Environment and Development Economics 12: 183–211 © 2007 Cambridge University Press
doi:10.1017/S1355770X06003469 Printed in the United Kingdom

Intergenerational cost–benefit analysis of climate change: an endogenous abatement approach*

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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 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 the potential to reduce the compliance costs with the control policy, current and near-future generations will bear some net costs. The higher the damage projected from climate change, the earlier the net benefit will arrive.

1. Introduction

A key challenge to the analysis of various dimensions of climate change and proposed control policies is the existence of considerable time lags endemic to the climate system. The results of climate change and all proposed control policies will accrue for decades and even centuries to come. Because of the long-run characteristics of the problem, it is natural to consider the distribution of costs and benefits associated with control policies over distinct generations. By pointing out the cost-saving potential of endogenous development of abatement technologies, this paper emphasizes the time scales of climate problems and studies the intergenerational welfare impacts of an emission stabilization policy.

In the economic analysis of climate change, the issue of intergenerational costs and benefits involvement has often been overshadowed by a focus on the relative efficiency of various tools and the concern about optimal policy design.[1] In order to achieve the Pareto optimal policy,

* First and foremost I would like to thank Shawn D. Knabb for his collaboration on Kavuncu and Knabb (2005) 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 their careful review and suggestions. Two referees provided constructive suggestions. Of course, all remaining errors are my own.

[1] For further discussion on intergenerational issues, see DeCanio (2003: chapter 3), Howarth (2001), IPCC (1996, chapters 4 and 6), and Portney and Weyant (1999).

https://doi.org/10.1017/S1355770X06003469 Published online by Cambridge University Press

the general methodology is the simultaneous use of a social planner and a representative agent framework within a dynamic general equilibrium setting. A hypothetical social planner maximizes a representative agent's utility function, internalizes all market imperfections, and makes the desired distributions across generations to balance the costs and benefits of a control policy. Such an approach, however, conceals the impact of control policies on each generation and blurs the distinction between allocative efficiency and distributional fairness across generations (Marini and Scaramozzino, 1995; Azar and Sterner, 1996; Chao and Peck, 2000; and Howarth, 2000).

The adverse consequences of climate change are likely to impose large uncompensated damages on future generations, while current control efforts cause present and near future generations to suffer from depressed economic activity. Clearly, the intertemporal dimensions of climate change compel us to use a more appropriate methodology to address generational welfare implications. Accordingly, this study employs a decentralized overlapping generations (OLG) model to analyze the generational welfare implications of an emission stabilization policy.

The second important feature of this study is the endogenous specification of the abatement process. The hypothesis that control policies could stimulate technological improvements is called induced innovation or induced technological change (ITC). Many researchers, such as Jaffe and Palmer (1997), Newell *et al*. (1999), and Popp (2002), warmly embrace the idea that policy prescriptions can create significant incentives for the innovation of more energy-efficient technologies and thus reduce the costs of compliance. However, the results from recent attempts of ITC modeling in climate change analysis have not eliminated all skeptical views.[2] On the one hand, Goulder and Schneider (1999), Fischer *et al.* (1998), and Nordhaus (2002) report that ITC does not significantly change the welfare gains or reduce the costs of compliance. On the other hand, Buonanno *et al*. (2003), Dowlatabadi (1998), Gerlagh and Lise (2005), Goulder and Mathai (2000), Popp (2004, 2006), and Van der Zwaan *et al.* (2002) find a good degree of potential for ITC, although the range of estimations varies considerably.

Two aspects of this study distinguish it from previous ones in terms of the methodology by which the ITC mechanism is modeled. First, the research and development (R&D) type of technological progress is used rather than disembodied knowledge accumulation such as learning by doing, which does not truly deal with the cost of creating new knowledge. This point is important because environmental R&D activities require considerable resources that could be used elsewhere in the economy. Second, this study explicitly demonstrates how the R&D process is stimulated as a result of a policy initiative, a focus of analysis that is largely missing in the literature. By assuming a hypothetical social planner who can allocate resources

[2] It should perhaps 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 the ITC-policy relationship. More comprehensive surveys of the induced innovation hypothesis can be found in Edmonds *et al.* (2000), Grübler *et al.* (2002), and Ruttan (2001).

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efficiently, previous studies suppress the two fundamental features of the ITC hypothesis: 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 properly addressed by solely relying on an unrealistic social planner assumption.

Based on the discussions of intergenerational issues and technological change, I employ a decentralized OLG model and designate the endogenous 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 of the driving forces of ITC. Within this framework, the production side of the economy is decomposed into three sectors: 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. Greenhouse gas (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 can be purchased back by firms in the final goods sector to reduce their emissions. To be able to enter the market, an abatement firm has to acquire a patent, which provides a temporary monopoly power for that 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 that prescribe new abatement goods.

It should be emphasized that the ITC characterization of the model crucially depends on the presence of a control policy. A positive emission tax is the necessary condition for the existence of ITC. 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 negative consequences of GHG emissions but also trigger the innovation and development of new abatement goods.

After the presentation of the theoretical framework, discussion from numerical simulations is provided. In order to trace generational well-being, I construct generational equivalent variation measures for different simulation scenarios. This approach allows me to map out the impacts of climate change and the control policy generation by generation. Furthermore, the use of generational equivalent variations 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 numerical exercises, I initially simulate the model without a control policy to obtain a baseline scenario where GHG emissions remain unregulated and emitting firms have no incentive to take action. Next, I consider a control policy that requires the emissions of GHG to be indefinitely fixed at the level of year 2000. When this policy is introduced, the induced abatement component of the model will be operative. However,

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the simulations of the controlled environment scenario are performed *with* and *without* endogenous abatement in order to demonstrate the significance of ITC in policy-making efforts. The results show that the omission of the rational agents' endogenous response to the existing incentives and conditions might overstate the welfare costs of implementing a control policy.

Even though ITC arguably provides the best opportunity for low-cost methods in addressing climate change, it does not imply a zero-cost or negative-cost outcome. Resources need to be deliberately allocated to environmental R&D, reflecting the education, training, and other costs that go into attracting enough human and physical capital to generate new energy-efficient technologies and abatement goods. In particular, the costs of stabilizing GHG emissions will fall greatly on the near future generations. The net benefits of the control will be accrued by generations living at least a century ahead.

Overall, the model makes a clear argument against the standard practice of cost–benefit discounting in the literature. That is, regardless of the value of the discount factor, whatever that may be, some generations will bear the net costs while others will receive the net benefits. Even though ITC has the potential to increase the political viability of a control policy, policymakers have neither the perfect information nor the necessary instruments to make the desired distributions at once across the generations 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 a limited role for government involvement and an intergenerational risk-sharing dilemma, which merits a high priority in the political economy 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

The model is based primarily on a decentralized OLG model introduced by Diamond (1965) and used by Kavuncu and Knabb (2005). Its production structure also benefits from Romer (1990). In this section, the behavior of all agents is described.

2.1. Individuals

The world is inhabited by a sequence of overlapping generations comprising a life span of two periods. At the beginning of each period, a new generation is born. This generation becomes old in the following period and dies at the end of that 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

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rate of δ_N.[3] As a result, the limiting argument for the population implies that $\lim_{t\to\infty} N_1(t) = \lim_{t\to\infty} N_2(t)$

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

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

Individual preferences are represented by a logarithmic life cycle utility function. The argument of the utility function is a homogeneous consumption good that is subject to the damage from climate change. Individuals consume $c_1(t)$ when they are young and $c_2(t+1)$ when they are old. Environmental damage denoted by $d(t)$ takes away a fraction of consumption and has a nonlinear functional form that will be discussed explicitly below.

When an individual is young, he or 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, an individual also saves $z(t)$, which is rented out to the production sector for a gross return, $R(t+1)$. At any point in time, the young and old generations might face income taxes denoted by $\tau_1(t)$ and $\tau_2(t)$, respectively. Assuming a positive time preference rate, ρ, each individual solves the following life cycle problem.

