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ScienceDirect

Energy Procedia 00 (2010) 000–000

Energy Procedia

www.elsevier.com/locate/XXX

GHGT-10

Assessing early investments in carbon capture and storage technology under uncertainty

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Elsevier use only: Received date here; revised date here; accepted date here

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Abstract

We investigate whether the existence of learning-by-doing and significant future uncertainties create circumstances where early investment in coal-fired power with carbon capture and sequestration (CCS) creates an option values for society, when broader greenhouse gas emissions policies are applied. A decision analytic framework is constructed using results from the MIT Emissions Prediction Policy Analysis (EPPA) model. The decision examined is whether to invest $5 billion annually in coal with CCS technology, and the uncertainties modeled are the stringency of the future US greenhouse gas emissions policy, the size of the US natural gas resource, and the nth-of-a-kind levelized cost of electricity from coal with CCS. We measure the cost to society for every scenario as economic welfare and perform sensitivity analysis on the probabilities of each uncertainty to determine the conditions under which society benefits from early investments in CCS and option values exist. We find that the net present value cost (using a 4% discount rate) to society of meeting a prescribed emissions policy could increase by up to $1.9 trillion or decrease by up to $2.4 trillion over a 100-year period by investing in CCS today. We find that the three uncertainties have different relative impacts on the early investment decision. The amount of natural gas resource has the smallest effect, while the stringency of the emissions policy is the most influential.

Keywords: Carbon capture and sequestration; CCS; economic modeling; uncertainty analysis; option values

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1. Introduction

The future energy mix of fuels and technologies that will develop depends on several factors that have significant uncertainty. These uncertainties include the stringency of future greenhouse gas (GHG) emissions policies, the abundance of fuel resources, and the technology costs, among others. However, many widely cited reports intended to inform policymakers about what energy sources should be used to avoid serious irreversible harms from climate change do not take uncertainty into account, such as Socolow and Pacala's wedge analysis [3] or the Electric Power Research Institute (EPRI) Prism Analysis [1]. Learning-by-doing, where costs are reduced with experience, is a generally accepted phenomenon supported by empirical evidence [2] and is represented in models in various ways

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as a form of technical change. Investment in technologies can promote innovation and effect technical change and cost reduction. Given that costs decrease with experience, and that we face substantial uncertainty over future demands for energy technologies, this motivates the investigation into whether there could be benefits to society from early investments in high-cost, unproven technologies, such as carbon capture and sequestration (CCS), to accelerate the learning-by-doing process so that we have the option of using them in the future at lower costs should demand increase unexpectedly.

This study uses outputs from the MIT Emissions Prediction Policy Analysis (EPPA) model, a top-down computable general equilibrium model, in a decision analytic framework to investigate the value of investments in coal with CCS when uncertainty is taken into account. We first explore deterministic scenarios and observe there are conditions where investment in CCS is beneficial to society, and others when it is not. Using the decision analytic framework, sensitivity analysis on the probabilities of the uncertainties examined shows how policymakers' investment decision in CCS should change as likelihoods of circumstances are varied, with the objective of optimizing societal welfare.

2. Emission Prediction and Policy Analysis (EPPA) model and decision framework

The MIT Emissions Prediction Policy Analysis (EPPA) model is a multi-region, multi-sector, recursive dynamic representation of the global economy [4]. EPPA was developed by the MIT Joint Program on the Science and Policy of Global Change and is designed to analyze economic growth under different policies and scenarios. EPPA is a computable general equilibrium (CGE) model, and thus represents the circular flow of goods and services within the economy, solving in 5-year time steps from 2000 to 2100. Individual energy technologies are represented, and so investments can be directed to specific technologies. Technology costs are defined by their markup, which is the levelized cost of electricity from n^{th}-of-a-kind generation relative to electricity prices in the 1997 base year of the model. EPPA represents capacity constraints on rapid expansion of new technologies in a way that emulates learning-by-doing, with costs decreasing as experience and capacity is increased, making EPPA an appropriate model to use for this investigation.

