Reconsidering Intergenerational Cost-Benefit Analysis of Climate Change: An Endogenous Abatement Approach*

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May 2003

Abstract

This paper studies the intergenerational welfare effects of climate change and a control policy within a decentralized overlapping generations framework including endogenous abatement activities. The model is based on the seminal work of Romer (1990). It incorporates a profit stimulated R&D with realistic market distortions to create an induced innovation structure. In this setting, a control policy has the dual role of discouraging emissions and triggering new abatement technologies. The results from numerical simulations show that the omission of entrepreneurial response to a control policy is likely to result in overestimation of costs associated with this particular policy. Although induced innovation has a potential to reduce the compliance costs with the control policy, current and near-future generations will bear some net costs. The higher the damage is projected from climate change, the earlier the net benefit will be realized.

Keywords: Climate Change, Environmental Policy, Induced Innovation, Intergenerational Cost-Benefit Analysis

JEL Classification: D90, H23, H30, O32, Q38

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* First and foremost I would like to thank Shawn D. Knabb for his collaboration on Kavuncu and Knabb (2001) from which this paper highly benefits and for personal communications with him on this paper as well. I am also grateful to Henning Bohn, Stephen J. DeCanio, and John M. Marshall for constant encouragement and helpful suggestions. Of course, all remaining errors are my own.

1 Introduction

Problems posed by climate change are unprecedented in complexity, length of time, and potential severity of effects.[1] The challenge of crafting control policies to cope with these problems is the central theme of climate change analysis. Despite voluminous and still growing literature, there is still no consensus on the practical implications of suggested policies.[2] In this paper, an analytically tractable induced innovation model is developed along with numerical simulations to study the intergenerational welfare impacts of climate change and control policies. By pointing out the cost-saving potential of endogenous abatement, this current study contributes to policy-making efforts.

The task of forming and implementing a global climate policy has been associated with the everlasting debate for its degree of stringency. While advocates of more stringent policies indicate the irreversible catastrophic consequences of unabated emissions of greenhouse gases (GHG), others contend the excessive burden of unnecessarily strict control policies. This debate is further overwhelmed by two additional significant questions: Who will pay for the abatement efforts and who will benefit from the control?

Seldom has the world consciously faced a set of decisions so likely to affect generations intertemporally dispersed. Despite the unanimous recognition of its importance, the issue of intergenerational fairness has been inadvertently sidestepped in the analysis of climate change. Because the time dimension over which climate change and the results of control policies will become evident in the next centuries, it is obvious that there will be differential welfare impacts on distinct generations. The adverse consequences of climate change are likely to impose large uncompensated damages on far future generations while current mitigating efforts cause present and near future generations to suffer from depressing production. When crafting control policies, it is necessary to take into consideration the potential conflicting issues facing different generations.

In the economic analysis of climate change, the cost-benefit discounting is the most commonly used method to assess alternative policies. However, employing representative agent

[1] Assessment reports prepared by *Intergovernmental Panel on Climate Change* (IPCC, 2001a and 2001b) are the premier references depicting the state of knowledge on climate change science.

[2] IPCC (1996), Nordhaus (1998), DeCanio *et al*. (2000), Laitner *et al*. (2000), Shogren and Toman (2000), Toman (2001), and Claussen *et al*. (2001) provide a great deal of summaries on the economics of climate change and further research directions.

and social planner techniques within this methodology conceals the impact of relevant policies on the distinct generations.[3] A hypothetical social planner maximizes a representative agent's lifetime utility function, internalizes all market imperfections, and makes the desired distributions across generations to balance the costs and benefits of a control policy. Decision-making about a specific policy then strips down to applying a single net benefit number rather than screening the entire transition during which a control policy will be effective. Obviously, such an approach blurs the distinction between allocative efficiency and distributional fairness [see Marini and Scaramozzino (1995), Azar and Sterner (1996), Chao and Peck (2000), and Howarth (2000a, 2000b), Gerlagh and van der Zwaan (2001), Rasmussen (2003)]. For a problem unprecedented in scope and complexity like climate change, it is virtually impossible to address all relevant attributes by using a single decision criterion obtained by employing a social planner and representative agent framework.

In analyzing various dimensions of climate change and prescribed control policies, it is notably critical to display the distributions of costs and benefits associated with distinct generations. Clearly, the intertemporal dimensions of climate change compel us to use a richer framework to address generational welfare implications. As such, the present study employs a decentralized overlapping generations (OLG) model to shed some light on the generational effects of an emission stabilization policy. A framework of this kind is more expedient in climate change analysis than the standard practice of the discounted cost-benefit analysis with the conjoint use of a social planner and a representative agent.

In addition to its emphasis on intergenerational considerations, the other important aspect of the current study is the endogenous specification of the abatement process. Many researchers have warmly embraced the idea that policies designed to reduce GHG emissions can create significant incentives for the innovation of more energy-efficient technologies and thus reduce the costs of control policies. Nonetheless, a vast majority of climate change studies have eschewed the potential of incorporating induced innovation into their models. Rather, they have assumed exogenously increasing energy efficiency (i.e. decreasing carbon intensity of productive activities), independent of existing opportunities in the market.

[3] For some discussion on this issue, a more interested reader can refer to Burton (1993), Howarth and Norgaard (1995), Marini and Scaramozzino (1995), Howarth (1996, 2000a), IPCC (1996 ch.4 and ch.6), Portney and Weyant (1999), and Laitner *et al*. (2000).

The hypothesis that control policies could stimulate technological improvements is called induced innovation or induced technological change (ITC).[4] The basic premise of the ITC hypothesis is that the omission of entrepreneurial response to a control policy is likely to result in overestimation of costs associated with this particular policy. In fact, it is increasingly recognized that induced innovation seems to be at the heart of resolving apparently irreconcilable costs of control policies. Because considering endogenous development of new abatement and energy efficient technologies offers some hope of meeting the control targets with a cheaper scheme, understanding the nature of ITC is of utmost importance in the analysis of climate change.

However, the task of measuring, modeling, and ultimately influencing the path of technological improvements is hampered by the inherent complexities and mounting uncertainties of the process. As a result, empirical applications of ITC in climate change modeling are rather slow. To date, there are few climate change models which focus exclusively on the analysis of ITC. The most prominent studies are Dowlatabadi (1998), Goulder and Schneider (1999), Fischer *et al.* (2000), Goulder and Mathai (2000), Nordhaus (2002), Popp (2002), and van der Zwann *et al.* (2002).[5]

Unfortunately, these existing studies raise considerable ambiguity on the importance of ITC in shaping control policies. While Fischer *et al.* (2000) and Nordhaus (2002) find that allowing ITC does not significantly change the welfare gains, the others reach an opposite conclusion. Even though my intention is not to provide a critical evaluation of earlier papers or draw policy conclusions from them,[6] it is valuable to highlight the distinguishing aspect of the current study. Specifically, it is the methodology by which ITC mechanism is modeled within a dynamic general equilibrium model of climate change.

In general, there are two types of possible ITC formulations: Learning by doing (LBD) and research and product development (R&D). LBD is the accumulation of knowledge, facilitating new processes and techniques that result in cutbacks in the quantity of emissions.

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[4] Endogenous technological change is also commonly used for the same incident. It is a broader concept to the extent which is the result of economy wide entrepreneurial rent-seeking activities. Induced technological change is a more specific concept in that changes in the relative price of emission affect the rate and direction of innovation.

[5] Perhaps, it should be emphasized that I only consider the models including ITC within a general equilibrium setting. There are also more specific theoretical, econometric, and partial equilibrium analysis studies on ITC-environmental policy relationship.

[6] More comprehensive surveys of the induced innovation hypothesis can be found in Stoneman (1995), Weyant and Olavson (1999), Edmonds *et al*. (2000), Jaffe and Palmer (2000), Ruttan (2001), Grübler *et al*. (2002).

R&D is associated with more tangible activities that bring about new durable goods and products eventually leading to fewer emissions. The R&D type endogenous technological change has not been rigorously incorporated into models in the relevant literature. Even though some of the existing studies assert that they include an R&D type of ITC, I believe their methodology has been mislabeled and should be suitably placed in the category of LBD. This conjecture is made because R&D activities in these models result in disembodied knowledge accumulation rather than the development of carbon-efficient physical inputs or abatement goods.

Furthermore, by assuming a hypothetical social planner who can make necessary distributions for the efficient resource allocation, previous studies suppress the fundamental features of the ITC hypothesis, which consist of the private profit incentive as a key source of innovation and the imperfect market structure from which innovation arises. The issue of why profit-seeking agents respond to policy initiatives and how the appropriability of innovation is achieved cannot be addressed by relying solely on an unrealistic social planner assumption.

In accordance with the discussions of generational and technological issues detailed above, I set up a decentralized OLG model integrating emission control policies and the development of abatement goods. When modeling the production side, I closely follow the theoretical approach of Romer's (1990) endogenous growth model, allowing an explicit consideration for two driving forces of ITC, which have been obscured in earlier studies. Within this framework, the production side of the economy is decomposed into three sectors, which are the final goods sector, the abatement goods sector, and the R&D sector.

The first sector produces final goods that can be consumed, converted into physical capital stock, or used for the production of abatement goods. GHG emissions also arise as negative externalities in the production process of final goods. The second sector buys inputs from the final goods sector and instantaneously converts them into abatement goods. Abatement products are purchased back by firms in the final goods sector to reduce their emissions. In order to enter the market, an abatement firm has to acquire a patent which provides a temporary monopoly power for that particular abatement firm. This implies that the competitive market assumption, a standard assumption in the literature, should be relaxed. Finally, the third sector, based completely on pure profit motives, performs R&D and generates blueprints for new abatement goods.

It should be emphasized that the induced innovation characterization of the production sector crucially depends on the presence of a control policy. A positive emission tax is the necessary condition for the existence of induced innovation in the model within which firms are forced to internalize the negative impacts of emissions. In other words, introducing an emission tax affects the relative price of emissions and consequently induces the emitting firms to demand abatement goods to alleviate the burden of the tax. Therefore, control policies not only provide a price signal to internalize the consequences of GHG emissions but also trigger the innovations of abatement goods. The more firms are forced to mitigate their emissions, the more they demand abatement goods.

After the theoretical framework is developed, numerical simulations are carried out based on the standard assumptions of previous climate change studies. In order to measure generational well-being, I construct percentage utility deviations for different simulation scenarios. This approach allows one to trace out the impacts of climate change and a control policy generation by generation. Furthermore, the utilization of generational utility deviations not only dispels skeptical views on the monetary labeling of simulation results but also vitiates the highly controversial discussions of the discounting practice in the literature.

In the numerical exercises, I first simulate the model without a mitigation effort to obtain a baseline scenario where GHG emissions remain unregulated and emitting firms do not have any incentive to take an action. Outcomes from this "business-as-usual case" only depict the impacts of climate change. Similar to previous studies, the results show that environmental deterioration is not expected to be very serious until the first half of the next century. Thereafter, more severe impacts from climate change are projected. If no control initiative is implemented, then irreversible damages from climate change might reach a point where the existence of homo sapiens becomes endangered.

Next, I consider a control policy which requires the emissions of GHG to be indefinitely fixed at the level of year 2000. The purpose of this control policy is to enable future generations to enjoy an undamaged environment. When a control policy is introduced, the induced abatement component of the model will be operative. However, the simulations of the controlled environment scenario are performed *with* and *without* endogenous abatement in order to compare relative welfare effects of each case. The results from this section show that ignoring the endogenous response of the agents to the existing opportunities might overstate the welfare costs of implementing a control policy. Specifically, the scope of cost reductions depends on the productivity of abatement technology. The higher the productivity of abatement, the larger the welfare gains from the control.