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

subject to

$$c_1(t) + z(t) = w(t)(1-\tau_1(t)) \tag{2.1.4a}$$

$$c_2(t+1) = R(t+1)(1-\tau_2(t+1))z(t) \tag{2.1.4b}$$

Under the assumption that people have perfect foresight for future economic conditions and prices, the solution to the individual's problem generates the following consumption and savings rule for each generation

$$\frac{c_2(t+1)}{c_1(t)} = \frac{R(t+1)(1-\tau_2(t+1))}{1+\rho} \tag{2.1.5}$$

$$z(t) = \left(\frac{1}{2+\rho}\right)[w(t)(1-\tau_1(t))] \tag{2.1.6}$$

2.2. Production

Based on Romer's (1990) variety-extension model, the production side consists of three sectors. The first sector produces final goods that can either be consumed or converted into physical capital stock or used for the production of abatement goods. The second sector buys inputs from the final goods sector and instantaneously converts them into abatement

[3] All growth and depreciation rates are in generational frequencies covering 35 years.

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goods using a linear technology. Abatement products are purchased back by firms in the final goods sector in order to reduce emissions. The third sector performs R&D and generates blueprints[4] for the development of new abatement goods.

2.2.1 Final goods sector

An arbitrary large number of competitive firms combine labor, $N_{1F}(t)$, and capital, $K(t)$, to produce a homogenous good, $Y(t)$. Each firm has an equal access to the Cobb–Douglas production function with a productivity, $B(t)$, and capital share $\gamma \in (0,1)$

$$Y(t) = B(t)N_{1F}(t)^{1-\gamma}K(t)^{\gamma} \tag{2.2.1}$$

The behavior of $B(t)$ over time is determined by the technological growth rate, g_B.

$$B(t) = B(t-1)(1+g_B) \tag{2.2.2}$$

GHG emissions arise as negative externalities in the production process of final goods.[5] The relationship between emissions and production is governed by the carbon intensity variable, $\sigma(t)$. Because this variable is equivalent to emissions per unit of gross output, it is also called the GHG emissions–output ratio. Production without abatement generates the following amount of GHG emissions

$$E_U(t) = \sigma(t)Y(t) \tag{2.2.3}$$

Similar to previous studies, I assume that $\sigma(t)$ decreases slowly at the historical rate, $g_\sigma(t)$, which is called natural decarbonization. For instance, Newell *et al.* (1999) demonstrate in their empirical study that only one-fifth to two-fifths of efficiency improvements were induced by changes in energy prices. Because some proportion of innovation seems to be independent of energy prices and regulations, all simulations in this study are also carried out with the assumption of gradually declining $\sigma(t)$. However, the decarbonization rate slows down over time at the rate δ_σ in accordance with empirical evidence (Nakicenovic *et al.*, 1995; Nakicenovic *et al.*, 1998)

$$\sigma(t) = \sigma(t-1)(1+g_\sigma(t)) \tag{2.2.4}$$

$$g_\sigma(t) = g_\sigma(t-1)(1-\delta_\sigma) \tag{2.2.5}$$

The decline in $\sigma(t)$ is due to natural carbon sinks, autonomous energy efficiency improvements (AEEI), and organizational enhancements within firms (Krause *et al.*, 2002 and 2003; Popp, 2002). More specifically, the decline of $\sigma(t)$ comprises all reductions in carbon and energy intensity that are not induced by relative price changes.[6]

[4] A blueprint is a set of descriptions and know-how showing how to combine raw materials (in the form of final goods) to produce abatement goods.

[5] Since CO_2 is more responsible than any other GHG for the greenhouse impact, I employ the term 'GHG' throughout the paper to represent the anthropogenic emissions of CO_2.

[6] Kelly and Kolstad (1999: 189) indicate that the CO_2 intensity of output has fallen worldwide from 0.409 tons of carbon per thousand dollars of output in 1929 to

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Competitive firms fail to internalize the negative effects of GHG emissions when there is no regulation. Thus, the government might require them to pay an emission tax, $\tau_E(t)$, to correct for this market failure and cause the relative price of emission to change. The emission tax alters the optimizing behavior of firms in the final goods sector and forces them to internalize some or potentially all of the externalities they create. Firms can ease the tax burden by purchasing abatement goods such as scrubbers, purifiers, filters, or new techniques that lead to reductions in emissions.[7] At any point in time, total abatement, $AB(t)$, is limited to the set of successfully designed blueprints up to date t. By denoting available abatement goods as $A(t)$ and the abatement good of type i as $X(t)$ at time t, abatement technology is defined as follows

$$AB(t) = \Psi \sum_{i=1}^{A(t)} X(i,t)^{\alpha} \tag{2.2.6}$$

where the parameter $\alpha \in (0,1)$ represents each abatement good's share in total abatement. The shift parameter, Ψ, represents the overall productivity of abatement technology. If $\Psi = 0$, abatement technology is not feasible.

Newly designed and commercialized abatement goods have one-period patent protection. Therefore, the producers of each abatement good enjoy monopoly power for one period. Once the patent protection expires, the monopolistic abatement good becomes a competitive good and the blueprint for this abatement good becomes available for any producer who wants to get into the market. Even though the transition from a monopolistic market to competitive market is assumed to be smooth, this may not always prove correct. If there are substantially high costs associated with operation of the blueprint of an abatement good, then the presence of perfect competition after the patent protection period may not necessarily be the case. That is, the appropriate use of technologically complex blueprints might require some additional resources and imitation costs. When these imitation costs are very high, there is a possibility that imperfect market conditions might continue even after the patent protection expires.[8]

0.232 tons of carbon per thousand in 1989. The same trend is emphasized by the IPCC-Mitigation report (2001: 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.

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

[8] I would like to thank a referee for pointing out this issue. The referee appropriately identified the problem of costly imitation and the questionability of assuming perfect competition when patent protection expires. In principle, I share the referee's view that abatement firms desiring to produce the abatement good that no longer has patent protection might incur some costs to figure out the formulation in the blueprint. However, an attempt to incorporate additional imitation costs will not contribute to this paper's main theme, which is highlighting the importance of a government policy to control climate change and the endogenous response of rational agents to this policy. This point is also recognized by the referee. Thus,

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One way to address the issue of costs regarding the deciphering of blueprints is to assume permanent patent protection. However, patents create monopolies and lead to waste of resources as a result of static inefficiencies. Thus, it is generally accepted that patents should continue just long enough so that monopoly profits can repay the costs of development of the invention. There should be an optimal term for patents, though in practice it would be very difficult to figure out what that optimal term should be. The administration of an optimal patent system is an issue that is still being vigorously debated at both theoretical and empirical levels.[9] As there is no consensus in the literature on how to deal with optimal term, imperfect patent protection, and the imitation problem, I assume that firms in the abatement goods sector have only one period of full protection from competition to keep the framework tractable. As a matter of fact, this is not a far-fetched assumption since one period in the model involves 35 years. Considering technological advancements, it should not be prohibitively costly for newly entering firms to decipher a blueprint whose creation goes back 35 years. In addition, I should highlight that production of actual abatement goods is always costly, whether before or after the patent protection expires. Neither initial creation of a blueprint nor the actual production of an abatement firm comes out of thin air as discussed below.

Patented (or monopolized) abatement goods, $i \in (A(t-1), A(t)]$, are those which are invented in the current period. All others, $i \in [1, A(t-1)]$, are competitive abatement goods. Overall, the flow of net emissions after abatement is described as follows

$$E(t) = \sigma(t)Y(t) - \Psi \sum_{i=1}^{A(t)} X(i,t)^{\alpha}$$

$$E(t) = \sigma(t)Y(t) - \left[\Psi \sum_{i=A(t-1)+1}^{A(t)} X_M(i,t)^{\alpha} + \Psi \sum_{j=1}^{A(t-1)} X_C(j,t)^{\alpha} \right] \tag{2.2.7}$$

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

$$\begin{aligned} max \prod_F = {} & B(t)N_{1F}(t)^{1-\gamma}K(t)^{\gamma} - w_F(t)N_{1F}(t) - Rent(t)K(t) \\ & - AC(t) - \tau_E(t)E(t) \end{aligned} \tag{2.2.8}$$

where $AC(t)$ is total abatement costs at time t.

the implications of imperfect patent protection and the results of costly imitations are suitably deferred to future research.