2.1. Deterministic scenarios

Societal welfare is an output from EPPA and the cost of a particular policy is calculated as the percentage difference from welfare in the Policy scenario to the welfare in the No Policy case. For the reference case, in which no emissions policy is applied, the energy technology mix is shown in Figure 1.

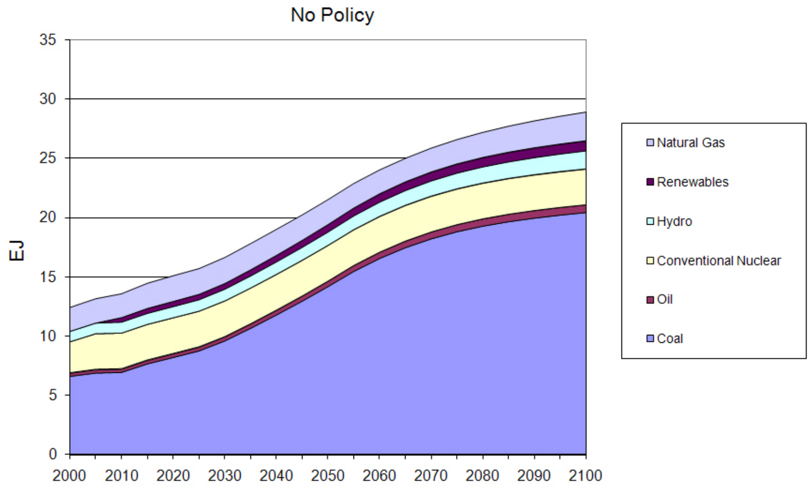

Figure 1 Energy use in the USA, No emissions policy

We also model a hypothetical policy case in which an economy-wide emissions cap is applied that reduces emissions to 75% below 2005 levels by 2100. Figure 2 shows the resulting technology mix, first with no early investment in CCS, and then with an early investment of $5B in every year from 2015 to 2050. This value is chosen for the investment as it is the same order of magnitude in terms of dollar amount and time scale of HR2454 passed in the House of Representatives. [5].

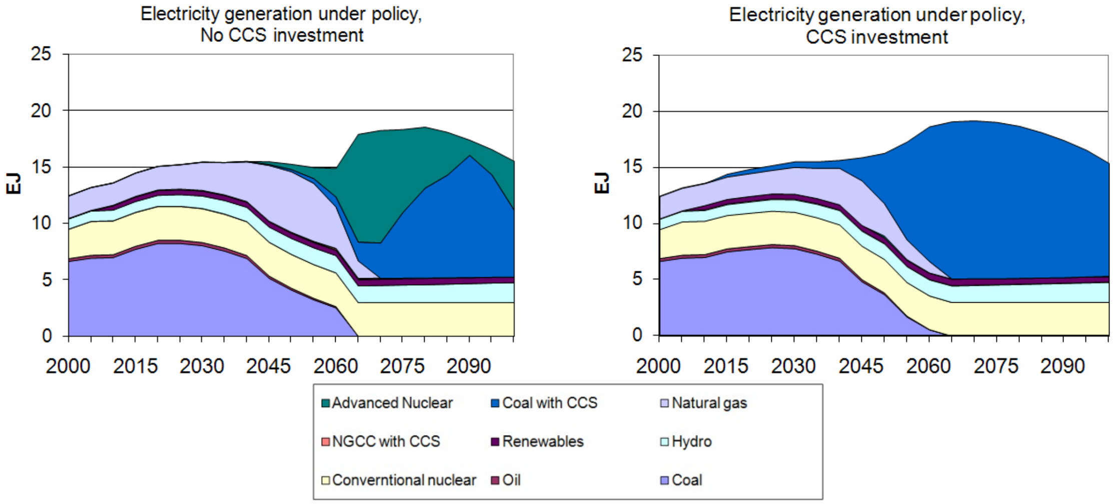

Figure 2 US Electricity mix under a CO_2 emissions policy without and with CCS investment.

