

Economic Structural Change as an Option for Mitigating the Impacts of Climate Change

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Abstract

Improving the resilience of the economy in the face of uncertain climate change damages involves irreversible investments to scale up new technologies that are less vulnerable to the effects of climate change. The benefit of having such options includes the avoided welfare cost of diverting consumption to scaling up the new technology after production possibilities have been diminished by climate change impacts. This needs to be balanced against the upfront cost of scaling up a technology that is potentially less productive than incumbent technologies. The paper uses a real options approach to investigate this trade-off, based on numerical simulation of a multi-period model of

economic growth and climate change impacts that includes a one-time cost associated with scaling up the alternative technology. The value of the option provided by investment in the more resilient technology depends on the ex-ante volatility of climate change damages, as well as how rapidly climate change degrades the productivity of the economy's established technology. In addition, the size of scale-up cost that leaves the economy indifferent between investing and not investing in the new technology can be used to define the value of early investment in the less climate change-vulnerable technology as a sort of call option.

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**ECONOMIC STRUCTURAL CHANGE AS AN OPTION FOR MITIGATING THE
IMPACTS OF CLIMATE CHANGE**

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ECONOMIC STRUCTURAL CHANGE AS AN OPTION FOR MITIGATING THE IMPACTS OF CLIMATE CHANGE

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1. Introduction

One key insight from research on the economics of greenhouse gas (GHG) mitigation has been the application of the theory of real options to bring out the economics of irreversible investment for reducing GHGs under uncertainty. Valuable options are maintained by making irreversible investments more slowly, but also by investing more rapidly in GHG mitigation to forestall irreversible climate change damages.²

Improving the resilience of the economy in the face of uncertain climate change damages involves similar tradeoffs. In particular, making the economy more resilient involves irreversible investments to scale up new technologies that are less vulnerable to the effects of climate change. Building up such capacity provides options for reducing losses of output and welfare if irreversible climate change damages turn out to be more severe than expected. The benefit of having such options includes the avoided welfare cost of diverting consumption to scaling up the new technology after production possibilities have been diminished by climate change impacts. This needs to be balanced against the upfront cost of scaling up a climate change-resilient technology that is potentially less productive than incumbent technologies. One could wait for the cost of more resilient technology to fall from further R&D. However, the advantage of postponing the initial scale-up cost has to be compared to the cost of not having earlier access to the new technology in the event of more severe than expected climate change impacts.³

Although applications of real options methods to climate change have focused mainly on mitigation rather than adaptation, a small literature has considered the role of real options in evaluating adaptation measures. Most of the literature to date on real options with climate change adaptation has focused on analysis of specific projects, notably for coastal protection and water resource management (see Jeuland and Whittington 2013; Kontogianni et al (2014); Linquiti and Vonortas 2012; Scandizzo 2011; and Watkiss et al 2015).

In this paper we use a real options approach based on a simple model of economic growth and climate change impacts. In the model, the global economy produces a homogeneous consumption/investment good, using initially a technology that is subject to adverse shocks over time from climate change. Future climate change states are not known ex-ante, but their probabilities are. An alternative technology is available that has much less climate change vulnerability; to simplify, we assume here that it has no vulnerability whatsoever. However, the alternative technology is initially less productive than the incumbent technology, though that changes over time after climate change reduces the productivity of the incumbent technology. We also assume that there is a one-time fixed cost associated with scaling up the alternative

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² Classic citations for this literature include Kolstad (1996), Fisher and Narain (2003), and Pindyck (2000). Kolstad (2013) provides a nice review of the topic.

³ Watkins et al (2015) review a number of "new economic decision support tools" that can be applied to climate change adaptation, including real options.

technology. This introduces a non-convexity into the introduction of the new technology, reflecting (albeit in a very stylized way) real-world concerns about the costs of transition with economic structural change.

The model we use is highly simplified and leaves aside many important elements, notably uncertainty about the future productivity of the alternative technology as it is being introduced. Despite the simplified structure, closed-form solutions are not readily obtainable given the sequential updating of decisions and the possibility of multiple different corner solutions within and across time periods. Accordingly, we use numerical simulations to assess the optimal investment and consumption trajectories under different parameterizations of climate change damages and risks.

We use the simulations to show, in particular, how the value of the option provided by investment in the more resilient technology depends on the ex-ante volatility of climate change damages, as well as how rapidly climate change degrades the productivity of the economy's established technology. In addition, the size of scale-up cost that leaves the economy indifferent between investing and not investing in the new technology can be used to define the value of early investment in the less climate change-vulnerable technology as a sort of call option.

Section 2 of the paper lays out our conceptual framework. Section 3 presents and interprets a set of numerical simulations. We show in particular how the decision whether or not to scale up the alternative technology depends on the period-by-period volatility of climate change damages, not just the expected trend. In Section 4 we consider other cases in which severe climate change damages are both worse and less likely than in the cases examined in Section 3. We also examine the conditions under which part of the capital stock for the incumbent, climate change-vulnerable technology, might need to be abandoned due to the adverse effects of climate change before it is naturally depreciated – a particular form of “stranded assets.” In Section 5 we show how analysis of the cost of initially scaling up the alternative technology offers insights as to the value of the option provided by making such an investment. Section 6 contains concluding remarks and comments on extensions of the analysis.

