The Economics of the Mega-Greenhouse Effect: A Conceptual Framework

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Abstract

Integrated assessment models of climate change typically analyze the case of a doubling of atmospheric CO_2.over the pre-industrial concentration of about 270 ppm. This is a serious shortcoming since under a scenario in which all accessible fossil fuels are burned, atmospheric CO_2 concentrations will more than quadruple. We introduce an analytical framework that endogenously accounts for potential climate change events related to this “mega-greenhouse” and examine economic implications of two alternative mitigation strategies: one in which only the rates of annual emissions are reduced, and one that places absolute limits on the total amount of carbon released into the atmosphere. (*JEL* C53, D61, Q20, Q21)

Economic analyses of climate change have been dominated by integrated assessment models which combine the natural science and economic aspects of climate change primarily for the purpose of assessing policy options for climate change mitigation (Nordhaus, 1994; Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000; Dowlatabadi and Morgan, 1993; Manne, Mendelsohn, and Richels, 1993). These models have yielded valuable insights into the complex relationship between climate change and economic activity, but it has become clear that they capture only a portion of the long-run costs of climate change damages and the benefits of climate change mitigation (see DeCanio, 2003; Laitner, DeCanio, and Peters, 2001; Spash, 2002).

A problem with the most widely used models is that they consider only a doubling of CO_2 over the pre-industrial level of 270 ppm (for example, Nordhaus and Boyer, 2000) which will produce only a modest increase in average temperatures. This is a serious shortcoming, since recent integrated carbon-climate models project that if CO_2 from current *in situ* fossil fuel resources continue to be released into the atmosphere, the peak concentration of atmospheric CO_2 will exceed 1400 ppm by the year 2300 and the average global temperature will warm by 8^{o}C (Bala *et al*., 2005).[1]

Ignoring these potential long-term effects of CO_2 emissions - the "mega-greenhouse effect" - can lead to conceptual errors when formulating climate change policy. For one thing, looking only at the effects of a CO_2 doubling reduces the analysis to an examination of the costs and benefits of slowing annual emission rates from fossil fuel use rather than considering the

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[1] Other models generate different numbers for CO_2 and temperature increases but the results are of the same order of magnitude (see the discussion in Bala *et al*. 2005). The conceptual framework we lay out in this paper does not depend on any particular estimates of CO_2 or temperature change.

costs and benefits of limiting total fossil fuel use to cap ultimate total atmospheric CO_2 concentrations. Most policy proposals have treated the problem of capping the atmospheric CO_2 content in terms of incremental reduction of CO_2 emissions. Annual emission reductions, however, will not stabilize ultimate CO_2 levels, because the final concentration of CO_2 in the atmosphere over the next several hundred years will depend primarily on the total amount of fossil fuel carbon released and only weakly on the annual emissions rate. This is due to the fact that current emission rates far exceed the ability of geochemical processes to remove carbon from the atmosphere (Caldeira and Kasting, 1993; Bala *et al.*, 2005). The CO_2 released to the atmosphere is only partially captured through exchange with the biota, soils and the surface ocean. Uptake by natural processes is too small to capture the massive amounts of carbon currently being released by fossil fuel burning. The capacity of the deep ocean reservoir to capture CO_2 on the other side is significant, but the time scale associated with carbon transfer into the deep ocean is 1,000 years or more, so the behavior of CO_2 on a policy relevant time scale is not affected by exchange with this reservoir (Walker and Kasting, 1992).

According to recent climate-carbon model predictions, only by halting fossil fuel combustion (or sequestering carbon on a massive scale) can CO_2 concentrations, and future climate conditions on earth, be stabilized (Bala *et al.*, 2005; Socolow *et al.*, 2004; Walker and Kasting, 1992). This represents an immense technological and political challenge for society, but the consequences of ignoring the mega-greenhouse implications of continued burning of fossil fuels in the development of policies could be catastrophic.[2] Table 1 shows the amount of carbon

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[2] Compared to climate regimes during the 200,000 year history of *Homo sapiens* the past 10,000 years (the Holocene) has been unusually stable. The temperature has only varied by plus or minus 0.5 °C over that period of time. According to some (Richerson and Boyd, 2005) it is this climate stability that made agriculture and human

stored in the earth’s carbon reservoirs. About 4000 gigatons (10^9 tons) are in the active environment.