[9] Gallini (2002) provides an excellent discussion of the effectiveness of patent protection and the recent patent reforms in the United States.

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$$AC(t) = \sum_{i=A(t-1)+1}^{A(t)} P(i,t)[1 - s_a(t)]X_M(i,t) + \sum_{j=1}^{A(t-1)} X_C(j,t) \tag{2.2.9}$$

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

Let the term $\vartheta(t) = [1 - \mu(t)]$ be the effective tax wedge and $\mu(t) = \tau_E(t)\sigma(t)$ be the standard control rate. Because of the 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

$$N_{1F}(t) : (1-\gamma)\vartheta(t)B(t)N_{1F}(t)^{-\gamma}K(t)^{\gamma} - w_F(t) = 0 \tag{2.2.10a}$$

$$K(t) : \ \gamma\vartheta(t)B(t)N_{1F}(t)^{1-\gamma}K(t)^{\gamma-1} - Rent(t) = 0 \tag{2.2.10b}$$

$$X_M(i,t) : \ -P(i,t)[1 - s_a(i,t)] + \alpha\tau_E(t)\Psi X_M(i,t)^{\alpha-1} = 0 \tag{2.2.10c}$$

$$X_C(j,t) : \ -1 + \alpha\tau_E(t)\Psi X_C(j,t)^{\alpha-1} = 0 \tag{2.2.10d}$$

It is clear from the first-order conditions that capital and labor receive higher returns when there is no attempt to control GHG emissions. The derived demand functions for the type i of patented abatement good and the type j of competitive abatement good are obtained from equations (2.2.10c) and (2.2.10d), respectively

$$X_M(i,t) = \left[\frac{\Psi\alpha\tau_E(t)}{P(i,t)[1 - s_a(i,t)]}\right]^{\frac{1}{1-\alpha}} \tag{2.2.11a}$$

$$X_C(j,t) = [\Psi\alpha\tau_E(t)]^{\frac{1}{1-\alpha}} \tag{2.2.11b}$$

In order for GHG-generating firms 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 purchase abatement goods as long as a positive emission tax is imposed at least between some time intervals. This is the crucial part of the model, in the sense that endogenous abatement occurs if the government implements a control policy.

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. After obtaining a blueprint formulated by an R&D firm, an abatement firm purchases inputs from the final goods sector and converts one flow unit of the final good into one flow unit of the abatement good. Abatement goods are immediately available for the firms in the final goods sector to

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reduce their emissions. Once an abatement firm purchases a blueprint with patent protection, it becomes the monopoly supplier of the most recently invented abatement good and receives monopoly rents for one period. After incurring the fixed cost (i.e., purchasing a patent), a monopolistic abatement firm maximizes the following profit function

$$max \prod_{M}(i,t) = P(i,t)X_M(i,t) - X_M(i,t) \tag{2.2.12}$$

Substituting the derived demand function for $X_M(i,t)$, as shown by equation (2.2.11a), 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

$$P(i,t) = \frac{1}{\alpha} > 1 \quad \forall i \in (A(t-1), A(t)] \tag{2.2.13}$$

Therefore, the monopoly price is constant over time across all patented abatement goods, $i \in (A(t-1), A(t)]$. Placing the constant mark-up price into equation (2.2.11a) leads to the demand function for the patented abatement good. Because the solution is symmetric for all abatement firms, it is possible to ignore the index i marking different abatement firms

$$X_M(i,t) = X_M(t) = \left[\frac{\Psi\alpha^2\tau_E(t)}{[1-s_a(t)]}\right]^{\frac{1}{1-\alpha}} \quad \forall i \in (A(t-1), A(t)] \tag{2.2.14}$$

It is worthwhile for an abatement firm to buy the blueprint of a new abatement good if the present value of monopoly profits sufficiently covers its purchase cost. Because the market structure is monopolistic competition with free entry, the arbitrage condition implies that the present value of monopoly profits should equal the value of the patent.

$$\textit{Value of Patent} = V_A(t) = \prod_{M}(t) = \left(\frac{1-\alpha}{\alpha}\right)\left[\frac{\Psi\alpha^2\tau_E(t)}{[1-s_a(t)]}\right]^{\frac{1}{1-\alpha}} \tag{2.2.15}$$

It is important to recognize that the demand function of abatement goods is inexorably linked to the emission tax, $\tau_E(t)$. Without a positive emission tax, firms in the final goods sector do not demand abatement goods. The lack of demand for abatement goods results in zero profit in the abatement goods sector and a value of zero for the patent. The implementation of a control policy is therefore an indispensable part of the ITC formulation. This point distinguishes the current model from previous induced innovation models since it explicitly shows where the inducement for new technologies and inventions comes from.

As previously discussed, the monopoly power due to patent protection lasts only one period. When the patent expires, an abatement good becomes competitive and available at the competitive price of one, which is its marginal cost. A competitive abatement firm also solves the profit maximization problem

$$max \prod_{C}(i,t) = P_C(i,t)X_C(i,t) - X_C(i,t) \tag{2.2.16}$$

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The competitive market assumption entails zero profit, which implies that $P_C(i,t) = 1$. Using equation (2.2.11b), the demand function for any competitive abatement is as follows

$$X_C(i,t) = X_C(t) = [\Psi \alpha \tau_E(t)]^{\frac{1}{1-\alpha}} \quad \forall i \in [1, A(t-1)] \tag{2.2.17}$$

Notice that the same discussion regarding the necessity of an emission tax for the presence of ITC also applies for competitive abatement goods.

2.2.3 R&D sector

The R&D sector consists of an arbitrarily large number of competitive firms that employ an effective labor force, $H_R(t) = \tilde{B}(t)N_{1R}(t)$, to develop designs for new abatement goods.[10] The inventing R&D firm obtains a patent from the government and then sells this right to an abatement firm for price $V_A(t)$. A blueprint can be invented, sold, and used in the same period. The newest technology is indexed as $A(t)$. The development of new designs is such that

$$\begin{aligned} A(t) &= A(t-1) + \psi H_R(t) \\ \Delta A(t) &= \psi H_R(t) \end{aligned} \tag{2.2.18}$$

where ψ is the shift or productivity parameter.[11]

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

$$max \prod_R(t) = V_A(t)\Delta A(t) - w_R(t)H_R(t) \tag{2.2.19}$$

Because the market structure is perfectly competitive, zero profit prevails. As discussed before, the equilibrium condition requires the price of the patent to simply be 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 the patent multiplied by the marginal product of labor) equals the marginal cost of this additional unit of labor

$$N_{1R}(t) : \psi V_A(t) - w_R(t) = 0 \tag{2.2.20}$$

Substituting equation (2.2.15) into the last equation gives the wage rate in the R&D sector

$$w_R(t) = \psi \tilde{B}(t) \left(\frac{1-\alpha}{\alpha}\right) \left[\frac{\Psi \alpha^2 \tau_E(t)}{[1 - s_a(t)]}\right]^{\frac{1}{1-\alpha}} \tag{2.2.21}$$

This last equation shows that the returns to labor in the R&D sector depend on the existence of an emission tax. If government does not impose

[10] The labor augmenting productivity is obtained from the Hicks neutral productivity; $\tilde{B}(t) = [B(t)]^{1/1-\gamma}$.

[11] Although the description of the R&D process here is admittedly very simple, the real-world process is highly uncertain and so complex that no current model perfectly describes R&D activities.

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an emission tax, the return to the R&D labor becomes zero, and no R&D takes place.