2. Conceptual Model

2.1 Notation

$i = 1$ or 2 : incumbent/old or alternative/new technology, respectively

t = time period

M = subscript for less adverse (Mild) climate change

H = subscript for more adverse (Harsh) climate change

ω_{tk} = exogenous random parameters representing how climate change affects the economy, with $k = M$ or H at date t (see eq. [1] below); $\omega_{0k} \geq 0$, $\omega_{tk} > 0$ for $t > 0$;

$\omega_{tH} > \omega_{tL} > 0$ and $\omega_{tk} < \omega_{t+1,k}$ for all t

π_{ij} = Probability {climate change state at t is j | climate change state at $t-1$ is i }

ρ_i = Probability {climate change state at $t=0$ is i }

K_{it} = available production capacity for technology i (old or new) at date t

Z_{it} = capacity utilization; $0 \leq Z_{it} \leq K_{it}$

Q_{it} = efficient output from technology i at date t , given K_{it}

C_t = consumption at date t

I_{it} = investment in technology i at date t ; $I_{it} \geq 0$

$U(C_t)$ = utility from consumption at date t

S_t = scale-up cost for the new technology when/if it first begins operating at date t

λ_t = discount factor applied at t to future utility

δ_i = capital depreciation rate for technology i

2.2 Model Specification

We specify Q_{it} , efficient output using technology i at date t , by

$$[1] \quad Q_{1t} = \max_{0 \leq Z_{1t} \leq K_{1t}} \{(A_1 - \omega_{tk} - p_1)Z_{1t} - (B_1/2)Z_{1t}^2\}$$

$$[2] \quad Q_{2t} = \max_{0 \leq Z_{2t} \leq K_{2t}} \{(A_2 - p_2)Z_{2t} - (B_2/2)Z_{2t}^2\}$$

In [1] and [2], the quadratic expression is the net output obtained from a particular capacity utilization. We can interpret p_i as a variable cost of production. In [1], climate change is represented as a downward shift in the productivity of the old technology. In [2] we have the assumption that climate change has no impact on the new technology.

$$[3] \quad U(C) = \ln\left(\frac{C}{\gamma} + \varepsilon\right) - \ln \varepsilon$$

The inclusion of the parameters γ and ε in [3] allow us to modify the curvature of U , U' and U'' through changes in those parameters. Note in particular that $-U''C/U' = C/(C+\gamma\varepsilon)$.

$$[4] \quad K_{i,t+1} = (1 - \delta_i)K_{it} + I_{it}, \text{ with } K_{10} > 0 \text{ and } K_{20} \geq 0 \text{ given}$$

$$[5] \quad C_0 = Q_{10} + Q_{20} - I_{10} - I_{20} - \begin{cases} S_0, I_{20} > 0 \\ 0, I_{20} = 0 \end{cases}$$

$$C_t = Q_{1t} + Q_{2t} - I_{1t} - I_{2t} - \begin{cases} S_t, I_{2t} > 0 = I_{2s} \text{ for all } s < t \\ 0, \text{ otherwise} \end{cases}$$

In [5] we have the representation of how scale-up cost affects the output left for consumption in the first period that the new technology is introduced. By allowing for $K_{20} > 0$ in [4], we allow for the possibility that there is initially a small amount of operating capacity in the new technology, perhaps as a result of pilot investments; but to significantly expand output, a scale-up cost is incurred.

3. Numerical Simulation of Optimal Investment

3.1 Approach to calculating numerical solutions

To illustrate how option values are affected by the different components of the model, we simplify the set-up by considering optimal consumption and investment choices over five periods ($t = 0, 1, 2, 3, 4$). To mitigate the influence of “end effects” on the interpretation of solutions, we focus mainly on optimal choices in the first three periods.

We assume the following information structure with respect to the uncertain climate change states. At $t = 0$, consumption and investment decisions are made without observing the climate change state in that period. We can think of this period as the time when it is known that climate change is posing a threat to future output with the old technology, but the ratio of noise to signal in assessing climate change is high. Since the state at $t = 0$ cannot be observed, the decision maker sets the climate change damage parameter for that period equal to its expected value.⁴

At $t > 0$, the current state of climate change can be observed before decisions are made. If the state at $t = 1$ is i , then π_{ij} represents the probability that the state is j at time $t = 2$. We impose the following assumptions on these transition probabilities:

$$[6] \quad \pi_{HM} = 0, \pi_{HH} = 1; 0 < \pi_{MH}, \pi_{MM} < 1$$

Note that Harsh climate change at t cannot revert to Mild climate change at $t+1$. Thus if the state is H at $t = 1$, then it is known that the state will be Harsh in all future periods – though the severity can increase over time, i.e. we can and do assume that $\omega_{t+1,H} > \omega_{tH}$. We could relax this assumption to allow for the possibility that a signal of harsh climate change could be noisy (i.e. there is a nonzero probability that the signal will come back Mild in the next period). We defer consideration of that possibility to future work. If the state at $t = 1$ is M , then there is still uncertainty about the state at $t = 2$. At $t = 2$, the current state of climate change again can be observed.