Table 1-CARBON IN THE ENVIRONMENT AND CARBON STORED IN FOSSIL FUELS

Environmental Reservoir of Carbon	**Size (Gigatons)**
Atmosphere	750
Forests	610
Soils	1,580
Surface Ocean	1,020
Total active carbon in the environment	3,960
Carbon Stored in Fossil Fuels	**Size (Gigatons)**
Coal	4,000
Oil	500
Natural Gas	500
Total Fossil Fuel Carbon	5,000

Adapted from Kasting (1998)

There is about seven times the amount of currently accessible carbon stored in fossil fuels (5000 gigatons) as is now in the atmosphere (750 gigatons). The amount of carbon stored in fossil fuels – mostly coal - is so vast that if coal continues to be burned, currently feasible mitigation options such as reductions in CO_2 emissions, limited sequestration, and re-forestation will have a negligible effect on stabilizing atmospheric CO_2 (Caldeira and Kasting, 1993).

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civilization possible. Dramatically increasing CO_2 and dramatically raising the earth’s temperature will likely interrupt this period of climate stability with unknown but most likely negative consequences.

Another shortcoming of most integrated assessment models is that the value of reducing potential damages from global warming on human and natural systems is weakly represented. Most economic models are based on an inter-temporal maximization framework where social welfare is driven exclusively by the consumption of commodities. Non-quantifiable environmental values such as the impact of fossil fuel extraction and combustion (as they relate to global warming) on human health, coastal ecosystems, and species loss are omitted from the social welfare function. Emissions are treated as an indirect proxy for production and as long as the welfare benefits of increased consumption outweigh the damages associated with CO_2 emissions, abatement is not justified (Courtois, 2004; Nordhaus, 1994; Nordhaus and Boyer, 2000). Tol (1994) found, for example, that endogenizing the amenity values alone associated with climate mitigation could justify a doubling of mitigation efforts in the short-run and a tripling in the long-run.

In this paper we introduce a theoretical framework in which the value to society of preventing possible catastrophic effects associated with increasing concentrations of atmospheric CO_2 are endogenously incorporated as a variable affecting society's welfare. The framework allows for evaluating the long-term mega-greenhouse effects of climate change policies. We go beyond the constraints of the standard economic approach to show the relationship between economic growth, human well-being, and fossil fuel use. We use the framework to explore scenarios that support two alternative mitigation strategies: (1) one in which annual rates of emissions are reduced, while fossil fuels continue to be burned with no restrictions other than the finite scarcity of the resource and (2) the case of a policy strategy aimed at capping the total amount of carbon emitted, implying the stabilization of a global climate before the mega-greenhouse effect takes place. While the policy exercises we conduct make use of the standard economic framework including using the controversial discounting approach (Dasgupta, 2006; DeCanio, 2003; Gowdy, 2004; Hall & Bell, 2006; Spash 2006), it does provide insights into the implications of properly accounting for the long-term (mega-greenhouse) effects of global warming and the conditions under which alternative policy prescriptions become relevant when these effects are included in the social welfare function to be optimized.

The next section uses the framework developed by Hotelling (1931) and refined by Krautkraemer (1985) to examine the case of slowing the rate of CO_2 emissions. Section II extends this analysis to look at the alternative policy of capping total cumulative CO_2 emissions. Section III concludes.