When the emissions policy is applied, conventional coal generation is forced out of the mix, and Advanced Nuclear and coal with CCS are phased in. Advanced Nuclear here represents electricity from new nuclear plants, while conventional nuclear represents the existing US fleet. However, the case where an emissions policy *and* investment in CCS is made, Advanced Nuclear is locked-out of the market and coal with CCS dominates. This is because CCS enters the market earlier due to the investment, and so undergoes learning by doing, reducing costs to nth-of-a-kind levels by the time the carbon price is high enough to create demand-pull for Advanced Nuclear. Since it had no early investments, Advanced Nuclear was not undergoing any learning and is too expensive to compete with CCS (i.e., it is locked-out).

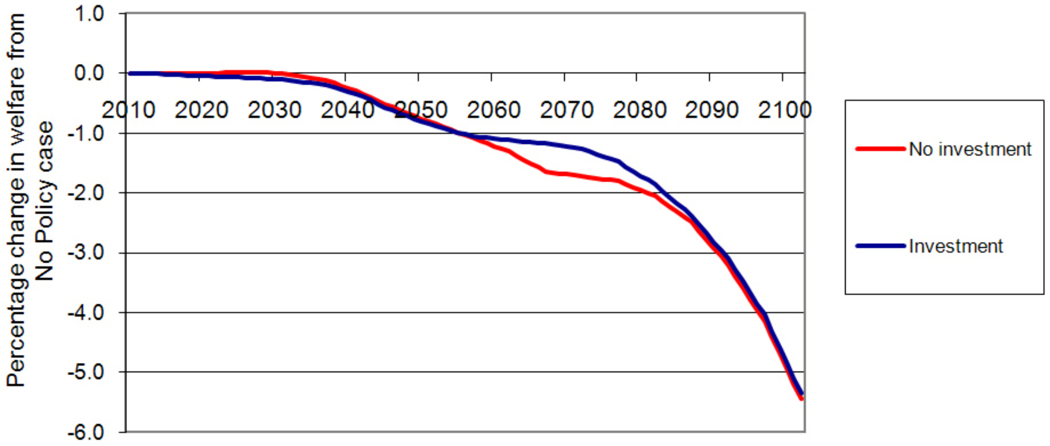

Figure 3 Graph of welfare comparison under CO_2 emissions policy

In order to determine whether it is a good policy to invest in CCS, we must compare societal welfare in each case. EPPA only measures the costs of emissions policies, and not the benefits, and so percentage changes in welfare are always negative when a policy is applied. The smaller the (negative) change in welfare, the more preferred the policy. Figure 3 shows that at the beginning of the century, the case with investment is worse, since CCS is not widely deployed. However, the situation reverses later in the century, when coal with CCS is demanded more to satisfy climate policy.

In order to determine whether the later benefits of the investment outweigh the upfront costs, the net present value (NPV) can be calculated by discounting the outputs of welfare in every period. For this study, we use a 4% discount rate (see Table 1). The benefit from investment is the difference in welfare between the two cases. The NPV of welfare in the case with investment is higher than the no investment case and, therefore, for this scenario investment in CCS better than not investing.

Table 1 Benefits of CCS investment under stricter emissions policy

	NPV of welfare 2005-2100 discounted at 4% (Trillions of $)	**Percentage change in NPV of welfare from No Policy NPV of welfare**
No Policy	3797.03	-
No investment	3741.77	-1.455
Investment	3743.10	-1.420
Benefit of investment	1.33	0.035