We then assume that for $t = 3, 4, 5$ the climate state remains fixed at its realization at $t = 2$, though the damage parameter associated with that state may continue to increase over time as climate change worsens. We can interpret $t = 3$ as the time at which uncertainty about the trajectory of climate change damage is resolved. This allows us to focus on whether the new technology is scaled up at $t = 0$, $t = 1$, or $t = 2$.

To determine the optimal investment and consumption trajectories and the associated net present value of utility, we start at $t = 2$. Given the climate state and damage parameter in that period as well as numerical values for the capital stocks, we can solve for the optimal investments and consumption from old and new technologies for $t = 2, 3, 4, 5$. By carrying this optimization out for a variety of (K_1, K_2) magnitudes, and for both of the possible climate states and associated damage parameters, we can compute a numerical approximation of the optimal trajectories and value function from $t = 2$ onward. Note that in computing this value function, we must allow for the possibility that $K_{22} = 0$, that $K_{22} > 0$ with scale-up cost incurred because this is the first

⁴ However, in choosing consumption and investments at $t = 0$, the decision maker anticipates being able to observe climate change states going forward from $t > 0$.

investment in the new technology, and $K_{22} > 0$ without scale-up cost incurred because the first investment in the new technology occurred previously.

Next we move back to $t = 1$ and determine the optimal outputs from the new and old technologies given different values of the capital stocks available at that date, and given realizations of the random climate change parameters in that period. With those calculations, we can find the state-dependent investments at $t = 1$ that maximize the expected present value of consumption utility starting at that date. As was done at $t = 2$, we need to separately calculate (based on [5]) optimal investment in the new technology with and without the $t = 1$ scale-up cost, since that cost may already have been borne at $t = 0$. We also need to allow for the possibility of zero new-technology investment.

As noted, we assume that decisions at $t = 0$ need to be made without observing which climate state obtains, so a mean climate damage parameter is used. Because of the recursive nature of the solution, the optimal technology investments at $t = 1$ will reflect the fact that actual investment decisions at $t = 2$ and output decisions for $t \geq 2$ will be made after that period's climate change state is known. In particular, the decision maker takes into account that the economy retains an option not to use the old technology to produce output at $t \geq 2$ if worsening climate change has destroyed its productivity. Similarly, the decisions made at $t = 0$ take into account the subsequent observability of climate states.

3.2 Parameter values

Table 1 below specifies values for many of the basic model parameters that we use in the numerical simulations.⁵ Note that the basic production parameters are set so that the new technology is less productive than the old technology, in the absence of climate change.

Note that the production function parameters are such that the marginal products of additional capacity utilization in the two sectors are parallel lines in light of [1]. The old sector line lies above the new sector line initially but shifts downward as climate change proceeds. The choice of $K_{10} = 3$ is below the long-term steady-state capital stock for the economy without climate change.⁶ We can thus interpret the simulations as describing a situation of a still-developing economy (versus a more mature developed economy) responding to the risk of climate change.

⁵ These values are not calibrated to any particular economy, but are intended to let us carry out a kind of numerical comparative dynamics exercise to explore how different climate change uncertainties affect investment paths.

⁶ That capital stock is about 7.4.

Parameters for:		
Utility Function	γ	12
	ε	0.05
	Single period discount <i>rate</i> *	15%
Capital accumulation	Depreciation rate	0.2
	Scale-up cost for the new sector	0.8
	Initial capital in the old sector	3
	Initial capital in the new sector	0
Production function	A_1 (old)	6.2
	A_2 (new)	5
	B_1 (old)	0.25
	B_2 (new)	0.25
	p_1 (variable cost old)	4
	p_2 (variable cost new)	4

*This high single-period rate implicitly assumes that the “periods” in the model are significantly longer than one year, in order to reflect a relevant time line for industrial transformation.

Table 1: Basic parameters for simulation model

Table 2 below gives the time-invariant one-period transition probabilities we use (the π_{ij}). As noted, “Harsh” is an absorbing state in our simulations. The transition probabilities from “Mild” are not that different than 0.5. We assume also that these figures represent the ex-ante probabilities at $t=0$ of mild or harsh climate change at $t=1$ (i.e., $\rho_M = 0.6, \rho_H = 0.4$).⁷ In other simulations presented further below, we examine alternative values for these probabilities.

	M	H
M	0.6	0.4
H	0	1

Table 2: Transition probabilities for the climate change state.

Tables 3a and 3b show values of the damage parameters (the ω_{tk}) at $t=0,1,2$ under two different assumptions about the variance of these damages, as explained below. The tables also show the corresponding expected values of the climate shocks based on the abovementioned ex-ante probabilities (0.6, 0.4). The tables are constructed so that these ex-ante mean damage values are the same across the two cases.

In Table 3a, the volatility of the climate change damage path is lower than in Table 3b, in the sense that variance at $t=1$ conditional on the state at $t=0$ being Mild is lower in Table 3a than

⁷ This simple two-state representation of climate change states can be thought of as a crude approximation of a more complex distribution that has distinct “Mild” and “Harsh” areas of the state space.