I. The Case of Slowing Emission Rates

Most policies suggested to mitigate the potential effects of CO_2 accumulation in the atmosphere have addressed alternative schemes of incremental reductions in emission rates. Scientific evidence suggests that these policies, including the Kyoto treaty, will not stabilize atmospheric CO_2 levels, but only slow the rate of CO_2 accumulation in the atmosphere (Broecker, 2007). As discussed above, the long-term maximum amount of CO_2 in the atmosphere, and the ultimate maximum temperature rise associated with this CO_2 increase, are insensitive to the timing of the use of fossil fuel stocks and associated emissions. Climate-related effects associated with higher levels of greenhouse gases can be postponed but cannot be avoided as long as fossil fuels continue to be burned (Bala *et al.*, 2005; Caldeira and Kasting, 1993).

Figure 1 shows the effects that reductions in emission rates may have in the timing of the occurrence of the mega-greenhouse effect. [3]

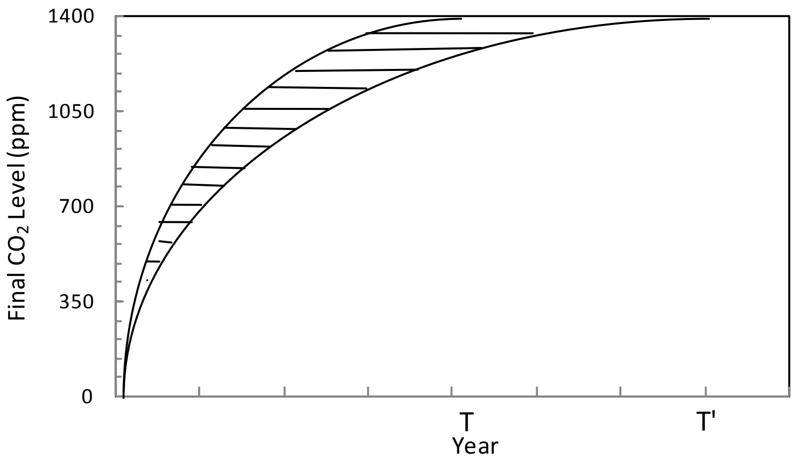

FIGURE 1. THE EFFECT OF SLOWING CO_2 EMISSION RATES

The timing of the maximum mega-greenhouse effect (T') will depend on the rate at which society is willing to postpone extraction and combustion of fossil fuels. That is, it will depend on the costs and benefits to society associated with the shaded area in Figure 1. The shaded area in Figure 1 can be interpreted as the difference between a business as usual approach where final CO_2 levels are reached at time T, compared to an emissions control approach where final CO_2 levels are reach at time T'. The economic problem is to calculate the costs and benefits of postponing the ultimate maximum CO_2 level. Neither the costs nor the benefits can be quantified with any degree of certainty, but in standard economic terms, these will depend on the rate at which society discounts the costs and benefits of delaying the ultimate climate change effects of burning the earth's available fossil fuels stock. The usual policy approach, aiming at an

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[3] Figures show results from the coupled climate-carbon cycle model of Thompson *et al*. (2004) as refined by Bala *et al.* (2005).

improvement in the efficiency of fossil fuel use and associated reductions in emission rates can be conceptualized as a reduction in the rate of discount at which the carbon stored in fossil fuels is extracted and used (Dasgupta, 2006; Nordhaus and Boyer, 2000; Stern, 2006). The higher society discounts the future effects of climate change, the higher the rate of fossil fuel extraction and use, and the sooner the climate change effects associated with the mega-greenhouse effects will be felt.[4]

The proposition that an increase in the discount rate leads to a faster use and depletion of a non-renewable resource such as fossil fuels is central to the economic theory of exhaustible resources and goes back to the work of Hotelling (1931). Hotelling's analysis of non-renewable resource depletion generates some basic implications for how variations in the availability and/or use of a non-renewable resource may affect its optimal extraction path and price. We draw from Krautkraemer (1985) to expand on Hotelling's initial intuition and examine the economics of the mega-greenhouse effect.