2.3 Government

The role of government is to stick to the basics. Foremost, 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, government should also use proper institutions for environmental protection and for the innovation of abatement goods. Environmental monitoring by government must be adequately credible so that a control policy can be effective. Finally, government is assumed to operate a balanced budget

$$G(t) + \sum_{i=A(t-1)+1}^{A(t)} P(i,t)[s_a(i,t)]X_M(i,t) = \tau_I(t)N_1(t)w_I(t) + \tau_R(t)N_2(t)R(t)z(t-1) + \tau_E(t)E(t) \quad (2.3.1)$$

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 $\frac{1}{\alpha}$ of marginal cost, the subsidy rate must also be a constant, $s_a(i,t) = s_a = 1 - \alpha$. It is assumed that government expenditures, $G(t)$, and the tax rate on the young generation's income, $\tau_1(t)$, equal zero for all periods to avoid further complexity in the analysis.[12] Using the equilibrium conditions, the government budget constraint can be rewritten as follows

$$\Delta A(t)\left(\frac{s_a}{\alpha}\right)X_M(t) = \tau_R(t)N_2(t)R(t)z(t-1) + \tau_E(t)E(t) \quad (2.3.2)$$

Solving the last equation for $\tau_2(t)$ gives us the tax rate on the second period's income

$$\tau_2(t) = \frac{1}{N_2(t)R(t)z(t-1)}\left[\Delta A(t)\left(\frac{s_a}{\alpha}\right)X_M(t) - \tau_E(t)E(t)\right] \quad (2.3.3)$$

2.4 Market clearing conditions

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

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

[12] Assuming that $G(t) = \tau_1(t) = 0$ 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.

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

$$w_F(t) = w_R(t) = w^*(t)$$

$$(1-\gamma)\vartheta(t)B(t)N_{1F}(t)^{-\gamma}K(t)^{\gamma} = \psi\tilde{B}(t)\left(\frac{1-\alpha}{\alpha}\right)\left[\frac{\Psi\alpha^2\tau_E(t)}{[1-s_a]}\right]^{\frac{1}{1-\alpha}} \tag{2.4.2}$$

Solving the last equation for $N_{1F}(t)$ gives us the equilibrium level of employment in the final goods sector when there is a control policy

$$N^*_{1F}(t) = \left[\frac{(1-\gamma)\vartheta^*(t)}{\psi\left(\frac{1-\alpha}{\alpha}\right)\left[\frac{\Psi\alpha^2\tau^*_E(t)}{[1-s_a(t)]}\right]^{\frac{1}{1-\alpha}}}\right]^{\frac{1}{\gamma}}\frac{K(t)}{\tilde{B}(t)} \tag{2.4.3}$$

Using the labor market clearing equation and equation (2.4.3), the equilibrium level of employment in the R&D sector, $N_{1R}(t)$, can also be calculated. Notice that γ, ψ, α, and Ψ are exogenous parametric values. Variables $K(t)$, $\tilde{B}(t)$, $\sigma(t)$, and s_a are predetermined variables at time t. Once we determine the emission tax, $\tau^*_E(t)$, we can then specify the allocation of the labor force across sectors for a given tax-wedge, $\vartheta^*(t) = [1-\tau^*_E(t)\sigma(t)]$. The method of finding $\tau^*_E(t)$ will be discussed in the next section.

The 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 aggregate capital dynamics is such that

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

The gross return to capital is $R^*(t) = 1 + r^*(t)$, where $r^*(t) = Rent\,(t) - \delta_K$. Thus, total payments to the capital stock can be obtained from equation (2.2.10b)

$$R^*(t)K(t) = \gamma\vartheta^*(t)Y^*(t) + (1-\delta_K)K^*(t) \tag{2.4.5}$$

The young generation's consumption profile in period t is

$$C^*_1(t) = N_1(t)c^*_1(t) = N_1(t)w^*(t) - N_1(t)z^*(t)$$

$$C^*_1(t) = N_1(t)c^*_1(t) = \left(\frac{1+\rho}{2+\rho}\right)[(1-\gamma)\vartheta^*(t)Y^*(t)] \tag{2.4.6}$$

The old generation's consumption in period t can be found from equation (2.1.4b), which is $C^*_2(t) = N_2(t)c^*_2(t) = [1-\tau_2(t)]\,R^*(t)K^*(t)$. Finally, using equations (2.3.1) and (2.4.5), we can determine $C^*_2(t)$

$$C^*_2(t) = \gamma\vartheta^*(t) = Y^*(t) + (1-\delta_K)K^*(t) - \Delta A(t)\left(\frac{s_a}{\alpha}\right)X_M(t) + \tau^*_E(t)E(t) \tag{2.4.7}$$

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

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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.[13] Nonetheless, this approach strips away unnecessary details and suffices to shed light on the issues that this paper focuses on. To be consistent with the existing literature, I accept that the time path of GHG emissions determines future climate conditions. The constant marginal atmospheric retention parameter, β, determines the amount of GHG that stays in the atmosphere over the long run. The effective concentration of GHG in the atmosphere denoted by $M(t)$ is measured in billion tons of carbon equivalent. The pre-industrial stock of $M(t)$ is taken to be 590 billions of tons of carbon equivalent, as generally accepted in previous studies. The stock of GHG in excess of the pre-industrial norm is dissipated by the constant fraction of δ_M as this stock diffuses into the deep ocean and other carbon sinks. Overall, $M(t)$ is governed by a first-order difference equation

$$M(t+1) = 590 + (1-\delta_M)(M(t) - 590) + \beta E(t) \tag{3.1.1}$$

The functional relationship between GHG emissions and environmental quality is expressed in terms of ground, $T(t)$, and oceanic, $O(t)$, temperature changes. The increase above mean ground temperature is a proxy or an index for the impacts on the global climate change.[14] In particular, the ground temperature is a nonlinear function of GHG concentration. As climatologists frequently state, this non-linear relation is approximately logarithmic

$$T(t+1) = T(t) + \lambda_1 Ln\left[\frac{M(t)}{590}\right] + \lambda_2 T(t) + \lambda_3 O(t) \tag{3.1.2}$$

where λ_1 is the nonlinear effect of GHG stock, λ_2 is general atmospheric cooling, and λ_3 is the effect of the deep ocean functioning as a carbon sink on temperature. 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

$$O(t+1) = O(t) + \lambda_4(T(t) - O(t)) \tag{3.1.3}$$

The final step is to translate climate change into the actual environmental damage that consequently harms the individuals' well-being. Following Kolstad (1996), I assume that the damage rises with increases in the mean of atmospheric temperature[15]

$$d(t) = \Phi\left[\frac{\theta_1 T(t)^{\theta_2}}{[1+\theta_1 T(t)^{\theta_2}]}\right] \tag{3.1.4}$$

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

[14] Using the standard approach in the literature, I approximate climate change and environmental deterioration through observing the change in the mean level of ground atmospheric temperature measured in Celsius degrees.

[15] The damage function here approximates the one employed by Kolstad (1996), which specifies the individual utility function in a Ramsey-type representative

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where θ_1, θ_2, and Φ are three important parameters in the damage function. While θ_1 indicates the scale effect of the temperature, θ_2 captures the nonlinear impact of climate change. Because there are many uncertainties about the extent to which 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 used to capture the severity of damage from climate change. Φ is assumed to take three values corresponding to minor, moderate, or major problems from climate change.[16] Any value of the scale parameter above the high damage value results in catastrophic consequences of climate change, which is a possibility recently receiving some attention.

4. Numerical simulations

In this section, the response of the decentralized market economy to a control policy is examined by numerically simulating the model. Before discussing the results from the simulations, a natural caveat is in order. Endogenous growth theories are still in flux. To date, there are few computable models of existing endogenous growth theories. Likewise, it is no secret that many climate models still suffer from large-scale uncertainties (DeCanio, 2003; Tol, 2005). Therefore, the primary objective in this section is to achieve some qualitative propositions regarding the intergenerational aspects of climate change rather than merely presenting quantitative outcomes. The benchmark parameters and initial conditions are provided in the appendix.