Table 3b (0.5 versus 0.9), for the given path of mean damage values (that is the same in both cases). This is accomplished by having the spread between Harsh and Mild damages for any given t larger in Table 3b than Table 3a. It turns out that this property has a large influence on the value of the option provided by new technology investment, as we discuss below. To draw out these points, we also include a third set of damage parameters with “medium” volatility (0.75) in Table 3c.

Climate Change State	Damage factor, $t=0$	Damage factor, $t=1$	Damage factor, $t=2$
Mild	--	0.29	0.32
Harsh	--	0.80	0.90
Mean	0.42	0.49	0.55

Table 3a. Magnitudes of climate shocks – lower ex-ante variance (SD = 0.5)

Climate Change State	Damage factor, $t=0$	Damage factor, $t=1$	Damage factor, $t=2$
Mild	--	0.12	0.14
Harsh	--	1.05	1.18
Mean	0.42	0.49	0.55

Table 3b. Magnitudes of climate shocks – higher ex-ante variance (SD = 0.9).

Climate Change State	Damage factor, $t=0$	Damage factor, $t=1$	Damage factor, $t=2$
Mild	--	0.21	0.23
Harsh	--	0.92	1.04
Mean	0.42	0.49	0.55

Table 3c. Magnitudes of climate shocks – medium ex-ante variance (SD = 0.75).

3.3 Simulation results

Table 4 contains the expected value of the sum of discounted utilities given the different ex-ante variances of damages in Tables 3a-3c. In the stochastic optimization, immediate initial deployment of the new technology at $t = 0$ would create an option to expand this technology in the next period at lower incremental cost (given the absence of additional scale-up cost), the exercise of which depends on information gained about the climate change state. Table 4 indicates that this option is valuable if the ex-ante variance of climate change damage is relatively high, while it is not valuable when the ex-ante damage variance is relatively low. Somewhere in between there would be a critical value of the ex-ante damage variance in which the decision maker would be indifferent between deploying the new technology and not doing so. The medium variance case was constructed to show this.

When new technology is deployed	Ex-ante expected value of welfare function under stochastic dynamic optimization			Certainty-equivalent value
	Lower ex-ante damage variance (SD=0.5)	“Medium” ex-ante damage variance (SD=0.75)	Higher ex-ante damage variance (SD=0.9)	
$t=0$	6.167	6.063	5.99	No uncertainty, same mean values of damages (SD=0.0)
$t=1$	6.216	6.064	5.95	6.451
$t=2$	6.124	6.063	5.75	6.484
Never	6.242	6.059	5.93	6.467
				6.506

Table 4. Ex-ante expected welfare under different damage variances

For comparison, the right-hand column of Table 4 shows the solution of the deterministic problem obtained by replacing all uncertain climate change damages with their ex-ante expected values as of $t = 0$, and then solving the deterministic optimization problem as an open-loop control problem with pre-committed decisions. Welfare would be higher with these non-stochastic damages.⁸ The new technology does not get introduced. This is consistent with the argument above, since there is zero ex-ante variance of damages in this case.

Tables 5a through 5d show the investment paths along different branches of the decision tree for the three different ex-ante damage variances, as well as for the certainty-equivalent. The second column shows the sequence of climate change states along the branches, e.g. MM means that climate change at $t = 1$ is Mild and it stays Mild at $t = 2$. Note that the old and new investments respectively at $t = 0$ are the same across the decision tree branches. This reflects the assumption that the climate change state at $t = 0$ is not observed, but its expected value is utilized in making investment decisions. At $t = 1$, the decision maker chooses investment rates for both of the technologies if the climate change state is observed to be Mild, and rates if it is observed to be Harsh. That is why, in the columns for $t = 1$, the investment rates in the MM and MH rows are same for both old and new technologies. Finally, at $t = 2$ the climate change state again is observed and optimal investments for that state are determined under the assumption that the observed climate change state continues over the rest of the periods (see discussion in section 3.1 above).

In Table 5a, with lower ex-ante damage variance and no investment in the new technology, there is fairly strong investment in the old technology at both $t = 1$ and at $t = 2$ along the branch MM. Investment made at $t = 1$ along HH is much lower than along the other two branches, since climate damage already has reduced the productivity of the old technology considerably and thus raised the opportunity cost of investment in terms of foregone consumption. The table shows the importance of state-dependent investment decisions for the old technology through the

⁸ Because the welfare function is concave, its value given mean values of the stochastic parameters is larger than the expected value of the function over realizations of the random parameters.

differences between investments at $t = 1$ and $t = 2$ depending on whether the climate change state is M or H.

In Table 5b, with higher ex-ante damage variance, there is investment in scaling-up the new technology at $t = 0$, which basically crowds out added investment in the old technology (given that the two technologies produce the same final consumption good). Given that the fixed cost of scaling up the new technology has been incurred at $t = 0$, further significant investment in the new technology occurs at $t = 1$, and at $t = 2$ if the climate state is Harsh and old-technology productivity has thus been significantly degraded. At $t = 1$, total investment in the old and new technologies is larger than the investments in the old technology in Table 5a, reflecting the lower productivity of the new technology compared to the old technology prior to the degrading effects of climate change. The economy incurs higher investment costs in Table 5b in order to have a hedge against the more severe impacts of climate change if the state is Harsh.