Consider a social planner whose objective is to maximize the present value of society's welfare obtained from the utility derived from the consumption of commodities (the fossil fuel resource being used in the production of these commodities) and from the amenity value associated with a milder (and more stable) climate. The planner's objective is constrained by the available technology and the initial fossil fuel stock; The planner may choose time paths for consumption of commodities *C(t)* and fossil fuels *R(t)* then, which maximize:

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[4] The so-called social rate of discount only takes into account some notion of the value of the utility of future generations *to the present generation.* It does not take into account the utility of future generations as valued by themselves.

$$(1) \qquad \int_0^T e^{-\delta t} U(C(t), S(t))dt$$

subject to

$$(2) \qquad \dot{S}(t) = -R(t)$$

$$(3) \qquad C(t) = e^{\tau t} R(t)$$

$$(4) \qquad S(0) = S_0$$

$$(5) \qquad R(t) \geq 0, S(t) \geq 0, \forall t,$$

where *S(t)* denotes the remaining fossil fuel resource stock in the ground, δ is the so-called social rate of discount, τ symbolizes the rate of technological progress (reflecting the rate of improvement in the level of consumption attainable from a given level of fossil fuel extraction) and *U(C(t),S(t))* denotes the utility function.[5]

In the standard formulation (Nordhaus, 1994, for example) society derives utility only from the flow of market, or pseudo-market, commodities. But society also benefits from the amenity value associated with leaving the remaining fossil fuels stock *S(t) in situ*. The environmental amenities associated with the fossil fuel stock left in the ground represent climate-change related benefits of limiting ultimate atmospheric CO_2 concentrations. These benefits

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[5] Following Krautkraemer (1985), the utility function *U(C,S)* is twice continuously differentiable with U_c and U_s positive, U_{cc} and U_{ss} negative, and $\lim_{t\to\infty} Uc(C,S) = \infty$. In addition, the cross-partial derivative $U_{sc}(C,S)$ is non-negative, with $U_{sc}(C,S)<U_s(C,S)/C$. This implies that a higher standard of living can contribute to the value of preserving fossil fuels in ground only at a decreasing rate.

include not only avoidance of potential negative impacts on natural and productive capital (such as coastal area loss due to sea-level rise, destruction due to extreme weather events and the impacts on human health) but also potential impacts on existence values such as biodiversity loss. Benefits of mitigation also include the insurance premium associated with avoiding truly catastrophic climate change, for example, a runaway greenhouse effect resulting from the release of methane clathrate from the ocean floor (Hansen *et al*., 2007). There is a functional relationship between the flow of these amenities and the flow of fossil fuel resource left in ground $S(t)$. We assume this relationship is irreversible, in the sense that once the fossil fuels are extracted and burned, and the greenhouse gases are released in the atmosphere, the related climate effects are unidirectional and cannot be altered by mitigation policies.

The current value Hamiltonian for the problem stated in equations (1) to (5) is:

$$H = U(C(t), S(t)) - p_s(t)R(t) + \lambda_R R(t) + \lambda_S S(t) \tag{6}$$

where p_S is the current value shadow price of the *in-situ* fossil fuel resource at time t, and the λ's are the Lagrangian multipliers associated with the non-negativity constraints. The current value shadow price p_s provides an indication of the implicit or "planning price" of the *in-situ* fossil fuel resource that emerges as a solution when the resource is optimally allocated over time. Notice that since the model optimizes society's welfare (a sum of discounted units of utility), the shadow prices derived are measured in utility units, so this figure represents society's utility gains from an additional unit of the *in-situ* fossil fuel resource.