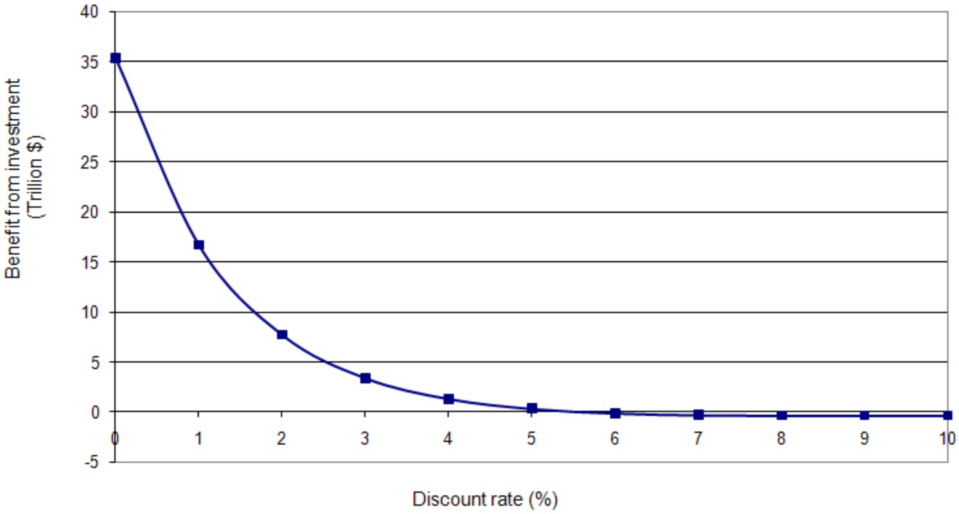

Figure 4 Sensitivity test of discount rate on investment benefit under CO_2 emissions policy

Because of the intertemporal tradeoffs of costs now for savings later, it is important to perform sensitivity analysis on the discount rate assumption (Figure 4). A lower discount rate gives a greater benefit, and a higher rate makes the benefit negative. In this case, if we know the emissions policy to be 75% reduction, and the discount rate is 4%, we know it is better to invest. However, if the policy is less stringent this may not be the case. Other assumptions in the scenario, such as fuel costs or technology costs, are also uncertain. This motivates the analysis of the decision of whether to invest or not using the uncertainty analysis framework presented below.

2.2. Uncertainty Analysis

A decision analytic framework was constructed to explore whether or not to make an early investment (i.e., before the technology is competitive) of $5B annually from 2015 to 2050 in coal with CCS technology. Three uncertainties were modeled: the stringency of the emissions path, the amount of natural gas resource available (affecting the natural gas price), and the cost of CCS technology[1]. The ranges of uncertainty are shown in Table 2. The gas resource size and the markup for coal with CCS in the reference case are the same values used for the deterministic case described in section 2.1.

Table 2 Parameter values and ranges for uncertainty analysis.

Uncertainty	**Reference**	**Lower extreme**	**Upper extreme**
Stringency of emissions path	50% reduction in GHG emissions from 2005 levels by 2100	'Stricter' path: in 2030 path changes from reference to 75% reduction in GHG emissions from 2005 levels by 2100	'Less stringent' path: in 2030 path changes from reference to 30% reduction in GHG emissions from 2005 levels by 2100
Size of US gas resource	1650 EJ	Small resource: 1100 EJ	Large resource: 2200 EJ
Levelized cost of electricity from n^{th}-of-a-kind coal with CCS	Markup 1.54	Markup 1.4	Markup 1.6