Standard integrated assessment models attempt to compare all costs and benefits in terms of monetary units. Because of highly conjectural modeling, monetized consumption values (the primary welfare and policy effectiveness measures in the existing literature) have raised some disputes on the reliability of the reports from climate change studies (Repetto, 1997; Nordhaus, 1998; Roughgarden and Schneider, 1999; Howarth, 2001). A decision analysis based on monetary labeling has some meaning if the range of physical, biological, and social outcomes is completely quantifiable (IPCC, 1996: 62–65). Not every impact from climate change (especially those related to biodiversity, human health, and social amenities) can be easily identified using monetary units. Thus, expressing total impacts in monetary terms does not satisfactorily address the comparison of the impacts of climate change and control policies.

To be able to more carefully assess the actual costs and benefits of the control policy across generations, I construct generational-equivalent variation measures which are unit-free demonstrations of the cost–benefit projections. This method better illustrates the well-being of successive but disconnected generations rather than placing some vague monetary labels on the costs and benefits of different policies. The term designated for the equivalent variation is the generational utility deviation (*GUD*), which

agent framework as follows: $U = Log[c(t) - \Delta d(t)]$ where the damage $d(t) = \frac{\theta_1 T(t)^{\theta_2} Y(t)}{[1+\theta_1 T(t)^{\theta_2}]N(t)}$ with the same characterization in this study.

[16] The specifications of Φ lie within the range of those assumed in Kolstad (1996).

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captures the fractional loss or gain in generational welfare in different cases. To construct equivalent measures, I use three versions of *generational utility*, which will be discussed below.

There are two main scenarios: the uncontrolled environment without any regulation and a controlled environment with emissions stabilization at the level of year 2000. Furthermore, I consider the controlled case *with* and *without* endogenous abatement so that the importance of induced innovation can be assessed.

4.1 Uncontrolled environment

In order to set up a benchmark case, I first consider the generational utility, $U_{nd}(t)$, assuming that there is no damage from climate change and no requirement for control. The subscript '*nd*' indicates that the per capita consumption is free of damage. To reduce the notational complexity, I omit the star superscript on consumption functions, indicating optimized values. Thus, young and old period consumption functions in all generational utilities should be understood as they are shown in equations (2.4.6) and (2.4.7).

$$U_{nd}(t) = Log[c_1(t)] + \left(\frac{1}{1+\rho}\right) Log[c_2(t+1)] \tag{4.1.1}$$

Once we incorporate damage from climate change *without* any attempt to control, we will have the second version of generational utility, $U_d^{uc}(t)$. While the subscript '*d*' indicates per capita consumption impaired as a result of damage, the superscript '*uc*' points out that the generational utility is associated with the uncontrolled scenario

$$U_d^{uc}(t) = Log\left[c_1^{uc}(t)(1-d(t))\right] + \left(\frac{1}{1+\rho}\right) Log\left[c_2^{uc}(t+1)(1-d(t+1))\right] \tag{4.1.2}$$

Based on equations (4.1.1) and (4.1.2), we can now construct the metric to determine the effects of climate change on generational well-being when there is no policy initiative

$$GUD_{WOC}(t) = \left(\frac{U_d^{uc}(t) - U_{nd}(t)}{U_{nd}(t)}\right) 100 \tag{4.1.3}$$

$GUD_{WOC}(t)$ measures the percentage of generational welfare loss within generational frequency when the environment takes its course without control. Figure 4.1 based on $GUD_{WOC}(t)$ illustrates the adverse effects of climate change under three damage scenarios. The costs of damage range from loss of 0.12 per cent to 2.30 per cent generational income in the short term. These numbers will climb to levels as high as 7 per cent for the minor damage scenario, 13 per cent for the moderate damage scenario, and 19 per cent for the major damage scenario in the long run.

Figure 4.1 also sheds some light on a general conclusion of many previous studies focusing exclusively on the Pareto optimal policy. When considering only the next 150 years, it is clear that there is no need to apply aggressive control policies. The costs of very stringent control policies in the near future are too great in exchange for modest benefits – a standard conclusion in the

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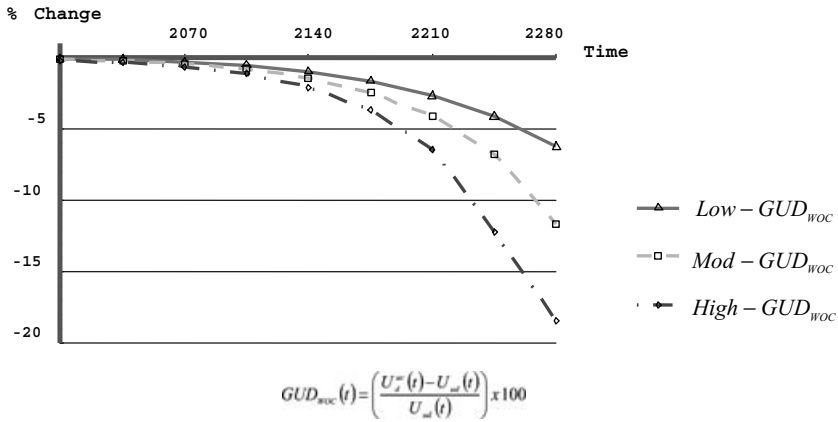


Figure 4.1. *The impact of climate change in the uncontrolled environment*
Note: This figure shows the loss in generational well-being under the three different damage scenarios. Environmental damage resulting from climate change for the next 150 years will not be as serious as that of subsequent periods.

literature. However, this argument is valid for the time horizon (such as 150 or 200 years) that most previous studies have considered. Therefore, it is not surprising to see reports of low emission tax rates and non-aggressive control policies targeted towards the achievement of efficiency. Once we stretch the time horizon beyond 200 years, the adverse effects of unchecked climate become more severe. In the long run, irreversible damage might reach a point where human life becomes highly vulnerable. In this situation, even improved life standards from the conventional growth process could not negate the catastrophic consequences of climate change.

4.2. Controlled environment

Given the implications of the uncontrolled scenario, the next step is to analyze the effects of a control policy and evaluate the implications of ITC. The motivation for the control policy is to reduce the negative impacts of climate change. The policy under consideration is a reflection of the Kyoto Protocol.[17] Even though it is not easy to agree on a common course of actions and to expect utter 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. Recognizing the challenges surrounding compliance, I assume that the binding standards ordain a stabilization of GHG emissions at the year 2000 level for all remaining periods.

The critical point in this scenario is to analyze the impact of induced innovation on generational well-being. For this purpose, I simulate the model *with* and *without* endogenous abatement to understand the relative importance of the induced innovation component in projecting cost

[17] The full text and some satisfactory discussion of the Kyoto Protocol can be found at http://unfccc.int/resource/docs/convkp/kpeng.html.