The first order (necessary) conditions for the existence of an internal optimal to the problem stated above are:

(7) $$p_s(t) = U_C(C, S)e^{\tau t}$$

(8) $$\dot{p}_s(t) = \delta p_s(t) - U_S(C, S)$$

(9) $$\frac{\dot{p}_s(t)}{p_s(t)} = \delta - \frac{U_s(C, S)}{p_s(t)}$$

In standard economic terms, equations (7) through (9) imply that at each point in time, the current value shadow price of the *in-situ* fossil fuel should equal the marginal utility of consumption derived from the resource, and its total rate of return should be equal to society's rate of discount minus the contribution to utility that the current value shadow price of the resource brings to society's welfare (U_S/p_S). Equation (9) implies that the current value shadow price of the *in-situ* fossil fuel stock should rise at society's rate of discount on utility when there is no amenity value associated with their preservation. This result is analogous to Hotelling's well-known rule. However, when the functional relationship between environmental amenities and the fossil fuel stock is incorporated in the welfare function to be optimized, the rate of growth of the value of the resource is lower, implying that extraction and combustion (and associated emissions and global warming effects) are postponed. The larger the amenity values associated with fossil fuel extraction, the smaller the rate of growth in the current value shadow price will be, and so the smaller the rate of extraction and combustion that will take place along an optimal time path. This effect is analogous to decreasing the rate of discount under Hotelling's framework. A larger insurance premium to avoid the possibility of catastrophic climate change would have the same effect.

Differentiating equation (7) with respect to time and equating to (8) gives the rate of change in society's consumption of commodities along the optimal path:

(10) $$\frac{\dot{C}}{C} = \frac{1}{\eta(C)}\left(\tau - \delta + \frac{U_s}{p_s} - \frac{RU_{cs}}{U_c}\right),$$

where $\eta(C)$ is the elasticity of marginal utility derived only from consumption, representing the proportionate change in marginal utility that arises for a given proportionate change in consumption:

(11) $$\eta(C) = -C \bullet U_{cs}(C)/U_s(C)$$

Notice from (10) and (11) that whenever $U_s > CU_{cs}$, the amenity value of the fossil fuel stock will increase the rate of change in the level of consumption, implying a lower initial level of consumption and extraction of fossil fuels *R(t)*, and so a shift in consumption and extraction from the present to the future along the optimal path.

Integrating eq. (8) with respect to time *t* to time *s* gives:

(12) $$p_s(t) = \int_s^T e^{-\delta(s-t)} U_s(C(s), S(s))ds + \lambda e^{\delta t},$$

where λ represents the *present value* user cost or *in situ* value of the fossil fuel stock associated with its scarcity. Equation (12) implies that the marginal value of welfare associated with an extra unit of the in-situ fossil fuel resource (p_s) is equal to the discounted stream (to time s) of the future marginal amenity value of the *in situ* fossil fuel resource (related to prevention of global-warming potential catastrophic effects) in addition to the utility related to its own scarcity. We have argued that a functional relationship exists between this *in-situ* fossil fuel stock and the amenity value to society's welfare associated with preserving a milder climate. Let the function

$$\phi_S(t) = \int_s^T e^{-\delta(s-t)} U_S(C(s), S(s))ds \tag{13}$$

denote this relationship to time s. If the form of this functional relationship is known, then solving for $\phi_S(t)$ provides an indication of the net benefits to society of implementing measures to delay or prevent potential global warming-related events.[6]

Whether the optimal path results in a full cumulative exhaustion of the earth's fossil fuel stock or not will depend on the magnitude of the function $\phi_S(t)$ relative to the utility society derives from the consumption of commodities produced by the fossil fuel resource. Notice that since the first order condition (7) requires that at $t=0$, $p_s(0) = U_C(C(0), S_0)$, and according to (12), $p_s(t) = \phi_S(t) + \lambda e^{\delta t}$, then if $\phi_S(0) < U_C(C(0), S_0)$ it must be that $\lambda > 0$ and so it follows that the fossil fuel reserve stock is exhausted along the optimal path. In other words, when the current value of cumulative benefits to society of preserving a milder climate are relatively

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[6] Notice that under the standard assumptions about utility, if $\tau > \delta$ (i.e., if the rate of technological progress is larger than the social rate of discount of utility so that consumption is non-decreasing) then

$$\frac{U_S(C(t), S(t))}{\delta} < \phi_S(t) < \lim_{t \to \infty} \frac{U_S(C(t), S(t))}{\delta}.$$