Considering induced innovation is vital, as it arguably provides the best opportunity for low-cost methods in addressing climate change. Nevertheless, the existence of induced innovation does not imply a zero or negative-cost outcome. Inducing innovation requires resources to be deliberately allocated to R&D, reflecting the education, training, and other costs that go into attracting enough human capital to generate new technologies and making abatement goods. In particular, the costs of stabilizing GHG emissions are likely to fall greatly on the near future generations. The net benefit of the control will accrue to generations living at least a century in the future.

Overall, the model makes a clear argument against the standard practice of cost-benefit discounting. That is, regardless of the value of discount factor --whatever that may be-- some generations will bear the net costs while others will receive the net benefits. Even though induced innovation has a potential to increase the political viability of a control policy by reducing the compliance costs, policy makers have neither the perfect information nor the necessary instruments to make the desired distributions across generations at once under the threat of climate change. Hence, the observation that the generations who will feel the burden of the control policy are not those who will be extensively suffering from the environmental deterioration indicates an intergenerational risk-sharing dilemma. This issue within a political economy context awaits a high priority in the research agenda.

The rest of the paper is organized as follows. Section 2 describes and details the model. Section 3 presents and interprets the results from numerical simulations. Section 4 discusses the environmental dynamics. The final section concludes and indicates some further research directions.

2 The Model Structure

In this section, a theoretical dynamic integrated model, which offers a basis for the numerical analysis is presented and discussed. A discrete Diamond (1965) type two-period overlapping generations model is employed to study the intergenerational cost-benefit aspects of climate change as well as a control policy. In particular, the methodology closely follows the one employed in Kavuncu and Knabb (2001). Because the model deals with climate-economy interactions in a dynamic setting, first a brief description of the agents' behavior should be given.

2.1 Individuals

In the model, the world is inhabited by a sequence of overlapping generations where individuals have a life span of two periods. At the beginning of each period, a new generation is born. This generation becomes old in the next period and dies at the end of the same period. Therefore, two generations --young and old-- are alive at any point in time. Let $N_1(t)$ and $N_2(t)$ denote the number of young and old individuals at time t, respectively. Then, $N(t) = N_1(t) + N_2(t)$ is the total population at time t. Successive young generations grow at the rate g_N, which monotonically declines with a constant decay rate of d_N.[7] As a result, the limiting argument for the population implies that $\lim_{t\to\infty} N_1(t) = \lim_{t\to\infty} N_2(t)$.

$$N_1(t) = N_1(t-1)(1+g_N(t)) \tag{2.1.1}$$

$$g_N(t) = g_N(t-1)(1-d_N) \tag{2.1.2}$$

Individual preferences are represented by a logarithmic life cycle utility function. The argument of the utility function is a homogeneous consumption good which deteriorates due to damage from climate change. An individual consumes $c_1(t)$ when she is young and $c_2(t+1)$ when she is old. In addition, both $c_1(t)$ and $c_2(t+1)$ are subject to environmental damage from climate change. While consumption provides enjoyment, environmental deterioration as a pure externality reduces the value of individual consumption. Per capita environmental damage marked by $d(t)$ to an individual's consumption takes a non-linear functional form that will be explicitly discussed below.

When an individual is young, she is endowed with one unit of labor, which is supplied inelastically to the economy in exchange for a total wage income, $w(t)$. During the first period of

[7] All growth and depreciation rates presented hereafter are in generational frequencies covering 35 years. To convert a constant growth rate from generational frequency into annual frequency, the following simple operation is performed: $\prod_{t=1}^{35}(1+g_{Ax}) = (1+g_x) \to (1+g_x)^{\frac{1}{35}} = (1+g_{Ax})$. Here g_x and g_{Ax} stand for the growth rate of the variable x in generational and annual frequency, respectively.

life, individuals also save an amount, *z(t)*. These accumulated assets, rented out to the production sector, provide a before-tax return of *R(t+1)*. At any point in time, the young and old generations might face income taxes denoted by $t_I(t)$ and $t_R(t)$, respectively.

$$\max_{c_1(t),\, c_2(t+1)} U(t) = Log[c_1(t)(1-d(t))] + \left(\frac{1}{1+r}\right) Log[c_2(t+1)(1-d(t+1))] \tag{2.1.3}$$

subject to

$$c_1(t) + z(t) = w(t)(1-t_I(t)) \tag{2.1.4a}$$

$$c_2(t+1) = R(t+1)(1-t_R(t+1))z(t) \tag{2.1.4b}$$

Under the assumption that people have perfect foresight for future economic conditions and prices, the solution to the individual's problem generates the Euler equation:

$$\frac{c_2(t+1)}{c_1(t)} = \frac{R(t+1)(1-t_R(t+1))}{1+r} \tag{2.1.5}$$

We can then rewrite the first order condition in terms of the optimal saving decision.

$$z(t) = \left(\frac{1}{2+r}\right)[w(t)(1-t_I(t))] \tag{2.1.6}$$

This gives necessary and sufficient conditions for an interior optimum as a consequence of the strictly concave objective function and linear constraints.

2.2 The Production

The foundation of the production side is based primarily on Romer's variety-based model (1990).[8] Specifically, the production side of the economy consists of three sectors. The first sector produces final goods which can either be consumed or converted into physical capital stock or used for the production of abatement goods. GHG emissions arise as negative externalities in the production process of final goods. The second sector buys inputs from the final goods sector and instantaneously converts them into abatement goods by using a linear technology. Abatement products are purchased back by firms in the final goods sector in order to reduce their emissions. The third sector, based on totally pure profit motives, performs R&D and generates blueprints for new abatement goods. The structure of each sector is detailed below.

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[8] The theoretical basis of the current study also draws partially from Knabb (2000).

2.2.1 Final Goods Sector

The final goods sector of the economy is based on the Neoclassical Growth Theory. An arbitrary large number of competitive firms combine labor and capital and produce a homogenous good, *Y(t)*, which can either be sold to consumers or converted into physical capital, or can be purchased by the abatement firms. The homogenous final good serves as a numeraire for the economy. However, GHG emissions also emerge as by products of the production process in this sector.

Each competitive firm has an equal opportunity to access the technology described by a labor-augmenting Cobb-Douglas production function. The arguments of the production function consist of capital stock *K(t)* and effective labor $H_F(t) = B(t)N_{1F}(t)$, where *B(t)* represents the productivity of the labor force.

$$Y(t) = H_F(t)^{1-g} K(t)^g \tag{2.2.1}$$

$$Y(t) = [B(t)N_{1F}]^{1-g} K(t)^g$$

As frequently used in dynamic general equilibrium models, we can also rewrite the production function in terms of Hicks neutral productivity.

$$Y(t) = \tilde{B}(t)[N_{1F}]^{1-g} K(t)^g \tag{2.2.2}$$

The labor augmenting form of productivity is equivalent to an appropriate rescaling, $B(t) = [\tilde{B}(t)]^{\frac{1}{1-g}}$. The behavior of $\tilde{B}(t)$ over time is determined by a technological growth parameter, $g_{\tilde{B}}$.

$$\tilde{B}(t) = \tilde{B}(t-1)(1 + g_{\tilde{B}}) \tag{2.2.3}$$

The emission of GHG arises as a negative externality during the production of final goods. The level of GHG emissions is linearly proportional to the production of the final goods. The key element in the linear relation between emissions and production is the carbon intensity variable, denoted by $s(t)$. Because this variable is equivalent to emissions per unit of gross output, it is also called the GHG emissions-output ratio. Thus, $s(t)$ simply captures the exogenous trend in the emissions of GHG over time. The production process without abatement generates the following amount of emissions:[9]

$$E_U(t) = s(t)Y(t) \qquad (2.2.4)$$

The GHG emissions-output ratio $s(t)$ plays an important role in this relation. Similar to previous studies, I assume that $s(t)$ decreases slowly at the rate $g_s(t)$, which is called natural decarbonization. However, the decarbonization rate slows down over time at the rate d_s in accordance with the empirical evidence documented in previous studies [Nakicenovic *et al.* (1995) and Nakicenovic *et al.* (1998)]. That is, even without any policy intervention, $s(t)$ levels off over time and asymptotically approaches zero.

$$s(t) = s(t-1)(1 + g_s(t)) \qquad (2.2.5)$$

$$g_s(t) = g_s(t-1)(1 - d_s) \qquad (2.2.6)$$

The reason for the decline in $s(t)$ is due to both autonomous energy efficiency improvements (AEEI) and organizational enhancements within firms [see Krause *et al.* (2002 and 2003) and Popp (2002)]. Strictly speaking, the decline of $s(t)$ compromises all reductions in the carbon and energy intensity that are not induced by relative price changes.[10] Newell *et al.* (1999) demonstrate in their empirical study that fully one-fifth to two-fifths of efficiency improvements were induced by changes in energy prices. Because a large proportion of innovation seems to be independent of energy prices and regulations, the benchmark simulations are based on the declining GHG-output ratio.

Because competitive firms fail to internalize the negative effects of GHG emissions emanating from the production process, the government might require them to pay an emission tax, $t_E(t)$ in order to correct for the market failures. By doing so, the government causes the relative price of emission to change, which in turn alters firms' optimizing behavior and

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[9] Even though I employ the term "GHG" throughout the paper to represent the anthropogenic emissions of carbon dioxide (CO_2), it is truly a broader concept including water vapor, methane, nitrous oxide, and the chlorofluorocarbons. Yet, CO_2 is responsible for a great deal of greenhouse impact more than any other GHG. Therefore, it is an acceptable method to employ the CO_2-equivalent of GHG.

[10] Kelly and Kolstad (1999 pp. 189) indicate that the CO_2 intensity of output has fallen worldwide from 0.409 tons of carbon per thousands dollars of output in 1929 to 0.232 tons of carbon per thousands in 1989. The same trend is emphasized by IPCC-Mitigation report (2001 pp. 26) in that energy intensity and carbon intensity have been declining for more than 100 years without any explicit government policies and have the potential to decline further.

internalizes some or potentially all of the externalities that are created. Firms can ease the tax burden by purchasing abatement goods which reduce emissions for a given level of output. Such abatement goods include scrubbers, purifiers, filters, or new techniques that lead to reduced emission.[11]

At any point in time, total abatement *AB(t)* is limited to the set of successfully designed blueprints up to date t. Let us denote available abatement goods *A(t)* and *X(t)* as the abatement good of type *i* used at time *t*, and then define the abatement technology as follows:

$$AB(t) = \Psi \sum_{i=1}^{A(t)} X(i,t)^{a} \tag{2.2.7}$$

where the parameter a represents each abatement good's share in the total abatement. Ψ is the shift parameter representing the overall productivity of the abatement technology. If $\Psi = 0$, abatement technology is not feasible.

In the model, an important assumption is that newly designed and commercialized abatement goods have one period patent protection. Therefore, the producers of each abatement good enjoy a monopoly power for one period. Once the patent protection expires, the relevant abatement good becomes a competitive good.[12] Patented (or monopolized) abatement goods, $i \in (A(t-1), A(t)]$ naturally are those which are invented in the current period. All others $i \in [1, A(t-1)]$ are competitive abatement goods. Thus, the flow of net emissions after abatement is described as follows.

$$E(t) = s(t)Y(t) - \Psi \sum_{i=1}^{A(t)} X(i,t)^{a} \tag{2.2.8}$$

$$E(t) = s(t)Y(t) - \left[\Psi \sum_{i=A(t-1)+1}^{A(t)} X_M(i,t)^{a} + \Psi \sum_{j=1}^{A(t-1)} X_C(j,t)^{a} \right]$$

Given the production technology and emission generation, firms in the final good sector solve a profit maximization problem. In addition to potential emissions tax $t_E(t)$, firms have to pay $w_F(t)$ per unit of labor and $Rent(t) = r(t) + d_K$ per unit of capital in the production process.

$$max \prod_F = H_F(t)^{1-g} K(t)^{g} - w_F(t)N_{1F}(t) - Rent(t)K(t) - AC(t) - t_E(t)E(t) \tag{2.2.9}$$

where *AC(t)* is the abatement cost at time *t*.