In Table 5c, the new technology scale-up occurs at $t = 1$. This causes a shift in old technology investment from $t = 1$ to $t = 0$ as the decision maker anticipates the introduction of the new technology at $t = 1$, whether the climate change state is Mild or Harsh then. If instead there was no new technology investment, the old technology investment pattern would resemble that of table 5a.

Table 5d shows the sequence of investments for the certainty-equivalent problem. As noted, there is no investment in the new technology in this case. Because the certainty-equivalent ignores the possibility for updating observations of climate change states and adjusting investments accordingly, it involves inefficiently high investment in the old technology for $t = 1, 2$ if the climate change state is Harsh.

Technology	Sequence of climate change states at $t = 1, 2$	investment at $t=0$	investment at $t=1$	investment at $t = 2$
OLD	MM	1.53	1.39	1.08
	MH	1.53	1.39	0
	HH	1.53	0.52	0
NEW	MM	0	0	0
	MH	0	0	0
	HH	0	0	0

Table 5a. Optimal investment with lower ex-ante damage variance (SD=0.5)

Technology	Sequence of climate change states at $t = 1, 2$	investment at $t=0$	investment at $t=1$	investment at $t = 2$
OLD	MM	0.52	1.07	1.89
	MH	0.52	1.07	0
	HH	0.52	0	0
NEW	MM	0.92	1.03	0
	MH	0.92	1.03	0.34
	HH	0.92	0.96	0.35

Table 5b. Optimal investment with higher ex-ante damage variance (SD=0.9)

Technology	Sequence of climate change states at $t = 1, 2$	investment at $t=0$	investment at $t=1$	investment at $t = 2$
OLD	MM	1.70	0.23	1.75
	MH	1.70	0.23	0
	HH	1.70	0	0
NEW*	MM	0	1.58	0
	MH	0	1.58	0.41
	HH	0	0.71	0.63

*Shown here are the results for new investment starting at $t = 1$. Since this case is constructed such that the decision maker is indifferent between scaling up the new technology and not doing so (see Table 4 above), and it turns out that having the new investment at $t = 1$ or $t = 0$ also is essentially a matter of indifference, the patterns of new and old investment shown here are only of three distinct possibilities including no investment in scaling up the new technology and investment in the old sector spread more evenly across $t = 0,1$.

Table 5c. Optimal investment with “medium” ex-ante damage variance (SD=0.75) and scaling up of the new technology

	investment at $t=0$	investment at $t=1$	investment at $t = 2$
OLD technology investment	1.60	1.22	0.52

Table 5d. Optimal old-technology investment for the certainty-equivalent

Tables 6a through 6c show the consumption paths for four periods given lower, higher and “medium” ex-ante damage variances. In all the tables the impacts of a Harsh realization of climate change on consumption are apparent. It is also noteworthy that the initial ($t = 0$)

consumption rate declines as the ex-ante variance grows. However, that pattern is affected by the effects of scale-up costs in Table 6b (at $t = 0$) and Table 6c (at $t = 1$).

Sequence of climate change states at $t = 1,2$	Consumption at $t = 0$	Consumption at $t = 1$	Consumption at $t = 2$	Consumption at $t = 3$
MM	2.69	4.20	4.86	5.91
MH	2.69	4.20	3.32	2.75
HH	2.69	3.05	3.08	2.48

Table 6a. Optimal investment with lower ex-ante damage variance (SD=0.5)

Sequence of climate change states at $t = 1,2$	Consumption at $t = 0$	Consumption at $t = 1$	Consumption at $t = 2$	Consumption at $t = 3$
MM	1.98	3.71	5.06	7.73
MH	1.98	3.71	3.07	2.92
HH	1.98	2.15	2.69	2.61

Table 6b. Optimal investment with higher ex-ante damage variance (SD=0.9)

Sequence of climate change states at $t = 1,2$	Consumption at $t = 0$	Consumption at $t = 1$	Consumption at $t = 2$	Consumption at $t = 3$
MM	2.51	3.55	4.98	7.41
MH	2.51	3.55	3.26	3.21
HH	2.51	1.50	2.36	2.84

Table 6c. Optimal investment with “medium” ex-ante damage variance (SD=0.75)

3.4. Parameter Sensitivity Analyses

Table 7 below shows the value of the welfare function under the two changes in parameter values – zero initial scale-up cost, and larger initial capital stock for the old technology. These are worked out assuming medium ex-ante variance of damages (SD=0.75), since with those damages the economy is indifferent between investing and not investing in the new technology at $t = 0$ by construction, given the initial parameter values.

Parameter changed:	Timing of initial investment in new technology	Expected present value of utility
Initial startup cost = 0	New technology $t=0$	6.42
Higher initial capital ($K_{10} = 3.3$ instead of 3.0)	No new technology	6.15
	New technology $t=0$	6.43
	New technology $t=1$	6.43

Table 7: Sensitivity analyses

As would be expected, no scale-up cost tips the balance in favor of new technology investment at $t = 0$ (compare the values above to the value of welfare of about 6.04 in Table 4). With higher initial capital for the old technology, the economy can produce more and thus faces a softer tradeoff between current consumption and new technology investment at both $t = 0$ and $t = 1$. As it turns out in this case, that makes new technology investment at $t = 0$ or $t = 1$ is better than not investing in the new technology.

