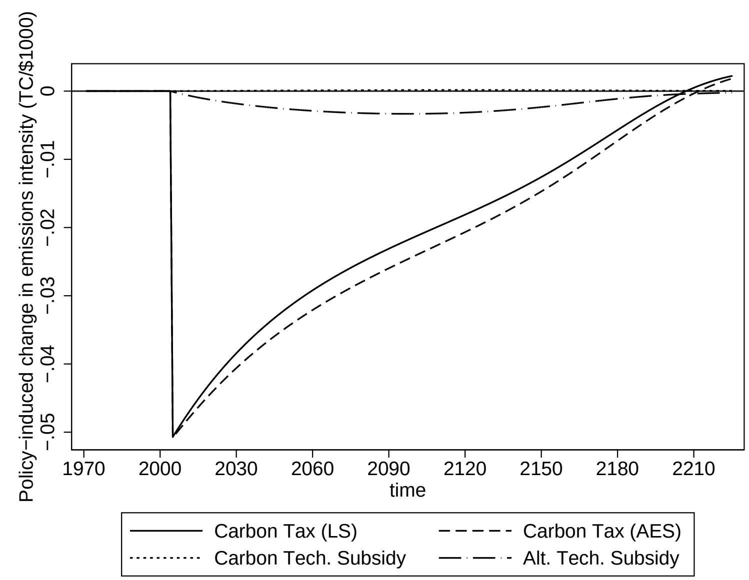

Fig. A.12. Policy-induced Reductions in Carbon Intensity

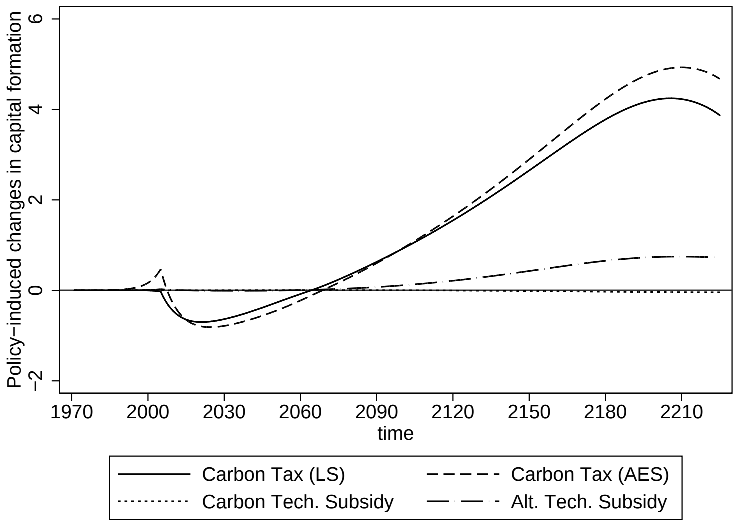

Fig. A.13. Policy-induced Differences in Domestic Savings (%)

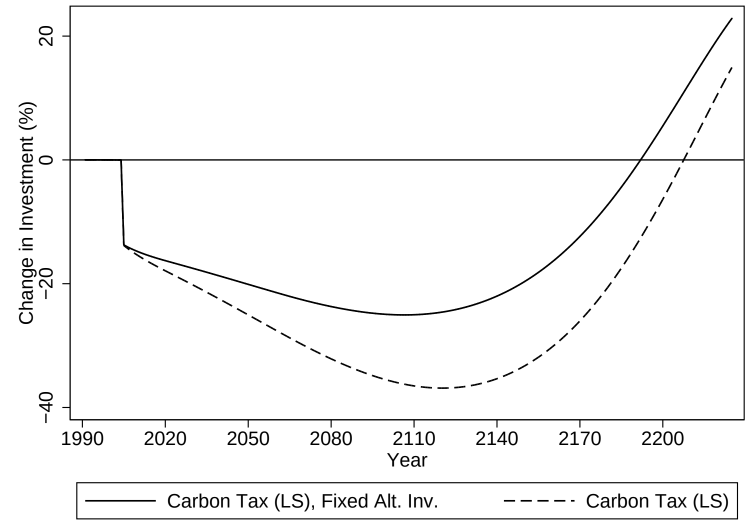

Fig. A.14. Changes in carbon technology investment induced by the Carbon Tax (LS) policy for cases of fixed and endogenous alternative technology investment.

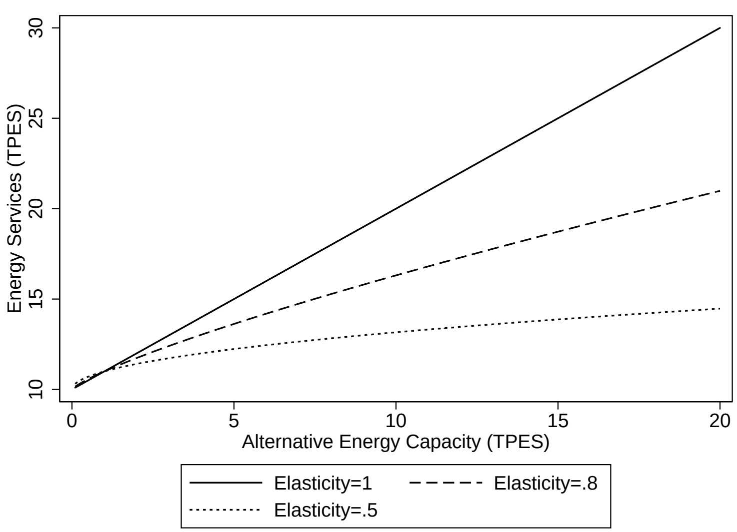

Fig. A.15. Marginal energy product of additional alternative technology, given carbon energy supply of 10 GTOE.

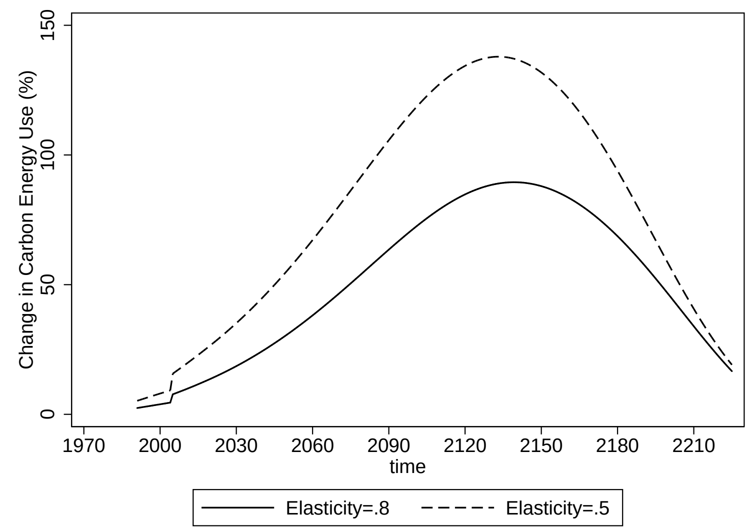

Fig. A.16. Change in carbon energy use from changes in ρ relative to the case of $\rho = 1$ for a \$50 carbon tax remitted through an alternative energy subsidy.