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[11] The interpretation of abatement goods is equivalent to that of Romer's (1990) intermediate goods.

[12] More explanation about abatement goods and abatement firms will be given in the next subsection.

$$AC(t)=\sum_{i=A(t-1)+1}^{A(t)} P(i,t)[1-s_a(t)]X_M(i,t)+\sum_{j=1}^{A(t-1)} X_C(j,t) \tag{2.2.10}$$

The price of monopoly abatement good i is denoted by $P(i, t)$, and $s_a(i, t)$ is the subsidy that the government potentially provides to eliminate the static-inefficiency resulting from monopoly power. Notice that the price of competitive abatement good equals *one*, which is the marginal cost. For the sake of brevity, I omit the inclusion of additional price notation for competitive abatement goods.

Let the term $J(t)=[1-m(t)]$ be the effective tax wedge and $m(t)=t_E(t)s(t)$ be the standard control rate. Because of Cobb-Douglas technology and perfect competition assumptions, after-tax returns to production factors exactly equal their marginal products. Profit maximization over labor and capital choice implies the following first order conditions:

$$N_{1F}(t):(1-g)J(t)H_F(t)^{-g}K(t)^g B(t)-w_F(t)=0 \tag{2.2.11a}$$

$$K(t):gJ(t)H_F(t)^{1-g}K(t)^{g-1}B(t)-Rent(t)=0 \tag{2.2.11b}$$

$$X_M(i,t):-P(i,t)[1-s_a(i,t)]+a\,t_E(t)\Psi X_M(i,t)^{a-1}=0 \tag{2.2.11c}$$

$$X_C(j,t):-1+a\,t_E(t)\Psi X_C(j,t)^{a-1}=0 \tag{2.2.11d}$$

We can find the demand functions for the type i patented abatement good and the type j competitive abatement good using equations (2.2.11c) and (2.2.11d), respectively.

$$X_M(i,t)=\left[\frac{\Psi a\,t_E(t)}{P(i,t)[1-s_a(i,t)]}\right]^{\frac{1}{1-a}} \tag{2.2.12a}$$

$$X_C(i,t)=[\Psi a\,t_E(t)]^{\frac{1}{1-a}} \tag{2.2.12b}$$

Clearly, the production factors $K(t)$ and $N_{1F}(t)$ receive a higher return when an environmental laissez-faire approach is accepted compared to the case in which there is an attempt to control GHG emissions. For firms to have the desire to demand abatement goods, they must be forced to internalize the adverse consequences of emissions. In other words, firms in the final goods sector will demand abatement goods as long as a positive emission tax at least between some time interval is imposed. This is the crucial analytical part of the study in the sense that endogenous abatement is viable if a control policy initiative is undertaken by the government.

2.2.2 Abatement Goods Sector

The market structure of the abatement goods sector is monopolistic competition with free entry. This sector consists of a discrete number of firms, each of which produces a single differentiated abatement good employing a linear technology. After obtaining a blueprint[13] generated by R&D firms, an abatement firm purchases inputs from the final goods sector and immediately converts one flow unit of the final good into one flow unit of the abatement good. Abatement goods are immediately available for employment by firms in the final goods sector to reduce the emissions that they create.

Once an abatement firm purchases a blueprint, which is effectively a patent to produce an abatement good of type $i \in (A(t-1), A(t)]$, it becomes the monopoly supplier of that good and receives monopoly rents for one period. When the patent expires, abatement goods become competitive and available at the competitive price of *one*, which is its marginal cost. Because the market structure is monopolistic competition with free entry, the present value of the profit stream obtained by the monopolistic abatement firm *i* will equal the value of the patent.

After incurring the fixed cost of invention (i.e., purchasing a patent), a monopolistic abatement firm in this sector maximizes the following profit function.

$$max \prod_M (i,t) = P(i,t) X_M (i,t) - X_M (i,t) \qquad (2.2.13)$$

Substituting the derived demand function for $X_M (i,t)$, as shown by equation (2.2.12a), into $\prod_M (i,t)$ and choosing $P(i, t)$ to maximize profits result in the mark-up price charged by each monopolistic abatement firm.

$$P(i,t) = \frac{1}{a} > 1 \quad \forall \ i \in (A(t-1), A(t)] \qquad (2.2.14)$$

Therefore, the monopoly price is the same over time for all patented abatement goods $i \in (A(t-1), A(t)]$. Replacing the constant mark-up price back into equation (2.2.12a) gives the demand function for any patented abatement good. Because the solution is symmetric across abatement firms, we can ignore the index *i* marking different abatement firms.

$$X_M (i,t) = X_M (t) = \left[\frac{\Psi a^2 t_E (t)}{[1 - s_a (t)]} \right]^{\frac{1}{1-a}} \quad \forall \ i \in (A(t-1), A(t)] \qquad (2.2.15)$$

[13] A blueprint is a set of description or know-how showing how to combine raw material (in the form of final goods) to produce abatement goods.

The blueprint of a new abatement good is worth buying for an abatement firm if it generates a present value of monopoly profits sufficiently covering its purchase cost. Because there is free entry into the sector, the arbitrage condition implies that the present value of monopoly profits should equal the value of the patent. As a result, the value of the patent equals one period profits of the monopolistic abatement firm due to one period of monopoly power.

$$Value\ of\ \ Patent = V_A(t) = \prod_M(t) = \left(\frac{1-a}{a}\right)\left[\frac{\Psi a^2 t_E(t)}{[1-s_a(t)]}\right]^{\frac{1}{1-a}} \tag{2.2.16}$$

It is important to recognize that the demand function for each abatement good is inexorably linked to the emission tax, $t_E(t)$. Without a positive tax rate on emissions, firms in the final goods sector do not demand abatement goods. This lack of demand for abatement goods results in zero profit in the abatement sector and zero value for the value of the patent. Therefore, the implementation of a control policy is an indispensable part of the induced innovation structure.

It is assumed that the monopoly power is temporary. The patent protection lasts only one period. Once this period lapses, the monopolistic abatement good becomes a competitive good. Just as a monopolistic firm, a competitive abatement firm solves the profit maximization problem:

$$max \prod_C(i,t) = P_C(i,t)X_C(i,t) - X_C(i,t) \tag{2.2.17}$$

The competitive market assumption entails that profits are zero, which implies that the price of a competitive abatement good equals its marginal cost, $P_C(i,t) = 1$. Using equation (2.2.12b), the demand function for any competitive abatement good is shown below. Notice that the same discussion regarding the necessity of emission tax also applies for the competitive abatement goods.

$$X_C(i,t) = X_C(t) = [\Psi a\, t_E(t)]^{\frac{1}{1-a}} \quad \forall\ i \in [1, A(t-1)] \tag{2.2.18}$$

2.2.3 R&D Sector

The R&D sector consists of an arbitrarily large number of competitive firms. R&D firms employ human capital $H_R(t) = B(t)N_{1R}(t)$ to develop designs for new abatement goods. When a new design is invented, the inventing R&D firm receives a patent protection from the government. It then sells the patent to an abatement firm with a willingness to pay of $V_A(t)$. A blueprint can be invented, sold, and used in the same period. The newest technology is indexed as $A(t)$ in this sector. The equation of motion for the development of new designs is such that:

$$A(t) = A(t-1) + yH_R(t) \qquad (2.2.19)$$

$$\Delta A(t) = yH_R(t)$$

where y is the shift or productivity parameter.[14]

Researchers benefit from economy wide productivity, $B(t)$ and earn a wage, $w_R(t)$ based on the value of the design that they invent. R&D firms maximize the following profit function.

$$max \prod_R(t) = V_A(t)\Delta A(t) - w_R(t)H_R(t) \qquad (2.2.20)$$

Because the market structure is perfectly competitive, zero profit prevails. As discussed above, the equilibrium condition requires that the price of the patent is simply the value of an intermediate firm. The first order condition for an R&D firm's problem indicates that the marginal revenue product of an additional unit of labor allocated to R&D (which is the value of patent multiplied by the marginal product of labor) equals the marginal cost of this additional unit of labor.

$$N_{1R}(t): y\ V_A(t) - w_R(t) = 0 \qquad (2.2.21)$$

Substituting equation (2.2.16) into the last equation gives the wage rate in the R&D sector.

$$w_R(t) = y\ B(t)\left(\frac{1-a}{a}\right)\left[\frac{\Psi a^2 t_E(t)}{[1-s_a(t)]}\right]^{\frac{1}{1-a}} \qquad (2.2.22)$$

This last equation shows that the returns to labor in the R&D sector crucially depend on the presence of an emission tax. If the government does not impose any emission tax, then the return to the R&D labor becomes zero, and no R&D takes place.

2.3 The Government

The role of the government is to stick to the basics. Foremost, the government should provide a credible patent system to ensure that inventors can reap the fruits of their efforts in inventing new abatement technologies. At the same time, the government should also use proper mechanisms for environmental protection and for the innovation of abatement goods.

[14] In reality, the results of R&D activities are highly uncertain. The real world process is so complex, no current model perfectly describes R&D activities.

Environmental monitoring by the government is assumed to be strong enough so that a control policy is effective when it is implemented. The government is also assumed to operate a balanced budget.

$$G(t)+\sum_{i=A(t-1)+1}^{A(t)} P(i,t)[s_a(i,t)]X_M(i,t)=t_I(t)N_1(t)w_I(t)+t_R(t)N_2(t)R(t)z(t-1)+t_E(t)E(t) \tag{2.3.1}$$

The government provides a subsidy, $s_a(i, t)$ to the monopolistic producers of abatement goods in order to eliminate static inefficiency due to mark-up pricing. Because the monopoly price of each abatement good is the same multiple $\frac{1}{a}$ of marginal cost, which is *one*, the subsidy rate must be also a constant, $s_a(i,t)=s_a=1-a$. It is assumed that government expenditures $G(t)$ and the tax rate on the young's income $t_I(t)$ equal zero for all periods to avoid further complexity in the analysis.[15] Using the equilibrium conditions, the government's budget constraint can be rewritten as follows:

$$\Delta A(t)\left(\frac{s_a}{a}\right)X_M(t)=t_R(t)N_2(t)R(t)z(t-1)+t_E(t)E(t) \tag{2.3.2}$$

Solving the last equation $t_R(t)$ gives us the tax rate on the old period's income.

$$t_R(t)=\frac{1}{N_2(t)R(t)z(t-1)}\left[\Delta A(t)\left(\frac{s_a}{a}\right)X_M(t)-t_E(t)E(t)\right] \tag{2.3.3}$$

2.4 Market Clearing Conditions

The labor market clearing condition requires that the sum of workers in the final goods and R&D sectors is limited to the young population at any point of time.

$$N_1(t)=N_{1F}(t)+N_{1R}(t) \tag{2.4.1}$$

Because labor force is perfectly mobile across sectors, the arbitrage condition implies the wage equalization.

$$w_F(t)=w_R(t)=w^*(t) \tag{2.4.2}$$

[15] Assuming $G(t)=t_I(t)=0$ does not nullify the significance of these fiscal policy tools in the analysis. In fact, incorporating them into the model allows an important extension where various intertemporal transfer schemes can be discussed to address intergenerational risk sharing. I believe this is the next step in future research endeavors.

$$(1-g)J(t)H_F(t)^{-g}K(t)^g B(t) = y\ B(t)\left(\frac{1-a}{a}\right)\left[\frac{\Psi a^2 t_E(t)}{[1-s_a]}\right]^{\frac{1}{1-a}}$$

Solving the last equation for $N_{1F}(t)$ gives the equilibrium level of employment in the final good sector.

$$N_{1F}^*(t) = \left[\frac{(1-g)J^*(t)}{y\left(\frac{1-a}{a}\right)\left[\frac{\Psi a^2 t_E^*(t)}{[1-s_a(t)]}\right]^{\frac{1}{1-a}}}\right]^{\frac{1}{g}} \frac{K(t)}{B(t)} \qquad (2.4.3)$$

Using the labor market clearing equation and equation (2.4.3), it is also possible to determine the equilibrium level of employment in the R&D sector, $N_{1R}(t)$. Notice that g, y, a, and Ψ are exogenous parametric values. Variables $K(t), B(t), s(t)$, and s_a are predetermined variables at time t. Given $J^*(t) = [1 - t_E^*(t)s(t)]$, if we find out the emission tax $t_E^*(t)$ we can determine the allocation of labor force across sectors. The method of finding $t_E^*(t)$ will be discussed in the next section.