4. Responses to Less Probable But More Extreme Climate Change Risks

4.1 Parameter values

In this section we examine the properties of different investment responses to climate shocks that are less likely but more severe than those considered in Section 3. Specifically, we assume that

$$\rho_M = 0.8, \rho_H = 0.2,$$

whereas previously we assumed $\rho_M = 0.6, \rho_H = 0.4$. Similarly, we assume that

$$\pi_{MM} = 0.8, \pi_{MH} = 0.2,$$

so that the Mild climate change state is more likely to persist than assumed before. With these assumptions, we also assume that if a Harsh climate change state occurs, its impacts are considerably more serious than assumed previously. Specifically, we assume the following set of climate damage parameters:

Climate Change State	Damage factor, $t=0$	Damage factor, $t=1$	Damage factor, $t=2$
Mild	--	0.32	0.36
Harsh	--	1.17	1.32
Mean	0.42	0.49	0.55

Table 8. Climate change damage parameters with less likely but larger Harsh-state damages (ex-ante SD=0.55)

Comparing Table 8 to Table 3a, in which the climate change damage parameters have roughly the same ex-ante variance, one sees that the sequence of ex-ante mean damage parameter values is the same but the Harsh damage parameters are much larger in Table 8. In fact, the Harsh damage parameters in Table 8 are considerably larger than those in Table 3b, in which the ex-ante variance of damages is much higher (SD=0.9).

One response to these less likely but more extreme climate change risks is simply to choose optimal investment and consumption trajectories as in the previous section. We compare that response to an alternative that we label as “precautionary,” in that it involves suspension of any investment in the old, climate change-vulnerable technology at $t = 0,1$, pending identification of the longer-term state of climate change at $t = 3$.

4.2 Simulations

Tables 9a and 9b show the optimal and precautionary investment trajectories, while Tables 10a and 10b show the associated consumption trajectories. Note from Table 9a that the optimal solution includes bearing the scale-up cost for the new technology at $t = 0$; this is necessarily the case in the precautionary solution. We see from Tables 9a,b that total investment in both technologies is lower with the precautionary approach, a reflection of the lower productivity of the new technology until climate change damages have become significant. In this case, in fact, total investment is lower in the precautionary approach in almost all cases.

Technology	Sequence of climate change states at $t = 1, 2$	investment at $t=0$	investment at $t=1$	investment at $t = 2$
OLD	MM	0.53	1.00	1.43
	MH	0.53	1.00	0
	HH	0.53	0	0
NEW	MM	0.90	0.86	0
	MH	0.90	0.86	0.39
	HH	0.90	0.92	0.39

Table 9a. Optimal investments with less likely but larger Harsh-state damages

Technology	Sequence of climate change states at $t = 1, 2$	investment at $t=0$	investment at $t=1$	investment at $t = 2$
OLD	MM	0	0	1.51
	MH	0	0	0
	HH	0	0	0
NEW	MM	1.19	1.21	0
	MH	1.19	1.21	0.18
	HH	1.19	0.86	0.30

Table 9b. “Precautionary” investments with less likely but larger Harsh-state damages

Sequence of climate change states at $t = 1,2$	Consumption at $t = 0$	Consumption at $t = 1$	Consumption at $t = 2$	Consumption at $t = 3$
MM	1.98	3.38	4.58	6.36
MH	1.98	3.38	2.44	2.44
HH	1.98	1.83	2.33	2.30

NPV = 6.12

Table 10a. Optimal consumption with less likely but larger Harsh-state damages

Sequence of climate change states at $t = 1,2$	Consumption at $t = 0$	Consumption at $t = 1$	Consumption at $t = 2$	Consumption at $t = 3$
MM	2.23	3.59	3.13	5.38
MH	2.23	3.59	2.63	2.32
HH	2.23	1.91	2.34	2.23

NPV = 6.02

Table 10b. “Precautionary” consumption with less likely but larger Harsh-state damages

In tables 10a,10b we see that less total investment in the precautionary approach is accompanied by more consumption in the near term ($t = 0,1$) but less consumption thereafter, compared to the optimal strategy. Even with more front-loaded consumption, the NPV of utility is notably lower in the precautionary approach. Thus, a precautionary approach defined only in terms of investing in the ostensibly less vulnerable technology actually is not precautionary at all. While the incumbent technology is more vulnerable, it still plays a critical role in the evolution of the economy to increasing but uncertain climate change shocks.

4.3 Climate risks and “stranded assets”

In discussions of climate change risks, the term “stranded assets” is sometimes used to describe quantities of previously productive capital that have become uneconomic to operate before they have been fully depreciated.⁹ Put another way, suppose the economy has evolved toward a steady-state with negligible climate change. Climate change then starts to be observed and built into investment and consumption decisions. How does this affect utilization of old technology capital and new technology investment?