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estimates. In order to solve the recursive structure of the system when endogenous abatement is the functional emission tax, $\tau_E(t)$ needs to be numerically obtained from equation (2.2.7), which is the net emissions after abatement. Once we obtain the emission tax rate, we can determine the remaining variables in the model, including per capita consumption and generational welfare

$$\overline{E} = \sigma(t)\left[\frac{(1-\gamma)[1-\tau_E^*(t)\sigma(t)]}{\psi\left(\frac{1-\alpha}{\alpha}\right)\left[\frac{\Psi\alpha^2\tau_E^*(t)}{1-s_a}\right]^{\frac{1}{1-\alpha}}}\right]^{\frac{1-\gamma}{\gamma}} K^*(t)$$

$$-\Psi\left[A(t-1)\left[\Psi\alpha^2\tau_E^*(t)\right]^{\frac{\alpha}{1-\alpha}} - \psi\xi^*(t)\left[\frac{\Psi\alpha^2\tau_E^*(t)}{1-s_a}\right]^{\frac{\alpha}{1-\alpha}}\right] \quad (4.2.1)$$

where

$$\xi^*(t) = \tilde{B}(t)N_1(t) - \left[\frac{(1-\gamma)[1-\tau_E^*(t)\,\sigma(t)]}{\psi\left(\frac{1-\alpha}{\alpha}\right)\left[\frac{\Psi\alpha^2\tau_E^*(t)}{1-s_a}\right]^{\frac{1}{1-\alpha}}}\right]^{\frac{1}{\gamma}} K^*(t)$$

If we assume that ITC is not operative (i.e.,$\Psi = 0$), then the control policy can only be implemented by depressing capital stock accumulation. Again using equation (2.2.7) with the hypothetical assumption$\Psi = 0$, the control policy entails capital dynamics to be determined according to the emissions target[18]

$$\hat{K}(t) = \left[\frac{\overline{E}}{\sigma(t)B(t)[N_1(t)]^{1-\gamma}}\right]^{\frac{1}{\gamma}} \quad (4.2.2)$$

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

$$\hat{\tau}_E(t) = \frac{1}{\sigma(t)} - \frac{\hat{K}(t+1)}{\left(\frac{1-\gamma}{2+\rho}\right)\sigma(t)Y(t)}$$

In order to analyze the effects of control policy, we first need to consider the generational utility definition for this scenario, $U_d^c(t)$. While the subscript 'd' indicates that per capita consumption is impaired as a result of damage, the superscript 'c' points out that the generational utility is associated with the controlled scenario

$$U_d^c(t) = Log\left[c_1^c(t)(1-d\,(t))\right] + \left(\frac{1}{1+\rho}\right) Log\left[c_2^c(t+1)(1-d(t+1))\right] \quad (4.2.3)$$

[18] Note that when endogenous abatement is absent, we have $N_{1R}(t) = 0$, and thus $N_1(t) = N_{1R}(t)\,\forall$t.

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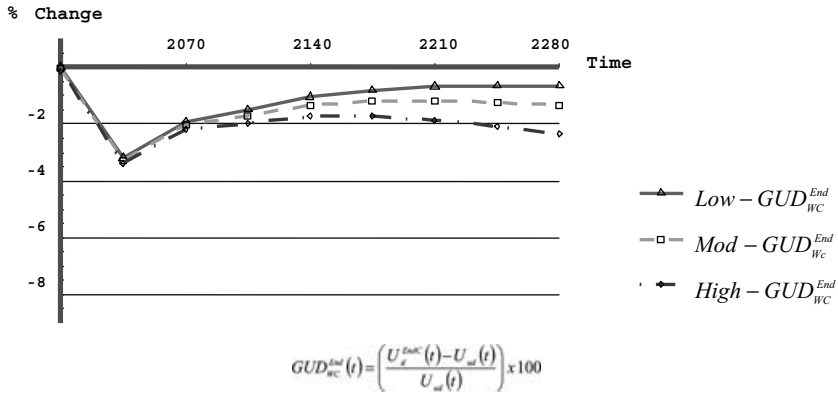


Figure 4.2. *The impact of the control policy* with *endogenous abatement in the controlled environment*
Note: This figure shows the potential consequences of the emission stabilization policy with endogenous abatement. The cost of control is larger when the climate change is projected to be more serious. 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.

Even though control policy can reduce negative effects, it cannot necessarily eliminate all of them. Thus, the damage function is still present in generational utility. However, the damage magnitude is naturally different in the uncontrolled (4.1.2) and controlled (4.2.3) scenarios. Based on equations (4.1.1) and (4.3.3), we can now construct the equivalent variation metric to determine the gross effects of a control policy on the generational well-being

$$GUD_{WC}(t) = \left(\frac{U_d^c(t) - U_{nd}(t)}{U_{nd}(t)}\right)100 \tag{4.2.4}$$

While $GUD_{WOC}(t)$ solely reflects the effects of the damage from climate change on generational well-being, $GUD_{WC}(t)$ captures both the costs and benefits of the control policy. The benefits of the control policy stem from the reduction in the intensity of the damage. On the other hand, the costs are the result of the reallocation of scarce resources to the abatement of emissions and environmental R&D activities. Figure 4.2 and figure 4.3 show the gross effects of the control policy *with* and *without* endogenous abatement, respectively. These figures demonstrate how much additional income a generation would need to offset the effects of both the control and the damage from climate change. However, they do not precisely illustrate what generations are better off or worse off, since the gross effects include both the costs and benefits of emission stabilization.

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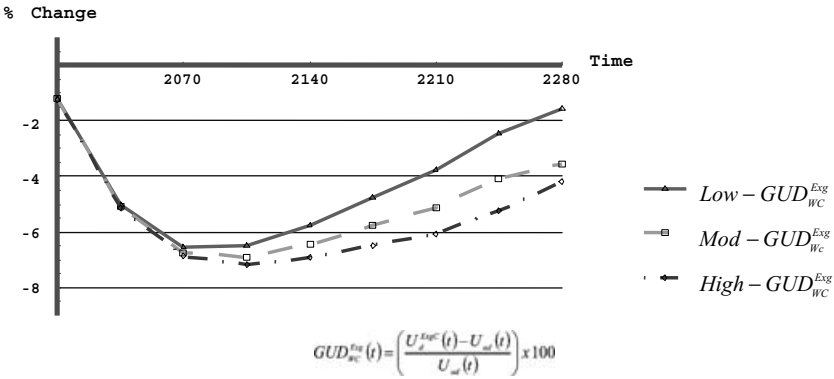


Figure 4.3. *The impact of the control policy* without *endogenous abatement in the controlled environment*
Note: This figure shows the potential consequences of the emission stabilization policy without endogenous abatement. The cost of control is larger when the climate change is projected to be more 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.

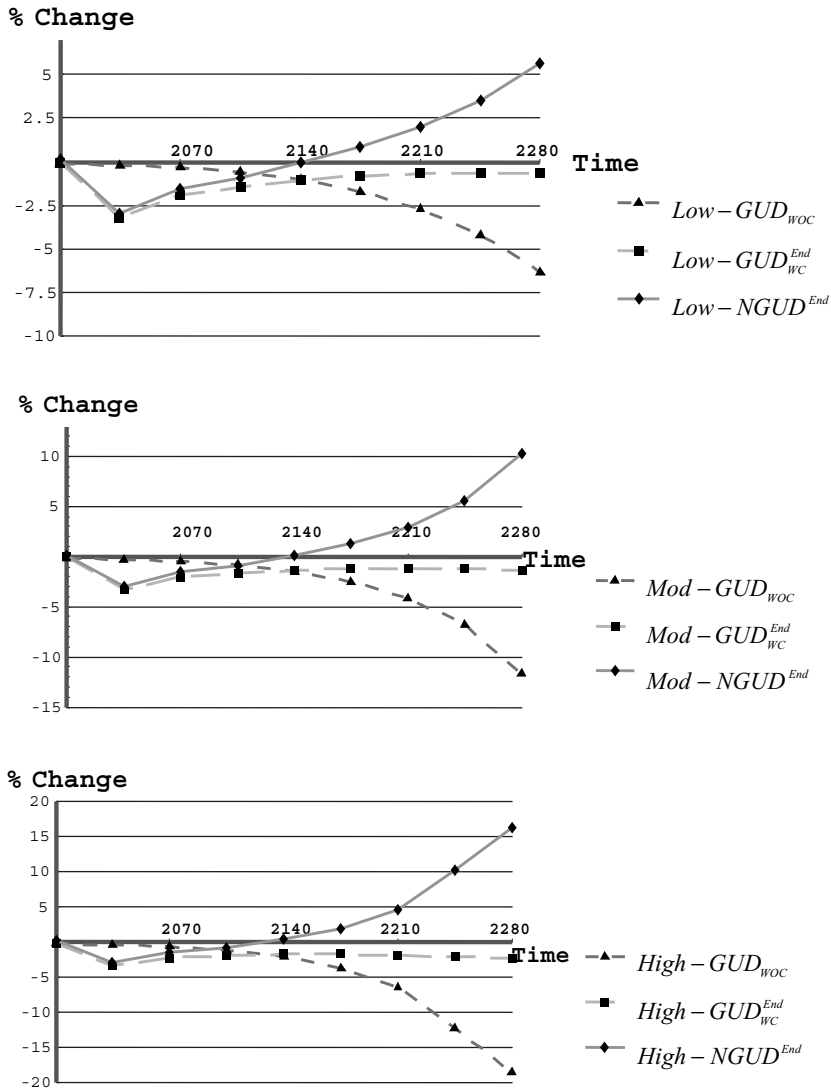
To find out the net impact of the control policy, $GUD_{WOC}(t)$ (representing the damage from climate change) is subtracted from $GUD_{WC}(t)$ (representing the gross effects of control)