Next period's capital stock is determined by the aggregate savings of the current young generation. Using the optimal saving equation (2.1.6), the capital dynamics can be specified as in the standard Diamond (1965) model.

$$K^*(t+1) = \left(\frac{1}{2+r}\right)N_1(t)w^*(t) \qquad (2.4.4)$$

The gross return to capital is $R^*(t) = 1 + r^*(t)$ where $r^*(t) = Rent(t) - d_K$. Total payments to the capital stock can be determined by using equation (2.2.11b).

$$R^*(t)K(t) = gJ^*(t)Y^*(t) + (1-d_K)K^*(t) \qquad (2.4.5)$$

The young generation's consumption at t is $C_1^*(t) = N_1(t)c_1^*(t) = N_1(t)w^*(t) - N_1(t)z^*(t)$ which results in

$$C_1^*(t) = N_1(t)c_1^*(t) = \left(\frac{1+r}{2+r}\right)[(1-g)J^*(t)Y^*(t)]$$

The old generation's consumption at time t can be found from equation (2.1.4b) which is $C_2^*(t) = N_2(t)c_2^*(t) = [1 - t_R(t)]R^*(t)K^*(t)$. Finally, using equations (2.3.1) and (2.4.5), we can determine $C_2^*(t)$.

$$C_2^*(t) = gJ^*(t) = Y^*(t) + (1 - d_K)K^*(t) - \Delta A(t)\left(\frac{s_a}{a}\right)X_M(t) + t_E^*(t)E(t)$$

Once a stabilization policy is implemented, each old generation receives a transfer payment in the amount of collected emission-tax revenues net of subsidy payments. Collected revenues of emission tax are redistributed to the old generation in a lump-sum fashion.

3 Environmental Dynamics

Closing the model calls for a characterization of the link between GHG emissions and the evolution of climate change. Admittedly, environmental dynamics involves a much more complex system than the simplified framework presented in this study.[16] Nonetheless, this framework strips away unnecessary details and suffices to shed light on the intergenerational cost-benefit analysis of environmental policies.

To be consistent with the existing literature, I accept that the time path of GHG emissions determines future climate conditions. As explained before, GHG emissions stem from the production of final goods as negative externalities. The constant marginal atmospheric retention parameter, b determines the amount of GHG that stay in the atmosphere over the long run. The effective concentration of GHG in the atmosphere, *M(t)* measured in billion tons of carbon-equivalent, increases with emissions. The pre-industrial stock of *M(t)* is taken to be 590 billion tons of carbon-equivalent, as generally accepted in previous studies. The stock of GHG in excess of the pre-industrial norm is dissipated by a constant fraction of d_M as this stock diffuses into the deep ocean and other carbon sinks. Overall, *M(t)* is governed by a first order difference equation.

$$M(t+1) = 590 + (1 - d_M)(M(t) - 590) + bE(t) \quad (3.1.1)$$

The functional relationship between GHG emissions and environmental quality is expressed in terms of ground, *T(t)* and oceanic temperature *O(t)* changes. The increase above the

[16] The description of environmental dynamics is adopted from Kolstad (1996).

mean ground temperature is a proxy or an index for the impacts of the global climate change.[17] In particular, the ground temperature is a non-linear function of GHG concentration. As climatologists frequently state, this non-linear relation is approximately logarithmic.

$$T(t+1) = T(t) + l_1 Ln\left[\frac{M(t)}{590}\right] + l_2 T(t) + l_3 O(t) \qquad (3.1.2)$$

where l_1 is the nonlinear effect of GHG stock, l_2 is the general atmospheric cooling, and l_3 is the effect of the deep ocean temperature that functions as a carbon sink. Over time the increasing heat in the atmosphere radiates into the ocean and causes its mean temperature to rise according to the first order difference equation:

$$O(t+1) = O(t) + l_4 (T(t) - O(t)) \qquad (3.1.3)$$

The final step is to translate climate change into the actual damage which consequently harms the individual well-being. Thus, a damage function is introduced to the model. Following Kolstad (1996), I assume that the damages rise with increases in the mean of atmospheric temperature.[18]

$$d(t) = \Phi\left[\frac{q_1 T(t)^{q_2}}{\left[1 + q_1 T(t)^{q_2}\right]}\right] \qquad (3.1.4)$$

q_1, q_2 and Φ are three important parameters in the damage function. While q_1 indicates the scale effect of the temperature, q_2 captures the nonlinear impact of the climate change. Because there are enormous uncertainties about the extent by how much damage from climate change will take place, a definitive model of valuation of environmental quality for individual well-being is extremely difficult. Therefore, another scale parameter Φ is employed to capture various intensities of environmental degradation from climate change. In other words, Φ allows us to control for different possibilities of climate change. The higher its value, the more detrimental the effect of climate change will be.

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[17] As a standard approach in the literature, we approximate the climate change and environmental deterioration through observing the change in the mean level of ground atmospheric temperature measured in Celsius degrees.

[18] The damage function here approximates the one employed by Kolstad (1996) which specifies the individual utility function in a Ramsey type representative agent framework as follows $U = Log[c(t) - \Delta d(t)]$ where the damage

$d(t) = \frac{q_1 T(t)^{q_2} Y(t)}{\left[1 + q_1 T(t)^{q_2}\right] N(t)}$ with the same characterization as presented in this study.

4 Numerical Simulations

In this section, the response of a decentralized market economy to a control policy is examined by numerically simulating the model outlined in the previous section. Because endogenous growth theory, which provides a theoretical ground in modeling the induced technological change, is still in a state of development, computable models based on it are currently very few. Therefore, the objective is to achieve some concrete qualitative propositions regarding intergenerational cost-benefit aspects of climate change rather than merely presenting quantitative outcomes. I adopt some benchmark parameters and initial conditions from Nordhaus (1994), Kolstad (1996), Howarth (1998, 2000a), and Jones and Williams (2000).

4.1 Generational Well-Being Measures

Specifically, I investigate two main cases; the uncontrolled environment *without* any regulation and the controlled environment *with* the emissions stabilization at the level of year 2000. Furthermore, I consider the controlled case *with* and *without* endogenous abatement so that the welfare effects of induced innovation can be observed. In particular, the scale parameter in the damage function, Φ governs the severity of damage from climate change.[19] Any value of the scale parameter above the high damage case results in catastrophic consequences of climate change, the possibility of which has recently been given some credence in the climate change literature [see Gjerde *et al.* (1999), Moretto and Tamborini (1999), Schneider and Kuntz-Duriseti (2001)].

Given any scenario, the important task is to find some measures that specify the cost of environmental deterioration and the benefit of control that are imparted by different generations. This task can be effectively handled by expressing the cost of environmental degradation and the gain from control in terms of percentage change in the generational utility. That is, the percentage deviation of the lifetime utility function provides an instrument to project the cost-benefit schemes under alternative scenarios.

[19] Φ is assumed to take three values corresponding to little, moderate, or big problems from climate change. The specifications of Φ lie within the range of those assumed in Kolstad (1996).

Canonical cost-benefit analysis attempts to compare all costs and benefits in terms of a common monetary unit. Because of highly conjectural modeling, monetized consumption and absolute utility levels (the primary welfare measures in the existing literature) might give a misleading gauge of individual well-being [see Repetto (1997), Nordhaus (1998), Roughgarden and Schneider (1999), Howarth (2000b), Nordhaus and Boyer (2000)]. A decision analysis based on monetary labeling has some meaning if the range of physical, biological, and social outcomes is completely quantifiable [IPCC (1996) pp. 62-65.] Not every impact from climate change (especially those related to biodiversity, human health, and social amenities) can be easily materialized by using monetary units. Therefore, monetary labeling or estimates raise serious doubts on the reliability of the reports from different scenarios. By employing utility deviations, it is possible to obtain monetary-free demonstrations of the cost-benefit projections for different scenarios. I believe that this method better illustrates the evolution of successive but disconnected generations' well-being rather than placing some vague monetary labels on the costs and benefits of different policies.

The term designated for this purpose is the generational utility deviation, (*GUD*). Depending on whether the control policy is in effect or not, there are two versions of *GUD*. The first case is $GUD_{WOC}(t)$ measuring the percentage generational utility loss when the environment takes its course without control. The second one is $GUD_{WC}(t)$ measuring the impacts of a control policy.

$$GUD_{WOC}(t) = \left(\frac{U_d^{uc}(t) - U_{nd}(t)}{U_{nd}(t)} \right) 100 \qquad (4.1.1)$$

$$GUD_{WC}(t) = \left(\frac{U_d^{c}(t) - U_{nd}(t)}{U_{nd}(t)} \right) 100 \qquad (4.1.2)$$

The term "*generational utility*" indicates the discounted lifetime utility function of a generation. There are three generational utility functions. $U_{nd}(t)$ is the lifetime utility of the generation born at time t, assuming there is no damage coming from climate change and thus no requirement for a control policy. That is, $U_{nd}(t)$ signifies a hypothetical situation where climate change would not take place. On the other hand, $U_d^{uc}(t)$ represents the generational utility exposed to the damage from climate change *without* any attempt to control it. Finally, $U_d^c(t)$

stands for also the generational utility when it is subject to the effects of the damage from climate change and a control policy.

$$U_{nd}(t) = Log[c_1(t)] + \left(\frac{1}{1+r}\right) Log[c_2(t+1)] \tag{4.1.3}$$

$$U_d^{uc}(t) = Log[c_1^{uc}(t)(1-d(t))] + \left(\frac{1}{1+r}\right) Log[c_2^{uc}(t+1)(1-d(t+1))] \tag{4.1.4}$$

$$U_d^{c}(t) = Log[c_1^{c}(t)(1-d(t))] + \left(\frac{1}{1+r}\right) Log[c_2^{c}(t+1)(1-d(t+1))] \tag{4.1.5}$$

The superscripts "*uc*" and "*c*" denote whether the per capita consumption and generational utility are associated with the uncontrolled or controlled cases, respectively. The subscripts "*nd*" and "*d*" indicate whether the per capita consumption remains intact or impaired as a result of the damage coming from climate change, respectively. Perhaps, it should be also emphasized that damage from climate change $d(\bullet)$ is different under uncontrolled-(4.1.4) and controlled-(4.1.5) cases.

Notice that $GUD_{WOC}(t)$ reflects solely the effects of the damage from climate change on generational well-being, whereas $GUD_{WC}(t)$ captures both harmful and beneficial effects of the control policy on generational well-being. The benefit of the control policy is found in the reduction of the intensity of the damage. On the other hand, the cost of control originates from the reallocation of scarce resources to the abatement and environmental R&D activities.