This equation yields an upper and lower bound to the function $\phi_S(t)$ - the value of resource amenities associated with the *in-situ* fossil fuel stock left in the ground. A proof of this lemma can be found in Krautkraemer (1985).

smaller than the cumulative value society derives from the consumption of commodities whose production requires the fossil fuel resource, all fossil fuel reserves will eventually be extracted and burned along an optimal path, and the occurrence of the mega-greenhouse effect becomes inevitable because as discussed above, as long as fossil fuels are extracted and burned, atmospheric CO_2 concentrations will continue to accumulate. However, because of the effect of the intrinsic amenity value on the fossil fuel stock's own rate of return, the extraction and use of fossil fuels – and the related mega-greenhouse effect – is postponed.

II. Limiting Total Cumulative CO_2 Emissions

The previous section examined the conditions under which policies that aim to reduce CO_2 emission rates without constraining the total amount of the fossil fuel resource extraction and combustion may be consistent with the maximization of society's welfare. We showed that if amenity-related current values associated with fossil fuel extraction and use are of smaller magnitude relative to the present value society derives from consumption, these efforts will only postpone the timing of occurrence of the mega-greenhouse, but will not allow the climate to stabilize in time to prevent mega-greenhouse effects.

A more aggressive policy approach is to reduce emission rates while limiting at the same time total cumulative emissions of CO_2. The effect of this approach is portrayed in Figure 2.

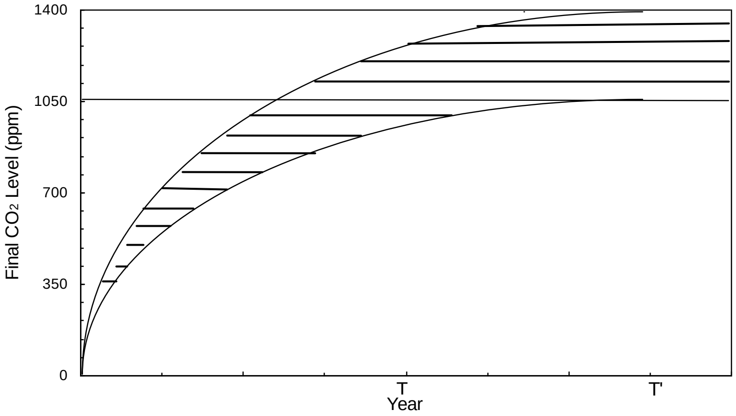

FIGURE 2. THE EFFECT OF LIMITING CUMULATIVE CO_2 EMISSIONS

This mitigation strategy would allow reaching a stable (and milder) equilibrium climate in the long-run, but requires that part of the carbon stored on fossil fuels be left permanently in the ground; otherwise, atmospheric CO_2 would continue to accumulate, as argued above. Results of integrated climate and carbon model simulations confirm this intuition. Walker and Kasting (1992) for example, concluded that keeping atmospheric CO_2 below critical levels would require switching to alternative energy sources long before the earth's fossil fuels reserves are depleted. Notice that potential benefits associated with this last scenario could be captured indefinitely, while in the previous case, benefits of postponing extraction end at the time of the exhaustion of the resource.

The proposition that it may become economically optimal to permanently preserve non-renewable resources (in this case non-extraction of fossil fuels) was presented formally by Krautkraemer (1985). He showed, using a similar formulation as the one presented in section II, the conditions under which it becomes optimal for cumulative extraction (and combustion of fossil fuels in the context of climate change) of the resource input to be less than the initial resource endowment. It may make economic sense to leave part of the resource stock permanently in the ground.