$$NGUD(t) = \left(\frac{U_d^c(t) - U_d^{uc}(t)}{U_{nd}(t)}\right) 100 \tag{4.2.5}$$

where the term $NGUD(t)$ illustrates the net change in generational welfare with respect to income when the emission stabilization policy is implemented. A negative $NGUD(t)$ reports how much income a generation would need, under the control policy, for the choice between the scenario *with* control and the scenario *without* control to be indifferent, while a positive $NGUD(t)$ reports how much income a generation would be willing to pay for emission stabilization. $NGUD(t)$ enables us to monitor the net impact of a control policy generation by generation. Clearly, those generations experiencing negative values of $NGUD(t)$ will be hurt by the control policy.

Figure 4.4 displays how the emission stabilization policy will affect generational well-being for minor, moderate, and major damage cases when endogenous abatement is present. On the other hand, figure 4.5 displays the results of the same policy when we assume that endogenous abatement is *not* operative. The common point from these figures is that current and near future generations will bear the greatest costs of the control policy, while far future generations will obtain the greatest net benefits. However, the existence of ITC makes the application of the control policy more attractive. Figure 4.6 signifies the relative importance of the ITC. The costs of a control policy are always lower with endogenous abatement than the case without

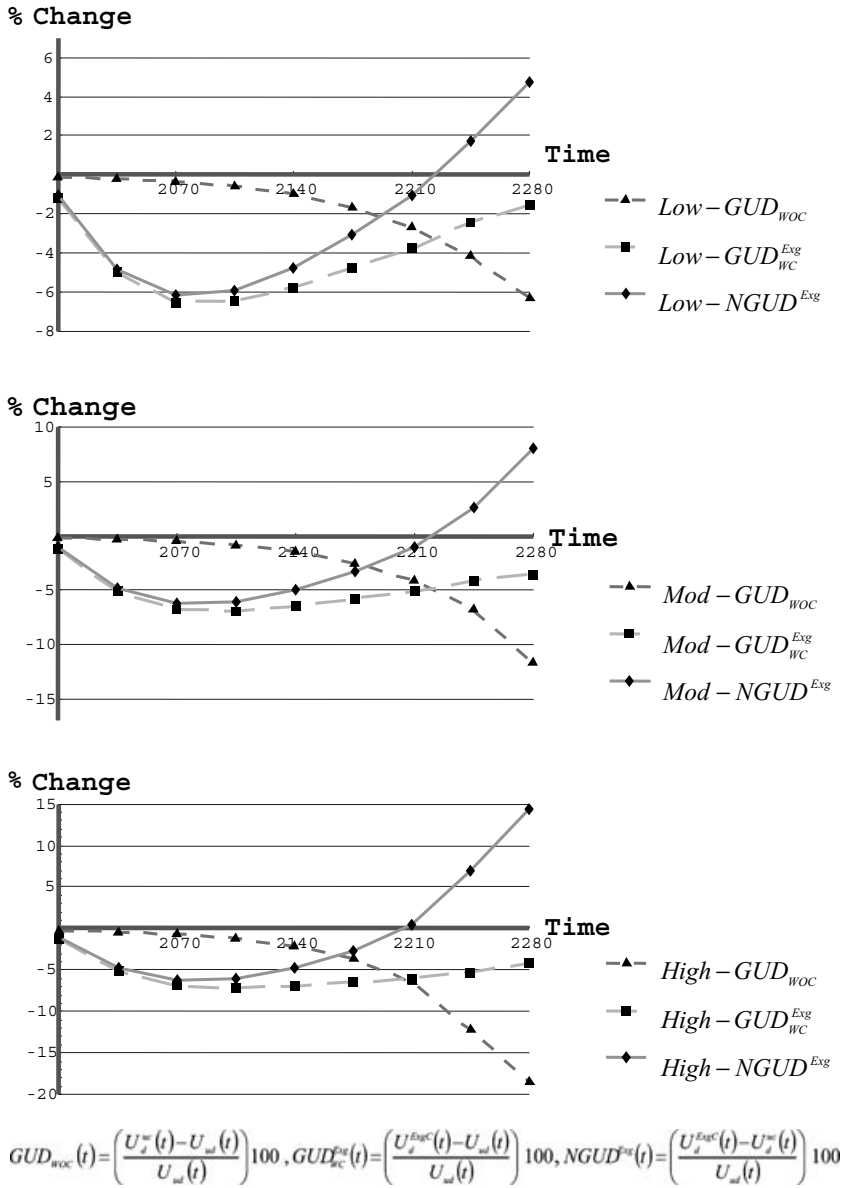
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$$GUD_{WOC}(t) = \left(\frac{U_d^{no}(t) - U_{nd}(t)}{U_{nd}(t)}\right)100, GUD_{WC}^{End}(t) = \left(\frac{U_d^{EndC}(t) - U_{nd}(t)}{U_{nd}(t)}\right)100, NGUD^{End}(t) = \left(\frac{U_d^{EndC}(t) - U_d^{no}(t)}{U_{nd}(t)}\right)100$$

Figure 4.4. *The net benefit from control policy* with *endogenous abatement*
Note: 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-twenty-second century. The generations living prior to the twenty-second century will lose from the implementation of control policy.

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

Figure 4.5. *The net benefit from control policy* without *endogenous abatement*
Note: 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 twenty-third century. The generations living prior to the twenty-third century will lose from the implementation of control policy.

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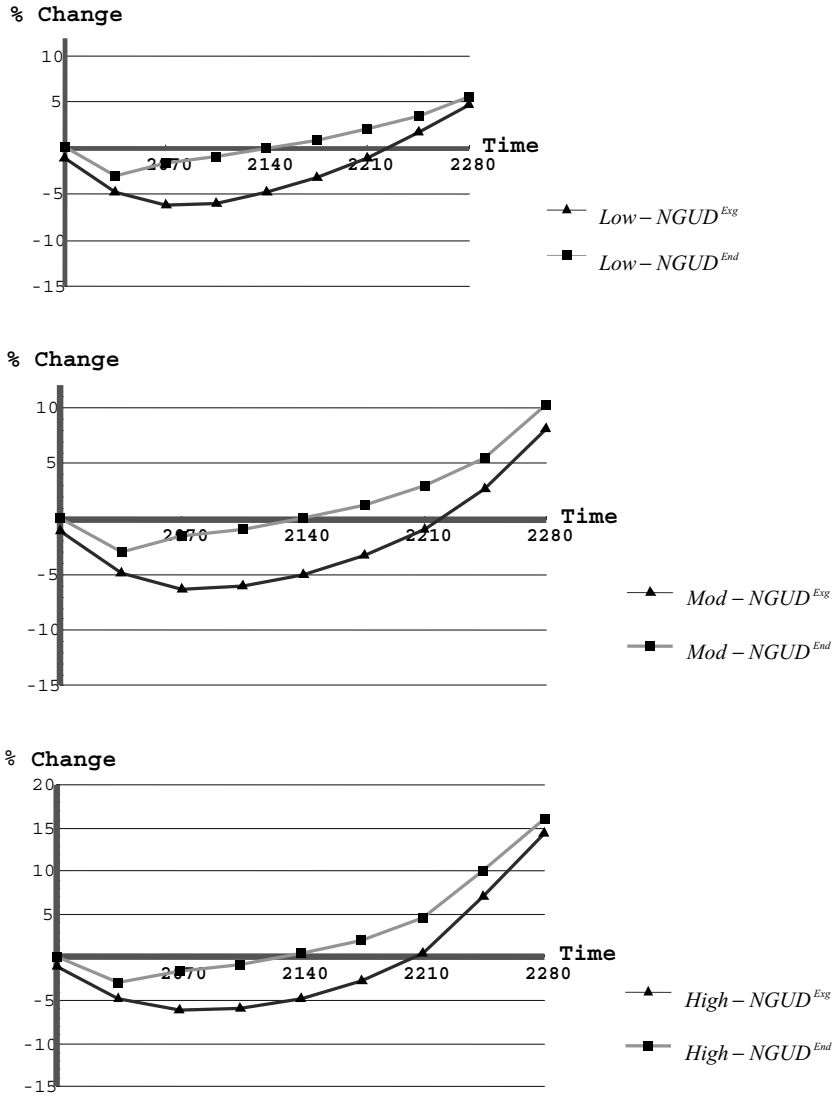