In order to find out the net impacts of a control policy, it is necessary to detangle two combined effects in $GUD_{WC}(t)$. In fact, one can easily obtain the net impact of the control policy on a generation's well-being if $GUD_{WOC}(t)$, (only representing the damage from climate change), is subtracted from $GUD_{WC}(t)$. As a result, the term $NGUD(t)$ illustrates the net change in the generational welfare when a control policy is implemented.

$$NGUD(t) = \left(\frac{U_d^{c}(t) - U_d^{uc}(t)}{U_{nd}(t)}\right) 100 \tag{4.1.6}$$

As long as $NGUD(t)$ is positive, the control policy is effective in the sense that its benefits exceed its costs. Otherwise, the control policy generates net costs. Therefore, generations experiencing a positive value of $NGUD(t)$ will be fortunate, since they can enjoy relatively higher welfare. Those generations having negative values of $NGUD(t)$ will be on the opposite side in terms of net gain and will ultimately be hurt from the control policy.

Generational utility measures are first-hand tools in presenting the simulation results which will be shortly discussed below.

4.2 Uncontrolled Environment

In the uncontrolled case, there is no effort to control the evolution of climate. The outcomes from this section establish a base-line case that matches the core quantitative results of the benchmark studies under the business-as-usual scenario. Based on generational consumption measure [i.e., $GUD_{WOC}(t)$], *Figure 4*.1 illustrates the adverse effect of environmental degradation under three damage scenarios. The cost of environmental deterioration ranges between a 0.12% and a 2.30% loss of generational well-being in the short term. These numbers climb to levels as high as 7% for a low damage scenario, 13% for a moderate damage scenario, and 19% for a high damage scenario.

Figure 4.1 also illustrates the intuition behind the general conclusion of some previous studies which seek exclusively the policy leading to efficient stabilization. Many previous studies indicate an apparent desirability for letting emissions rise well into the end of the next century [see Kelly and Kolstad (1999) and Shogren and Toman (2000)]. An efficient stabilization policy aims to equate the marginal cost of a control policy to the discounted future benefits from this policy. Researchers considering only the next 150 years report that there is no need to apply aggressive control policies and the costs of very stringent control policies in the near future are far too expensive for exchange of modest benefits [such as Peck and Teisberg (1993), Nordhaus (1994), Kolstad (1996), Nordhaus and Boyer (2000)]. Their conclusion is appropriate for the time horizon under investigation. It is clear from figures that the environmental damage resulting from climate change for the coming 150 years will not be as serious as that of subsequent periods. Therefore, it is not surprising to report low emission tax rates and non-aggressive control policies targeted towards the achievement of efficiency.

However, if one stretches the time horizon beyond 150 years, it is evident from the figure that the adverse effects of climate change become more severe. Therefore, the results will diverge from those based solely on near future analysis. The larger the emissions projected from the baseline scenario, the more GHG emissions need to be reduced in the short-term and near future. Another implication of the baseline scenario concerns about the sustainability of environmental quality. Irreversible damages emanating from climate change might reach a point where human life becomes highly vulnerable. In this situation, even the improved life standards from the conventional growth process cannot obliterate the catastrophic consequences of climate change. Given the implications of the business-as-usual scenario, the next step is to analyze the effects of a control policy and compare these results with those presented in this subsection.

4.3 Controlled Environment

In the controlled case, I analyze the potential effects of the forceful stabilization of GHG emissions. The motivation for the control is to reduce the negative impacts of climate change. This policy is the reflection of the Kyoto Protocol, the most prominent global initiative.[20] According to the Kyoto Protocol, parties agree to take measures to limit emissions and promote adaptation to future climate change impacts.[21] Even though it is not easy to agree on a common course of actions and to expect faithful compliance across countries, the ultimate objective of the Protocol is to stabilize GHG emissions at a level that would prevent dangerous interference with the climate system. With the recognition of challenges surrounding compliance, I assume that the binding standards as long term objectives ordain a stabilization of GHG emissions at the year 2000 level for all the remaining periods, $\overline{E} = E(2000)$.

The critical point in this scenario is to analyze the presence of induced innovation on the generational well-being when the control policy is put into effect. In particular, I simulate the model *with* and *without* endogenous abatement to understand the relative importance of the induced innovation component in projecting cost estimations. In order to solve the recursive structure of the system when endogenous abatement is viable, the emission tax, $t_E(t)$ needs to be numerically obtained from equation (2.2.8) which displays the net emissions after abatement.

[20] The full text and some satisfactory discussion of the Kyoto Protocol can be found at http://www.unfccc.de/ and http://cop4.unfccc.de/kp/kp.html.

[21] The Kyoto Protocol institutes specific numerical limits for GHG emissions complied by Annex I countries, which consist of essentially high income OECD, Eastern Europe, and most former Soviet Union countries within the first decade of 21st century [Haites and Aslam (2000).]

$$\overline{E} = s(t)\left[\frac{(1-g)\left[1-t_E^*(t)s(t)\right]}{y\left(\frac{1-a}{a}\right)\left[\frac{\Psi a^2 t_E^*(t)}{1-s_a}\right]^{\frac{1}{1-a}}}\right]^{\frac{1-g}{g}} K^*(t) \qquad (4.3.1)$$

$$-\Psi\left[A(t-1)\left[\Psi a^2 t_E^*(t)\right]^{\frac{a}{1-a}} - y\,x^*(t)\left[\frac{\Psi a^2 t_E^*(t)}{1-s_a}\right]^{\frac{a}{1-a}}\right]$$

where

$$x^*(t) = B(t)N_1(t) - \left[\frac{(1-g)\left[1-t_E^*(t)s(t)\right]}{y\left(\frac{1-a}{a}\right)\left[\frac{\Psi a^2 t_E^*(t)}{1-s_a}\right]^{\frac{1}{1-a}}}\right]^{\frac{1}{g}} K^*(t)$$

Once the emission tax rate is computed from equation (4.3.1), we can determine the rest of the variables including per capita consumptions in the model. On the other hand, if we assume that the induced innovation is not operative (i.e., $\Psi = 0$), then the control policy can only be implemented by depressing capital stock accumulation. Again using equation (2.2.8) with the hypothetical assumption $\Psi = 0$, the control policy entails capital dynamics to be determined according to the emission target.[22]

$$\hat{K}(t) = \left[\frac{\overline{E}}{s(t)\tilde{B}(t)[N_1(t)]^{1-g}}\right]^{\frac{1}{g}} \qquad (4.3.2)$$

After deriving the required amount of $\hat{K}(t)$ for time t to hit the target level of emissions, the next step is to recover the emission tax from capital accumulation dynamics displayed in equation (2.4.4).

$$\hat{t}_E(t) = \frac{1}{s(t)} - \frac{\hat{K}(t+1)}{\left(\frac{1-g}{2+r}\right)s(t)Y(t)} \qquad (4.3.3)$$

[22] Note that when the induced innovation is absent in the model $N_{1R}(t) = 0$ and thus $N_1(t) = N_{1R}(t)\ \forall t$.

Using generational utility deviations, $GUD_{WOC}(t)$ we can keep track of the generational consequences of the stabilization policy. *Figure* 4.2 and *Figure* 4.3 show the gross effects of the control policy *with* and *without* endogenous abatement, respectively. These figures intuitively show that the gross cost is larger when the climate change is projected to be more serious. However, they do not illustrate the entire story about net generational cost-benefit involvement since the gross cost includes both costs and benefits of stabilization. That means we need another instrument to understand the net effects of this control policy. As it is discussed above, $NGUD(t)$ enables us to monitor the net impact of a control policy generation by generation.

Figure 4.4 displays how the emission stabilization policy will affect generational well-being for low, moderate and high damage cases when endogenous abatement is operative. On the other hand, *Figure* 4.5 displays the results of the same policy when we assume endogenous abatement is *not* operative. The common message from these figures is that current and near future generations will bear the costs of the control policy while far future generations will obtain the net benefits. However, the existence of induced innovation phenomenon makes the application of the control policy more attractive. *Figure* 4.6 signifies the relative importance of the induced innovation in cost-benefit assessments. The costs of control policy are always lower with the benchmark case of endogenous abatement than the case without it. As a result, the omission of entrepreneurial response to a control policy is likely to result in overestimation of welfare costs associated with this particular policy.

It is also evident from these *figures* that there is no free lunch *per se* when applying a control policy. Although induced innovation has a potential to reduce the compliance costs with the control policy, current and near future generations will bear some net costs. It is because the imposition of an emission tax changes the relative price of emission and requires scarce resources to be deliberately allocated to abatement and R&D activities.

The timing of the first appearance of the net benefit depends on the productivity of the abatement technology. *Figure* 4.7 and *Figure* 4.8 display the arrival of the net benefit depending on the abatement technology being lower or higher than the benchmark case, respectively. The lower productivity of abatement relative to the benchmark case pushes the arrival of the net benefit further into the future while the higher productivity of abatement relative to the benchmark case causes the arrival of the net benefit to come earlier time.

5 Concluding Remarks

Because of the vast intertemporal dimensions of the problem, an emerging convention in the analysis of climate change strongly echoes the need for more meticulous deliberations on intergenerational fairness. As such, this paper has developed an analytically tractable and numerically simulated model to study intergenerational welfare effects of climate change and a control policy such as the one envisaged by the Kyoto Protocol. As a theoretical foundation, a decentralized overlapping generations model with an endogenous abatement specification is set forth. This framework is more expedient in assessing the intergenerational welfare issues than the standard practice of discounted cost-benefit comparisons by using a social planner and a representative agent.

In addition to the intergenerational issues, the endogenous abatement specification in the model offers a realistic structure to examine the implications of induced technological change. Incorporating induced innovation is important because it arguably provides the best opportunity to lower the costs associated with a control policy. In fact, one way to increase the political viability of the Kyoto Protocol is to demonstrate that benefits are attained at the lowest costs when the possibility of entrepreneurial response is considered.

By using a decentralized R&D specification, the fundamental features of induced technological change are realistically captured. Abstaining from an unrealistic social planner framework enables us to follow the Schumpeterian trichotomy of technological change, which is the sequence of invention-innovation-commercialization. This analytical model reveals that the occurrence of induced innovation crucially depends on the existence of a control policy. Without an emission tax, firms generating emissions do not take any action to internalize the negative externalities that they create. Therefore, a control policy has the dual role of discouraging emissions and triggering new abatement technologies.

Numerical simulations are carried out under the standard assumptions of earlier studies. In the literature, the convention focused on numerical exercises is a pure quantitative appraisal of climate change and various policies. Because of the complexities and uncertainties of climate change and economic modeling, absolute numerical estimates of physical impacts remain rather scanty. A critical question of how much confidence we can put into these analyses in terms of their qualitative insights remains unanswered. Hence, I largely emphasize the qualitative implications of the results rather than drowning the reader in a cluster of numbers without any useful insight.

I have introduced generational utility deviations, monetary-free measures, to evaluate alternative scenarios. These measures facilitate a generation by generation tracing of the impacts of different scenarios. First, I have considered a case where no action is taken to control climate change. The results from this case confirm the core implications of previous studies in the literature. The damage from climate change will not be a major problem for the generational well-being until the mid-22nd century. Nevertheless, the loss of generational welfare from climate change will become increasingly severe for future generations if no action is taken.

In the second scenario, I assume a control policy involving an emission stabilization at the current level. An effective control policy is a necessary condition in order for the induced innovation to be operative in the model. In order to demand abatement goods, emitting firms have to bear additional burden apart from the usual input costs needed for the production. Even though the endogenous abatement is effective in the presence of the control policy, the simulations in the controlled scenario are performed *with* and *without* endogenous abatement to compare relative the welfare effects of each case.