In our simulations in Section 3, old-technology capacity is fully utilized in almost all cases. This is in part due to our assumed value for K_{10} that is below the steady-state level for the economy in the absence of climate change. There is still room for growth in the economy facing the climate change risks evaluated in Section 3, and that growth is best accomplished by continuing to use and even add to the capacity of the incumbent technology, while adjusting investment in that

⁹ In public utility economics, the term “stranded assets” refers to assets unexpectedly rendered unproductive to operate due to a shaft in policy or unanticipated market conditions. An analogy in the context of climate change is the possibility that more carbon-intensive energy production facilities, or facilities for the production of other goods using carbon-intensive energy, could become uneconomic because of domestic carbon emissions constraints or border taxes imposed by other countries on such commodities.

technology downward over time as climate change damages become more serious and, if economic, the new sector is built up.

The one exception we observe in the simulations in Section 3 is that if the climate change state is M at $t = 1$ but H at $t=2$, some old technology capacity is not utilized but is simply depreciated. Because the state of climate change remains uncertain at $t = 1$, with continuation of Mild being more likely than a switch to Harsh in the next period, it is economic to build up the old sector in the nearer term, even though there is some prospect of that additional capital not being used if the subsequent climate change state is Harsh.

In the simulations in Section 4.2 above, there are no stranded assets (in the way we define the term here) under the optimal solution, and necessarily none in the precautionary solution.¹⁰ We do however find significant stranded assets for both old and new technologies if we consider “ignorant,” non-adaptive investment trajectories. To show this, we return to the sort of certainty-equivalent solution already discussed in connection with Table 4 above. This solution is computed as the optimum for the open-loop control problem with all damage parameters set at their ex-ante expected values as of $t = 0$, as shown in Table 8. Actual damage parameters assume the values shown in Table 8 for realizations of Mild or Harsh climate change states.

Suppose we fix the investment trajectories at their certainty-equivalent outcomes, while actual outputs and consumption adjust over time depending on how climate change damages evolve. Table 11 shows the implications for old sector capital utilization. Because investments are based entirely on ex-ante expectations of damages over time, in this non-adaptive investment solution there is not an economic motivation to scale up the new technology – though doing so is optimal, as shown in Table 9a. Instead, significant investments are made based on a fixed set of a priori beliefs regarding moderate and gradually rising climate change damages. This investment works out if the climate change state remains Mild. However, it results in significant unutilized capacity if the climate change state turns to Harsh: having over-built the old technology based on erroneous, non-adaptive expectations of climate change damages, the only option when old sector productivity is more severely affected by climate change is to leave some capacity unused. This is especially the case at $t = 2$.

¹⁰ Some stranded old-technology assets are observed if, contrary to the optimal investment plan, the new technology is not scaled up at $t = 0$. In that case the economy would choose more initial investment than optimal in the old sector, leaving more assets exposed to stranding if the climate change state subsequently changes from Mild to Harsh.

	Climate change states for $t = 1,2$	$t = 0$	$t = 1$	$t = 2$	$t = 3$
Pre-determined Old sector investment*	any combination	1.60	1.22	0.52	0
Actual Old sector unutilized capital**	MM	0	0	0	0
	MH or HH	0	0	0.89	1.04

*As determined by the certainty-equivalent solution.

** As determined by the actual evolution of climate change states, output, and consumption.

Table 11. Implications of non-adaptive investment planning

5. Calculating a Real Option Value for New Technology Investment

Investing in the new technology earlier provides an option for less costly incremental investment in the new sector later if climate change is persistently Harsh.¹¹ On the other hand, deferring new technology investment also defers the sunk cost of the initial scaling-up. In addition, because the outputs of the old and new technologies are perfect substitutes in consumption in [5], and the climate damage is additive in [1], we cannot discuss option values solely in terms of the new technology. A larger early investment in the old technology provides an option for higher consumption later on even if climate change is Harsh, and it provides an option for deferred investment in the new technology with lower impact on future consumption (taking into account in particular the scale-up cost).

The scale-up cost for the new technology provides a convenient way to value a kind of call option for developing production capacity using the new technology. Specifically, we can vary the scale-up cost so as to find a value that leaves the economy indifferent between investing and not investing in the new technology at $t = 0$. If and only if the scale-up cost is lower than this break-even value then the economy finds it efficient to make the investment.

The implied real option value can be defined by the difference between the break-even value of scale-up cost for new technology for a given level of volatility, and the break-even value of scale-up cost for new technology, assuming volatility equals zero:

$$[7] \quad ROV(v) = BEC(v) - BEC(0)$$

where $ROV(v)$ denotes a real option value of the new technology for a given volatility v , and $BEC(v)$ stands for a break-even value of scale-up cost for the new technology given volatility v . The interpretation of [7] is as follows: if volatility was zero, and thus there were no risk, there would be no need to keep options open. The right-hand side of [7] is how much more the planner would be willing to pay at $t=0$ to have the option of access to the new technology at $t=1$.

¹¹ If climate change is Harsh and there was no investment in the new sector, production using the old technology would sharply decline. That would in turn raise the cost of subsequent investment in the new technology because of sharper competition between consumption and investment with more limited total output.