Figure 4.6. *Net benefit comparisons in the benchmark abatement productivity case*
Note: These figures show the comparisons of net benefits from the emission stabilization policy with and without endogenous abatement in the benchmark case. The net benefits are higher when the endogenous abatement is operative.

it. In fact, one way to strengthen the political viability of any proposed policies is to demonstrate that benefits are attained at the lowest costs when the possibility of entrepreneurial response is taken into account.[19]

[19] Similar demonstrations of figure 4.6 for low and high abatement productivity cases are available upon request.

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It is also evident from these figures that there is no free lunch *per se* when applying a control policy. 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.[20] Although ITC has the potential to reduce the compliance costs with the control policy, current and near future generations will bear some net costs. The time differential between the arrival of net benefits and the presence of net short-term costs from the control policy suggests that redistribution across generations through government policies may not necessarily be feasible. Because real-life demographics are deterministically based on finite lives, these generations who suffer the most from the control policy are different from those who reap the fewest benefits. These facts underlie why the mechanical application of the cost–benefit discounting framework combining a fictitious social planner and a representative agent fails as a climate modeling strategy and demands a more appropriate treatment of intertemporal comparisons of costs and benefits.

5. Concluding remarks

The purpose of this paper is to analyze intergenerational welfare effects of climate change and an emission stabilization policy when there is an endogenous creation of abatement process. A decentralized overlapping generations model with induced technological change is set forth as the theoretical foundation. The analytical part of the model suggests that the existence of endogenous development of abatement technologies crucially depends on the imposition of a control policy. Therefore, the model explicitly shows that 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. The conventional approach in the literature is the pure quantitative appraisal of climate change and various policies. Because of the vast complexities and uncertainties of climate change and economic modeling, the critical question of how much confidence we can put into these analyses remains unanswered. Hence, the emphasis in this study is given to the qualitative implications of the results rather than drowning the reader in a cluster of numbers without any useful insight.

Using generational equivalent variations which are unit-free metrics, I was able to appropriately trace the effects of different scenarios generation by generation. In terms of policy scenarios in the simulations, both uncontrolled and controlled cases are considered. First, I analyzed the

[20] In passing, I should briefly point out what happens if we assume a permanent patent protection to overcome the cost problem regarding the imitation and decoding of blueprints. When there is a permanent patent protection, the monopoly power and static inefficiency remain forever. Thus, the government always provides the subsidy to eliminate this inefficiency and further reduces the transfers to the old generation in each period. In such a situation, the effectiveness of the control policy decreases though the main messages do not change unless the imitation or decoding costs are prohibitively high, which is not likely in this study.

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uncontrolled environment case where no action is taken against the threats of 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 generational well-being until the mid twenty-second century. Nevertheless, the loss of generational welfare from climate change will become increasingly severe for future generations if no action is taken in the present or in the near future.

In the second scenario, I assume a control policy involving emission stabilization at the current level. Even though the ITC component of the model is operative in the presence of the control policy, the simulations in the controlled scenario are performed *with* and *without* endogenous abatement to compare the relative welfare effects of each case. The results indicate that ignoring ITC might overstate the welfare costs of implementing a control policy. Even though ITC can enhance the viability of any proposed policies, it does not entail a zero-cost outcome 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 make abatement goods.

Another implication of the results is that the costs of control will fall on the present and near future generations who are least likely to experience the detrimental effects of climate change. Generations living beyond the mid twenty-second century will receive the net benefits of the control. Therefore, the model is not subject to the shortcomings of the highly controversial issue of discounting. Regardless of the value of a discount factor – whatever that may be – 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 the damage projected from climate change. As the damage project increases, the control policy becomes more desirable.

Naturally, some caveats apply. Modeling climate change with ITC 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. Because of this, 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 climate change modeling.

In brief, the primary outcome of this study is that the distributional impacts of climate change and any potential control policy lead to intergenerational welfare and risk-sharing dilemmas. Induced innovation can increase the political desirability of a control policy. However, policymakers have neither the perfect information nor the necessary instruments to make the desired distributions to create net benefits for all generations under the threat of climate change. As a result, an important contribution to the literature would be to construct an ITC model to study the risk-sharing issue within the context of political economy. I believe this should be a high priority on the research agenda.

https://doi.org/10.1017/S1355770X06003469 Published online by Cambridge University Press

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https://doi.org/10.1017/S1355770X06003469 Published online by Cambridge University Press

Appendix: List of symbols

Parameters

Parameter	*Description*	*Value*
Δt	one period $[(t+1)-(t)]$	35
ρ	individual time preference rate	0.03 *per year*
γ	capital share	0.3
Ψ	productivity of abatement	1, 3, 5 (*Low, Moderate, High*)
α	share of an abatement good	0.75
ψ	productivity of human capital in *R&D*	1
g_B	growth rate of Hicks neutral productivity	0.015 *per year*
s_a	subsidy rate per abatement good	0.25
δ_K	depreciation rate of capital stock	0.1 *per year*
δ_N	decay rate in the population growth	0.02 *per year*
δ_σ	decline rate in the natural decarbonization rate	0.0046 *per year*
δ_M	depreciation of GHG concentration	0.087 *per year*
β	atmospheric retention ratio	0.64
λ_1	nonlinear effect of GHG concentration	2.7
λ_2	general atmospheric cooling	–0.1
λ_3	deep ocean effect	0.1
λ_4	warming-sink effect parameter	0.02
Φ	intensity of environmental damage	1, 2.5, 5 (*Low, Moderate, High*)
θ_1	the scale effect of warming	0.01
θ_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	–
τ_R	tax rate on returns to savings	–
N_1	young population (total labor force)	$N_1(1965) = 2.2$ & $N_1(2000) = 3.95$ *billions*
N_2	old population	$N_2(1965) = 2.2$ & $N_1(2000) = 3.95$ *billions*
g_N	population growth rate	$g_N(1965) = 0.0203$ *per year*
B	Hicks neutral productivity	$B = 67.85$
E	greenhouse gas emissions (GHG)	–
σ	GHG-output (emissions intensity)	$\sigma(1965) = 0.52$
Y	output-production	–
K	capital stock	$K(1965) = 16$ & $K(2000) = 56$ *trillions*

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Variable	*Description*	*Initial (predetermined) value*
N_{1F}	employment in the final goods sector	$N_{1F}(1965) = 2.2$ *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	$P = 1/\alpha$ (*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	–
τ_E	emissions tax rate	–
$\vartheta = 1 - \mu$	effective tax wedge (with $\mu = \tau_E \sigma$)	–
V_A	value of a patent	–
M	GHG concentration	M(*pre-industrial level*) = 590 *GGt*
T	increase in mean atmospheric temperature	$T(1965) = 0.2$ & $T(2000) = 1.7$
O	increase in mean oceanic temperature	$O(1965) = 0.1$ & $O(2000) = 0.102$
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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