The results from this section show that the costs of control will fall on the present and near future generations who are not likely to experience negative impacts of climate change. Those generations living beyond the mid-22nd century will receive the net benefits of the control. Therefore, the model makes a clear argument on the highly controversial issue of discounting. Regardless of the value of a discount factor, some generations will be net losers by either incurring damage from climate change or bearing the costs of the control policy. The relative importance of the distributional impacts of the control policy depends on the scope of damage projected from climate change. As the damage is expected to be greater in magnitude, the desirability of the control policy increases.

Another implication of the controlled case is that ignoring the endogenous abatement or induced innovation might overstate the welfare costs of implementing a control policy. Specifically, the scope of cost reductions depends on the productivity of abatement technology. The higher the productivity of abatement, the larger the welfare gains from the control. Even though induced innovation can enhance the viability of the control policy, it does not entail a zero or negative-cost outcome. Inducing innovation requires resources to be deliberately allocated to R&D, reflecting the education, training, and other costs that go into attracting enough human capital to generate new technologies and making abatement goods.

Naturally, some caveats need to be acknowledged. Modeling climate change with an induced innovation structure is challenging. The real world process is extremely complex. No current model establishes a benchmark framework or workhorse for technological change. Neither does the model presented here. The precision of the results is severely restricted due to weak empirical evidence on fundamental functional relations and parametric values. In this sense, I focus on discussing the qualitative implications of the results rather than the absoluteness of the numerical estimates due to the frequently stated forewarning regarding highly conjectural results in the climate change modeling.

In brief, the primary result of this study is that the distributional impacts of climate change and any potential policy lead to intergenerational welfare and risk sharing dilemmas. Induced innovation can increase the political desirability of a control policy. However, policy makers have neither the perfect information nor the necessary instruments to make the desired distributions to create a net benefit for a generation at once under the threat of climate change. Until now, no mechanism has been offered to solve this problem. As a result, an important contribution to the literature would be to construct a model involving induced innovation structure and the risk sharing issue within the context of political economy. I believe this should be a high priority on the research agenda.

APPENDIX: List of Symbols

Parameters

Parameter	*Description*	*Value*
Dt	one period [*(t+1)-(t)*]	35
r	individual time preference rate	0.03 *per year*
g	capital chare	0.3
Y	productivity of abatement	1, 3, 5 *(Low, Moderate, High)*
a	share of an abatement good	0.75
y	productivity of human capital in *R&D*	1
$g_{\tilde{B}}$	growth rate of Hicks neutral productivity	0.015 *per year*
s_a	subsidy rate per abatement good	0.25
d_K	depreciation rate of capital stock	0.1 *per year*
d_N	decay rate in the population growth	0.02 *per year*
d_s	decline rate in the natural decarbonization rate	0.0046 *per year*
d_M	depreciation of GHG concentration	0.087 *per year*
b	atmospheric retention ratio	0.64
l_1	nonlinear effect of GHG concentration	2.7
l_2	general atmospheric cooling	-0.1
l_3	deep ocean effect	0.1
l_4	warming-sink effect parameter	0.02
F	intensity of environmental damage	1, 2.5, 5 *(Low, Moderate, High)*
q_1	the scale effect of warming	0.01
q_2	non-linear effect of warming	1.8

Endogenous Variables

Variable	*Description*	*Initial (Predetermined) Value*
c_1	young period consumption	–
c_2	old period consumption	–
d	environmental damage	–
z	individual savings	–
w	wage rate	–
R	gross return on savings	–
t_R	tax rate on returns to savings	–
N_1	young population (total labor force)	$N_1(65)=2.2$ & $N_1(00)=3.95$ *billions*
N_2	old population	$N_2(65)=2.2$ & $N_1(00)=3.95$ *billions*
g_N	population growth rate	$g_N(65)$=0.0203 *per year*
$\tilde{B}$	Hicks neutral productivity	$\tilde{B}=67.85$
E	greenhouse gas emissions (GHG)	–
s	GHG-output (emissions intensity)	$s(65)=0.52$
Y	output-production	–
K	capital stock	$K(65)=16$ & $K(00)=56$ *trillions*
N_{1F}	employment in the final goods sector	$N_{1F}(65)=2.2$ *billions*
N_{1R}	employment in the *R&D* sector	–
X_M	monopolistic abatement good	–
X_C	a competitive abatement good	–
P_M	price of monopolistic abatement good	$P=1/a$ *(in equilibrium)*
A	total number of abatement goods	–
AB	abatement	–
AC	total abatement costs	–
w_F	wage rate in the final goods sector	–
w_R	wage rate in the *R&D* sector	–
t_E	emissions tax rate	–
$J=1-m$	effective tax wedge (with $m=t_E s$)	–
V_A	value of a patent	–
M	GHG concentration	*M(pre-industrial level)=590 GGt*
T	increase in mean atmospheric temperature	$T(65)=0.2$ & $T(00)=1.7$
O	increase in mean oceanic temperature	$O(65)=0.1$& $O(00)=0.102$
U_{nd}	generational utility without damage	–
U_d^{uc}	generational utility without control	–
U_d^{c}	generational utility with control	–
GUD_{WOC}	generational well-being measure under ‘no-control’ scenario	–
GUD_{WC}	generational well-being measure under ‘controlled environment’ scenario	–
$NGUD$	net generational impact of control policy	–

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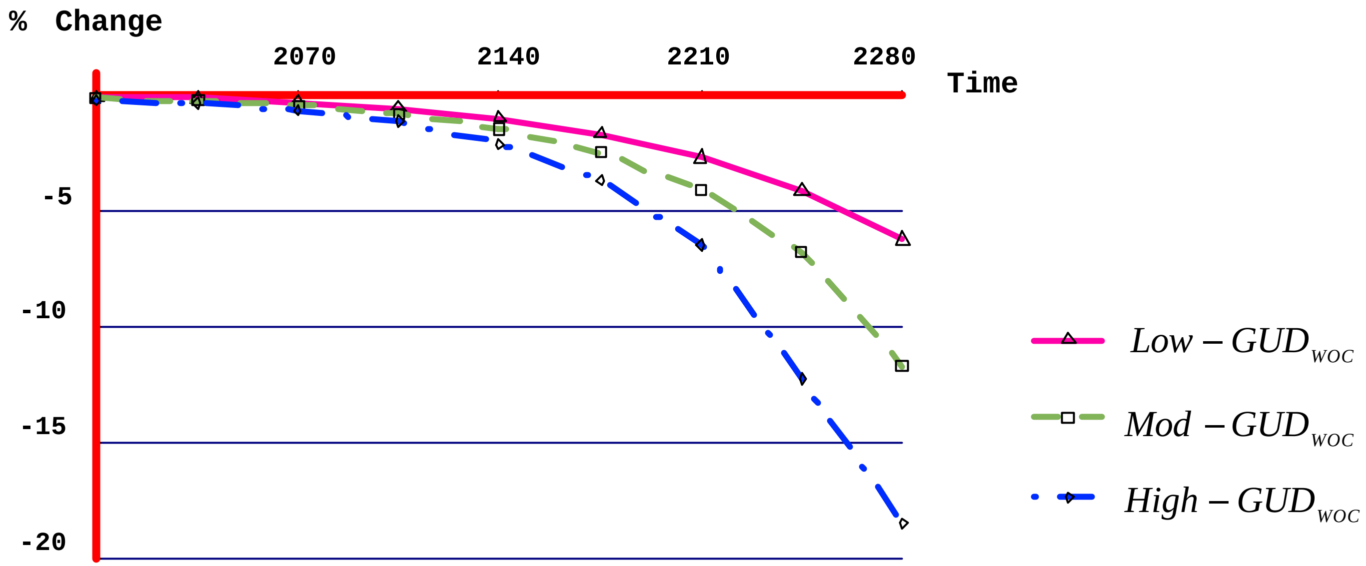
FIGURE - 4.1

The Impact of Climate Change in the Uncontrolled Environment

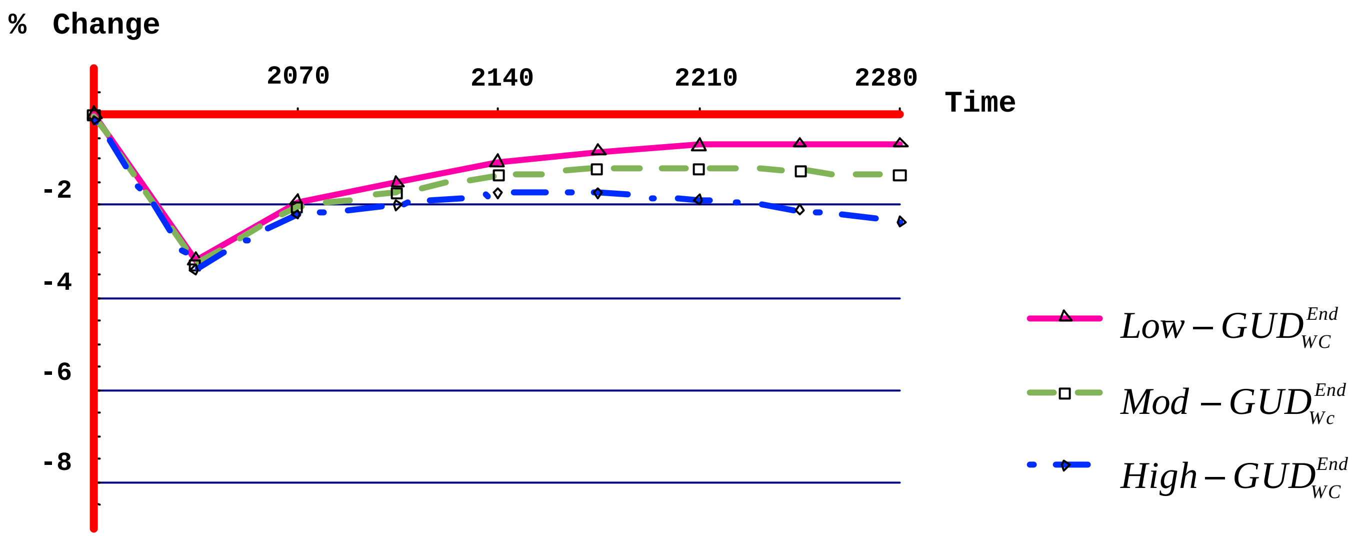


$$GUD_{WOC}(t) = \left(\frac{U_d^{uc}(t) - U_{ud}(t)}{U_{ud}(t)} \right) x\, 100$$

This figure shows the loss in generational well-being under the three different damage scenarios. Environmental damage resulting from climate change for the next 150 years will not be as serious as that of subsequent periods.