The scale-up cost of $S_0 = 0.8$ is the value of $BEC(\nu)$ when climate change damages have “medium” ex-ante variance (see Table 3c and Table 4). More generally, the second column of Table 12 shows the start-up costs that render the decision maker indifferent between scaling up and not investing in the new technology at $t = 0$ for a variety of different ex-ante damage variances. All of these are constructed using the same sort of assumptions as those underlying Tables 3a – 3d. In particular, all the break-even scale-up costs assume the same transition probabilities and ex-ante mean damages over time as those assumed in Section 3.

Ex-ante volatility (SD)	Break-even value of scale-up cost for new technology	Real option value (in terms of output and consumption)
0	0.33	0
0.3	0.45	0.12
0.5	0.58	0.24
0.6	0.67	0.34
0.75	0.81	0.48
0.9	1.00	0.66
1.1	1.31	0.98
1.3	1.70	1.37

Table 12. Values of break-even scale-up costs and associated real option values for different ex-ante damage variances

As expected, the option value associated with early deployment of the climate-resilient production technology increases with a higher ex-ante damage variance. Figure 1 below traces out the mildly convex curve relating ex-ante standard deviations of damages against the associated real option values.

An option value of the new technology is high enough to make a difference in decision on deployment a new technology. For instance, if $\nu=0.9$, $ROV=0.66$. It is about 10% of the total monetized value of discounted utility.

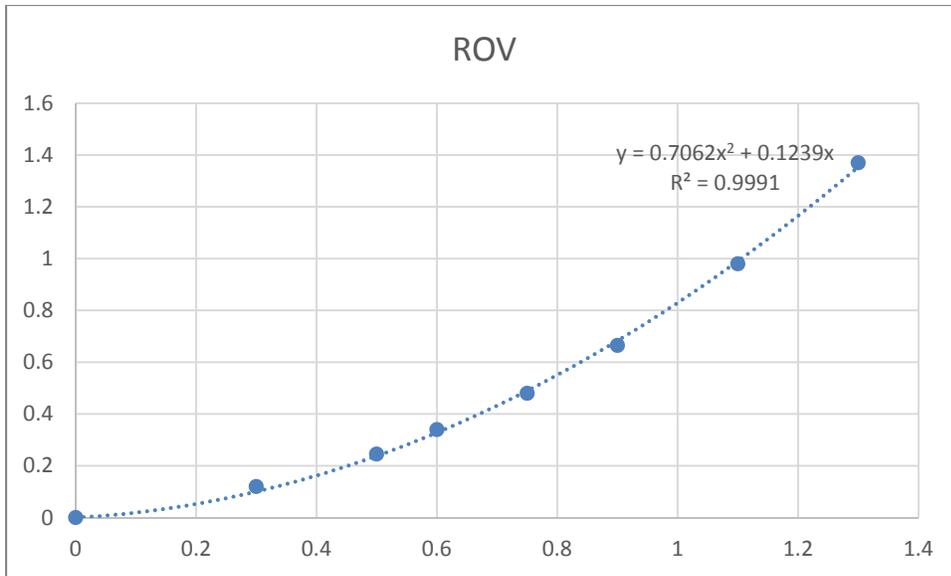


Figure 1. Graph of real option values for different ex-ante standard deviations of climate change damages.

6. Concluding Remarks

In this paper we use numerical examples based on a simple analytical model of adaptive sequential investment and consumption decisions to show how the option of early investment in a not-yet-competitive but less climate change-vulnerable technology can be an effective hedging strategy against the possibility of serious future climate shocks. The value of the option depends on how rapidly climate change degrades the productivity of the economy's established technology, but it also depends on how volatile damages over time are expected to be, ex-ante. A higher ex-ante variance increases the value of the hedge.

Investment in the new technology also depends on the cost of initially scaling it up, which introduces a non-convexity into the choices of efficient investments and consumption. As expected, lower scale-up costs imply more aggressive investment in the new technology. In addition, a higher ex-ante damage variance increases the impetus for earlier investment in the new technology, for any given scale-up cost. In fact, the size of scale-up cost that leaves the economy indifferent between investing and not investing in the new technology can be used to define the value of early investment in the less climate change-vulnerable technology as a sort of call option.

Even if the new technology is being scaled up, investment in the old technology may continue for some period of time. The incentives for continued old technology investment depend on several factors, including the size of the risk that climate change will rapidly render the old technology uneconomic; the value in expanding old technology capacity to help smooth consumption while new technology production capacity is built up; and the starting level of total productive capacity in the economy. By the same token, optimal adaptive investment trajectories do not result in many cases of excess old-technology capacity in the face of climate change damages. In our simulations the economy still benefitted from increasing overall productive

capacity. Only if the capital stock were near saturation prior to a rapid onset of damaging climate change might one see large amounts of old-technology capacity “stranded.”

One high-priority extension of the paper is to introduce uncertainty on the cost performance and climate-resilience of the new technology. More generally, further investigation of the value of scaling up more climate-resilient technology under different combinations of uncertainty and irreversibility may help to identify an adequate deterministic approximation of the option values associated with such investments, as in e.g. Dixit (1992).

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