As shown above, a functional relationship exists between the *in-situ* fossil fuel stock and the amenity value to society's welfare associated with preserving a milder climate. We used equation (13) $\phi_S(t) = \int_s^T e^{-\delta(s-t)} U_S(C(s), S(s))ds$ to denote this relationship to time s. Again, the first order condition for the existence of an interior optimal for the problem presented in equations (1) to (5) requires that at *t=0*, $p_s(0) = U_C(C(0), S_0)$ (see equation 7). Since $p_s(t) = \phi_S(t) + \lambda e^{\delta t}$ (see equation 10), if $\phi_S(0) > U_C(C(0), S_0)$ then it must be that λ =0 and so it follows that it becomes optimal to aim for a level of cumulative fossil fuel extraction which is less than the initial resource endowment.

This result is important in the context of climate change: if the (negative) cumulative present value of potential global-warming events (associated with continuing the extraction and combustion of fossil fuels) is larger than the current utility value society derives from consumption of commodities, then it becomes optimal to stop using fossil fuels before the resource stock is exhausted, implying a switch to an alternative source of energy. Following this prescription, the mega-greenhouse effect could be avoided, and the benefits of such policy (or the costs of not adopting it) are captured by the monetary (and non-monetary) value of the function $\phi_S(t)$.

III. Summary and Conclusions

We have introduced a theoretical framework for long-term climate change analysis in which the value to society of preventing possible catastrophic effects related to the occurrence of the mega-greenhouse endogenously affects society's welfare. We showed that two alternative policy prescriptions considered at the present time will be consistent with different magnitudes of this value.

When the cumulative benefits of avoiding the climate-related events associated with the mega-greenhouse are relatively smaller than the value society derives from the consumption of commodities, it becomes optimal to exhaust the fossil fuel resource stock – with the inevitable occurrence of the mega-greenhouse effect. However, the process should take place at a smaller pace than if the amenity value associated with preserving the fossil fuel resource *in situ* and avoiding catastrophic events were not considered in the welfare function to optimize – implying a delay in the timing of occurrence of the mega-greenhouse effect. This result portrays the effect of the policy taken at the present time on most mitigation related policies that aim at reducing rates of emission. These policies, under our analytical framework, are implicitly assuming that amenity values related to preserving fossil fuels in the ground – and preventing potentially catastrophic events associated with the mega-greenhouse effect - are small enough to prevent from unrestricted and continuous fossil fuel use. Climate-related benefits associated with this policy scenario arise from a reduction in societal and environmental vulnerability. The major benefits of delaying emissions arise from the extra time allowed for environmental, technological, and socio-economic adaptation. Given more time, ecosystems may be able to adjust without catastrophic change and human institutions may be better able to adapt to the new climate regime.

Our second policy scenario comes into play when the current value of climate-related events associated to unrestricted burning of fossil fuels is relatively larger in magnitude than the cumulative value of consumption along the optimal path. In this case, it becomes optimal to stop cumulative extraction - and emissions - before the earth's fossil fuel stock is exhausted, implying permanent preservation of (part of) the resource *in-situ*. Evidence during the last few years that supports the hypothesis that potential long-term events associated with increasing concentrations of CO_2 – such as displacement and loss of productive coastal zones, impediments in food production, water availability and destruction of physical capital - may be of catastrophic magnitude (Hansen *et al*., 2007), suggesting the possibility that this second scenario is the relevant one. The recognition of the need to account for a maximum amount of carbon to emit (rather than a reduction in a rate of emissions) is growing among the scientific community: Broecker (2007), for example, recently introduced the idea of a "carbon pie" to conceptualize the maximum permissible amount of carbon reserves to be burned in order to achieve a stabilization of climate. In this case, the development of technologies that reduce the rate of emissions of greenhouse gases to the atmosphere – such as the ones under consideration at the present time - should be seen as temporary measures to buy additional time for phasing out fossil fuel use. If this last scenario is the relevant one to consider, then policies should be geared towards the development of backstop technologies - and the use of alternative renewable sources of energy to replace fossil fuels. The availability of backstop technologies at lower costs than conventional sources will certainly favor a shift from use of fossil fuel sources to alternative ones. But again, if the goal is to stabilize the climate at moderate levels these backstop fuels should be substitutes for, not supplements to fossil fuel resources.

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