FIGURE - 4.2

The Impact of the Control Policy *with* Endogenous Abatement in the Controlled Environment

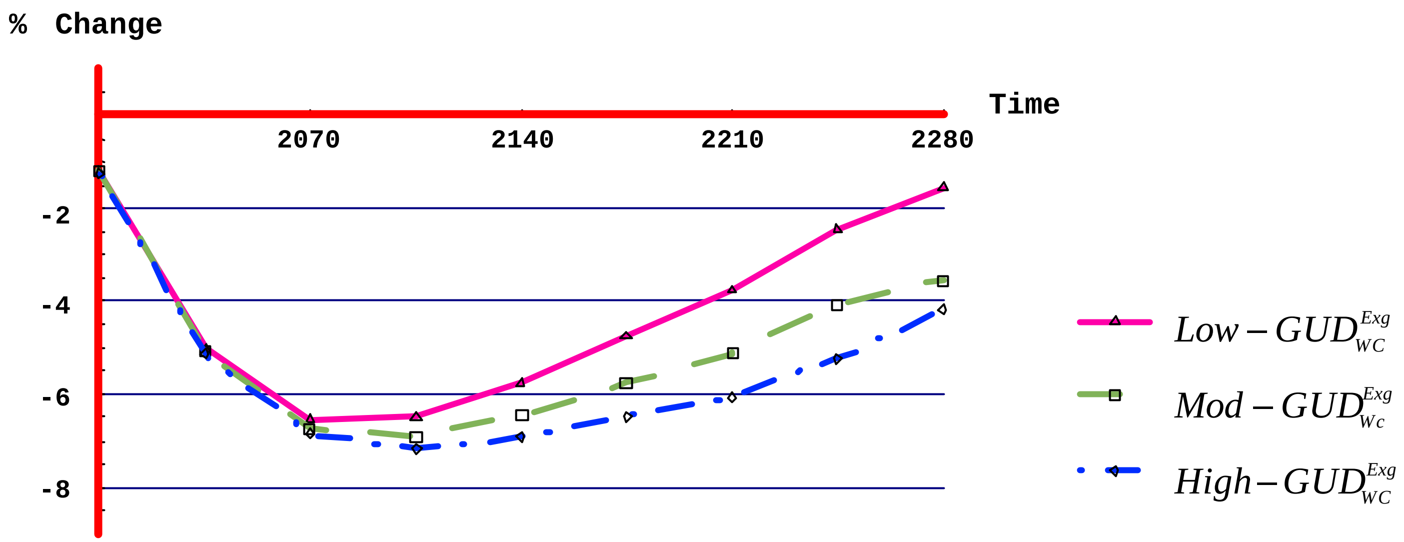


$$GUD_{WC}^{End}(t) = \left(\frac{U_d^{EndC}(t) - U_{ud}(t)}{U_{ud}(t)} \right) x100$$

This figure shows the potential consequences of the emission stabilization policy *with* endogenous abatement. The cost of control is larger when the climate change is projected to be more serious. The stabilization of the emissions has larger costs for the current and near future term generations. However, the gross cost itself does not tell the whole story about generational loss and gain since it contains both the cost and benefit aspects of stabilization.

FIGURE - 4.3

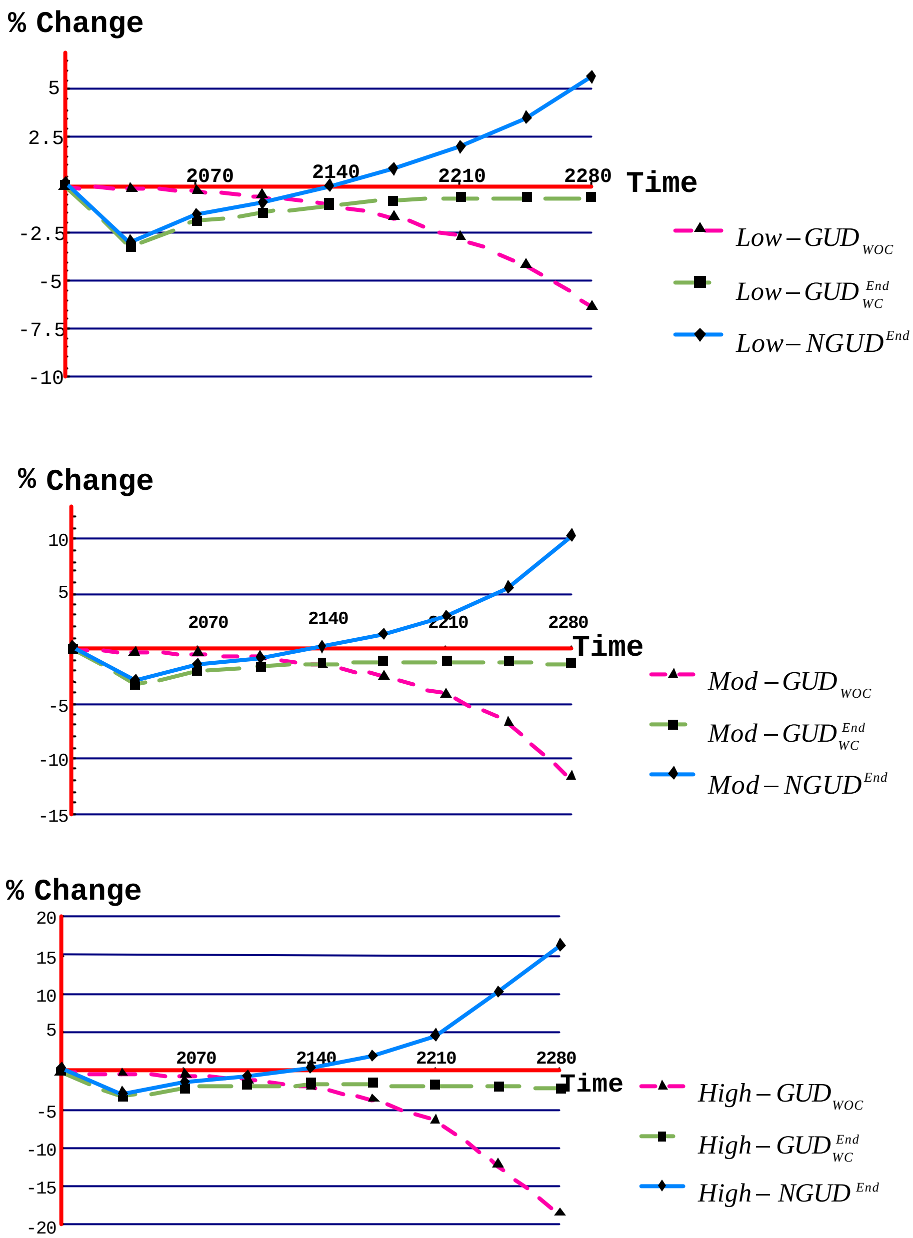
The Impact of the Control Policy ***without*** Endogenous Abatement in the Controlled Environment



$$GUD_{WC}^{Exg}(t)=\left(\frac{U_d^{ExgC}(t)-U_{ud}(t)}{U_{ud}(t)}\right)x100$$

This figure shows the potential consequences of the emission stabilization policy ***without*** endogenous abatement. The cost of control is larger when the climate change is projected to be more serious. The stabilization of the emissions has obviously larger costs for the current and near future term generations. However, the gross cost itself does not tell the whole story about generational loss and gain since it contains both the cost and benefit aspects of stabilization.

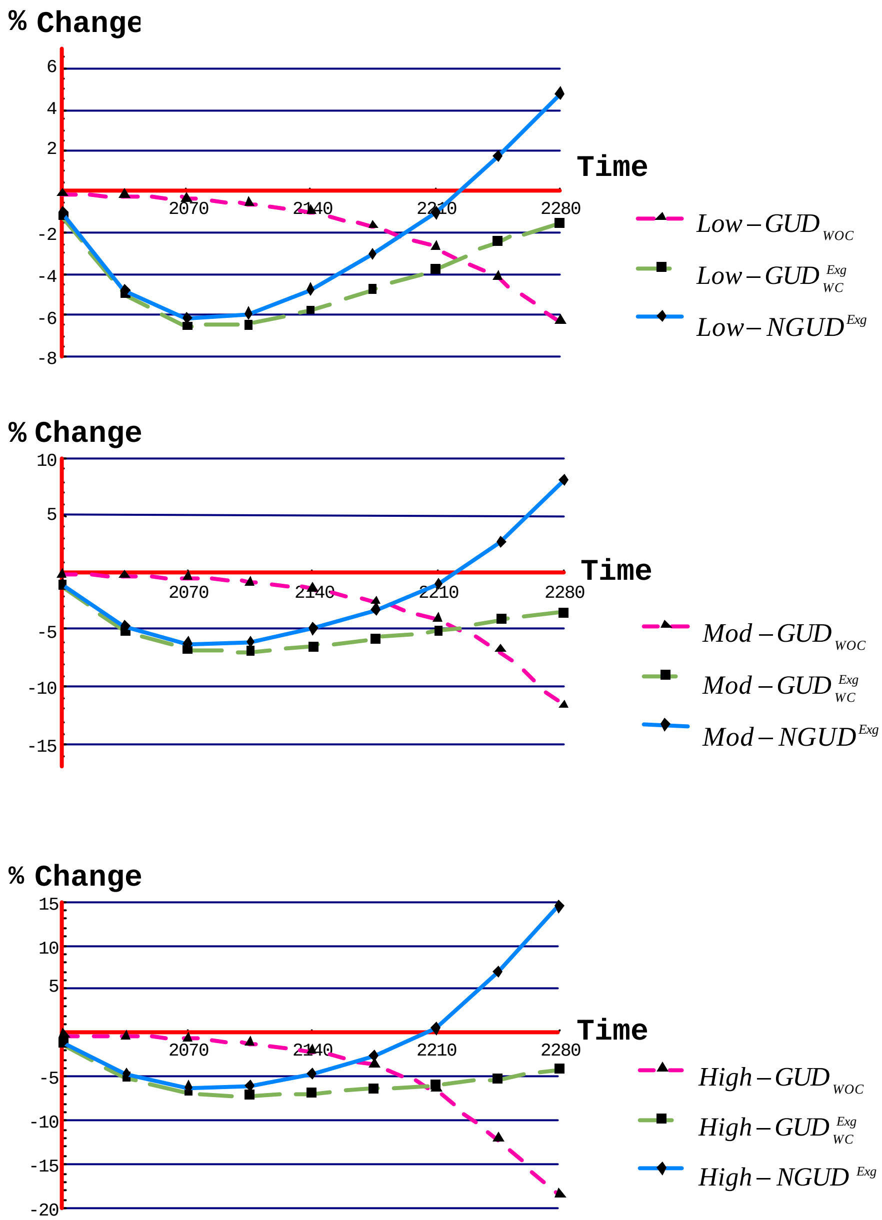
FIGURE – 4.4
The Net-Benefit from Control Policy ***with*** Endogenous Abatement



$$GUD_{WOC}(t)=\left(\frac{U_d^{uc}(t)-U_{ud}(t)}{U_{ud}(t)}\right)100\,,\; GUD_{WC}^{End}(t)=\left(\frac{U_d^{EndC}(t)-U_{ud}(t)}{U_{ud}(t)}\right)100\,,\; NGUD^{End}(t)=\left(\frac{U_d^{EndC}(t)-U_d^{uc}(t)}{U_{ud}(t)}\right)100$$

These figures show the net impact of the emission stabilization policy ***with*** endogenous abatement. The benefits of the control policy will not appear until the mid-22nd century. The generations living prior to the 22nd century will lose from the implementation of control policy.

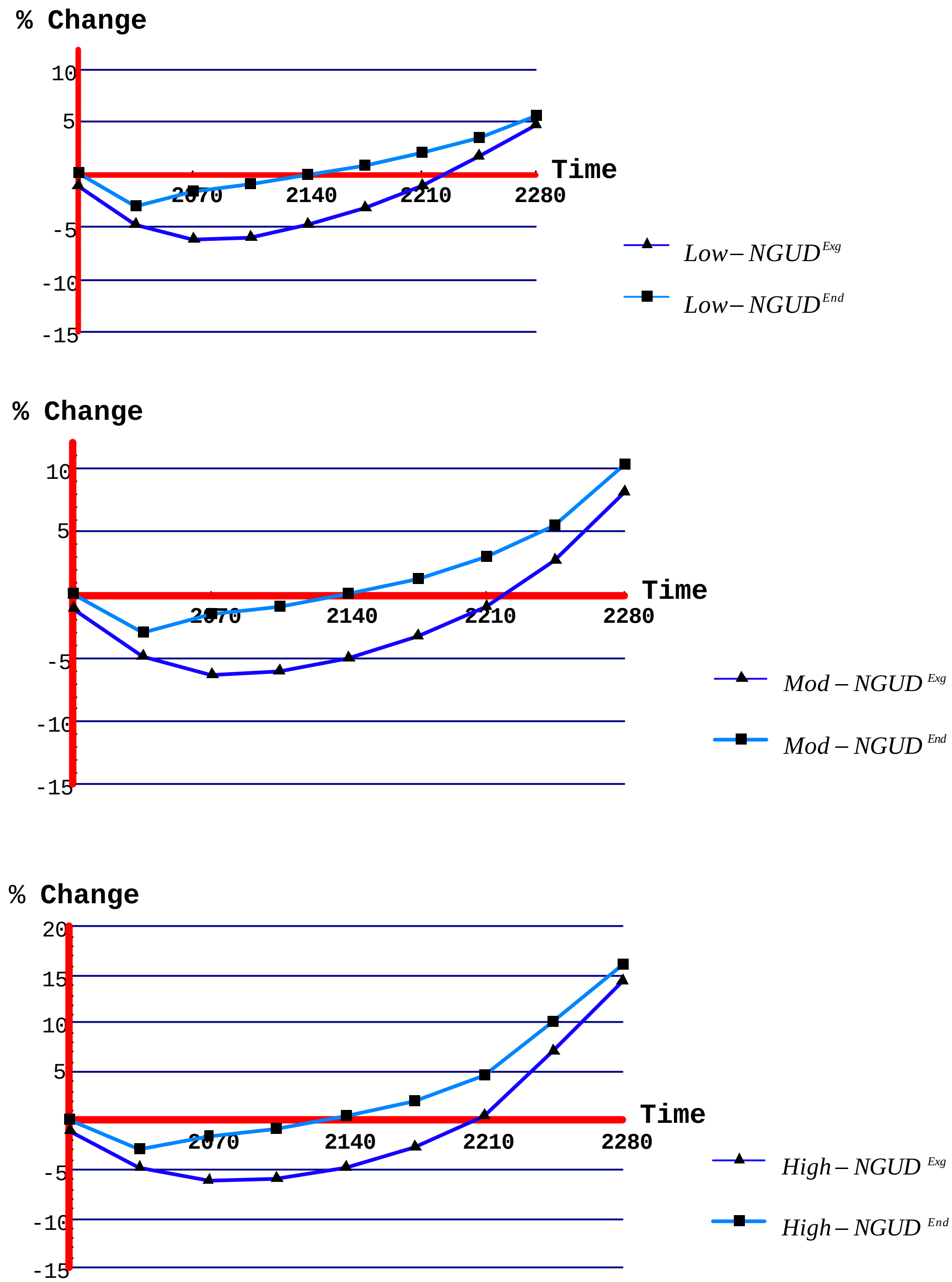
FIGURE – 4.5
The Net-Benefit from Control Policy ***without*** Endogenous Abatement



$$GUD_{WOC}(t)=\left(\frac{U_d^{uc}(t)-U_{ud}(t)}{U_{ud}(t)}\right)100\ ,\ GUD_{WC}^{Exg}(t)=\left(\frac{U_d^{ExgC}(t)-U_{ud}(t)}{U_{ud}(t)}\right)100,\ NGUD^{Exg}(t)=\left(\frac{U_d^{ExgC}(t)-U_d^{uc}(t)}{U_{ud}(t)}\right)100$$

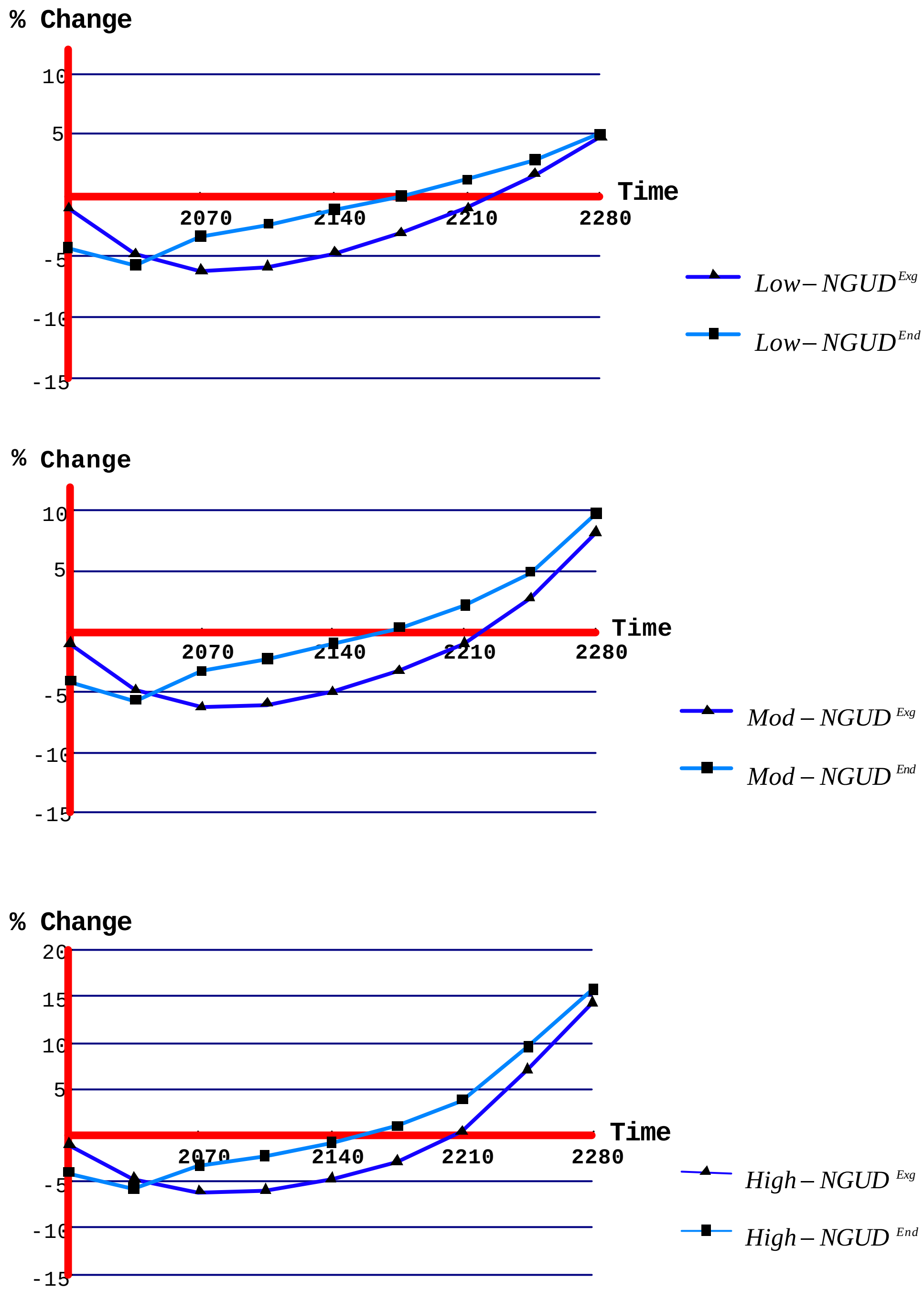
These figures show the net impact of the emission stabilization policy ***without*** endogenous abatement. The benefits of the control policy will not appear until the beginning of the 23rd century. The generations living prior to the 23rd century will lose from the implementation of control policy.

FIGURE – 4.6
Net-Benefit Comparisons in the Benchmark Abatement Productivity Case



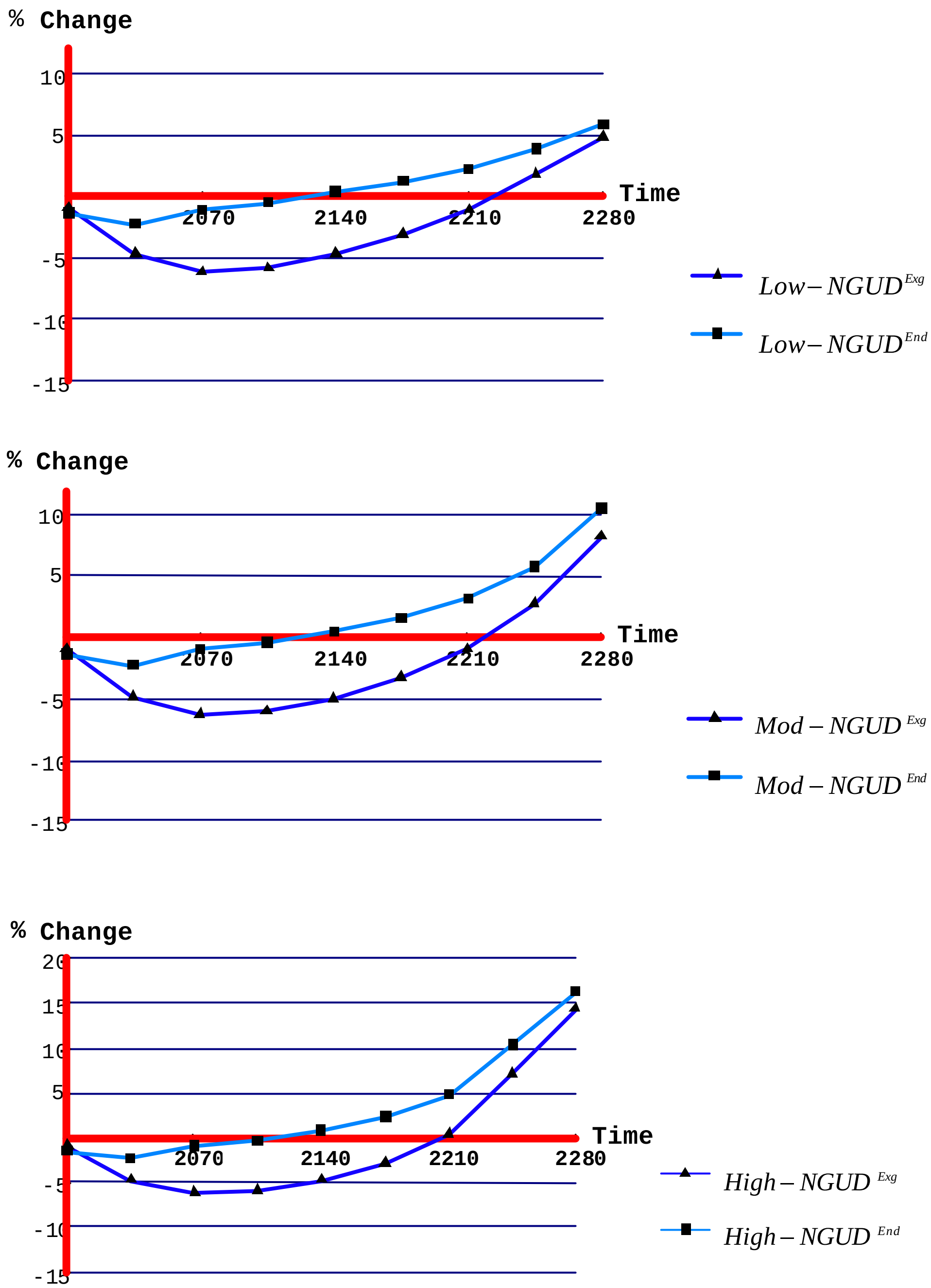
These figures show the comparisons of net benefits from the emission stabilization policy ***with*** and ***without*** endogenous abatement in the benchmark case. The net benefits are higher when the endogenous abatement is operative.

FIGURE – 4.7
Net-Benefit Comparisons in the Low Abatement Productivity Case



These figures show the comparisons of net benefits from the emission stabilization policy ***with*** and ***without*** endogenous abatement in the low productivity case.

FIGURE – 4.8
Net-Benefit Comparisons in the High Abatement Productivity Case



These figures show the comparisons of net benefits from the emission stabilization policy ***with*** and ***without*** endogenous abatement in the low productivity case.