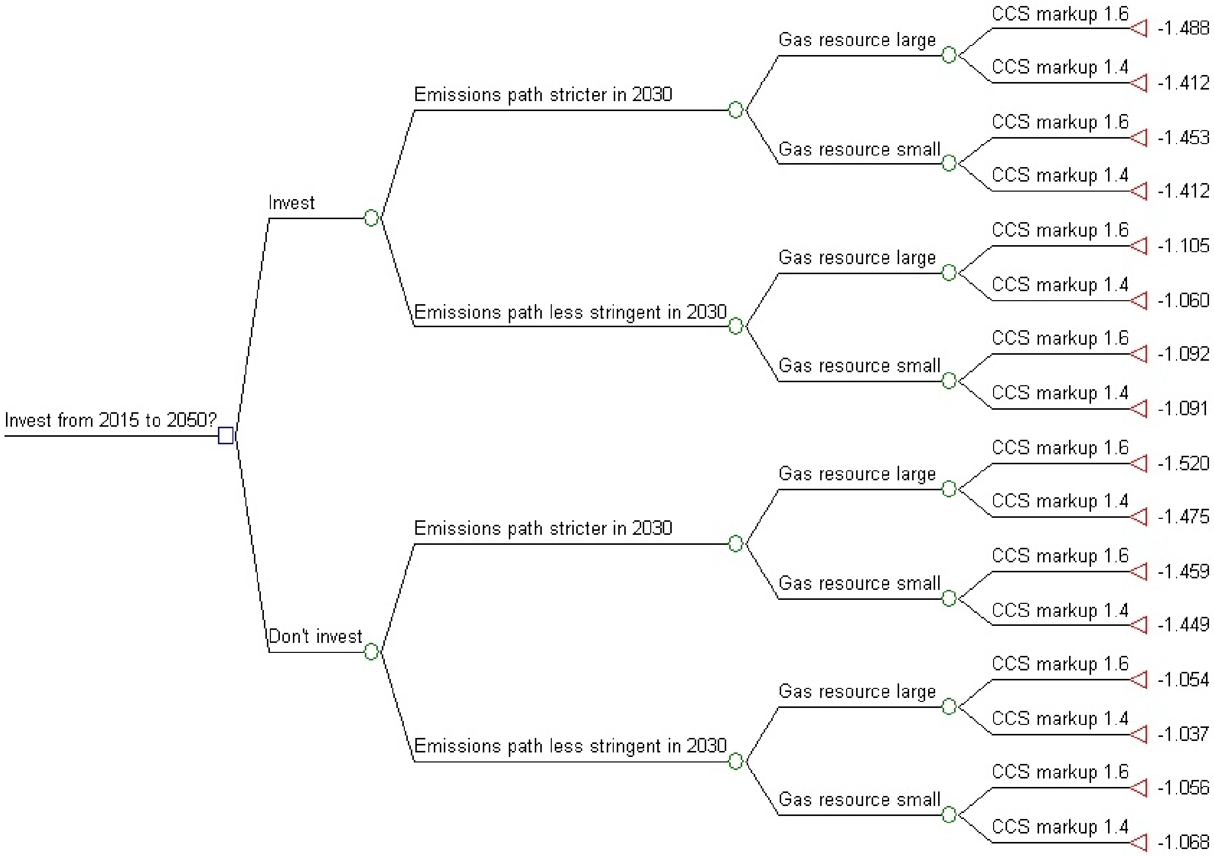

Figure 5 Decision tree with percentage change in NPV from No Policy NPV as outputs

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[1] The relative technology cost in EPPA is defined by the markup. Conventional coal plants have a markup of 1. In the reference case, coal with CCS has a markup of 1.54, meaning that electricity from coal with CCS is 54% more expensive conventional coal. It should be noted that the markup is based on market prices (includes transmission and distribution costs), not just production costs.

Based on these uncertainties, we construct the decision framework shown in Figure 5. Each branch is one scenario run in EPPA. The payoffs are the percentage change in NPV of welfare for the particular case, from the NPV of welfare for the No Policy case.

Once the initial decision, 'invest' or 'don't invest', is made, the future possibilities and their associated probabilities are the same. Comparing one end payoff following the 'invest' choice, to the corresponding payoff following the 'don't invest' choice allows one to see whether investment for a particular scenario has net savings. If we make early investments in CCS, the maximum payoff scenario on the above tree is \$2.4 trillion[2] over the century, corresponding to the emissions path becoming stricter, the gas resource being large, and a CCS markup of 1.4. We find the greatest loss of welfare to be \$1.9 trillion[3] the emissions path becomes less stringent, the gas resource being large and a CCS markup of 1.6.

Rather than assume fixed probability distributions for each uncertainty, we perform two-way sensitivities on two of the uncertainties, holding the third uncertainty constant at a low probability of 0.1, and then 0.9, and solving the tree for every possible pair of probabilities. In this way, we can determine the circumstances when society would benefit from an early investment and when it would not. These results are shown in Figure 6.

The graphs show that as the probability of high cost CCS increases, it is less beneficial to invest; we should not invest in a technology that ultimately will be expensive instead of a more competitive alternative such as Advanced Nuclear. The graphs also show that as the probability that the emissions path will become stricter increases, it is better to invest early in CCS.

For the uncertainty ranges examined, comparing the graphs on the left to the corresponding graphs on the right show that the stringency of the emissions policy affects the investment decision the most, while the size of the gas resource affects it the least. The effect of the stringency of the emissions path uncertainty is so strong that when its probability is either 0.1 or 0.9, then the investment decision does not depend on the probabilities of the other uncertainties at all.

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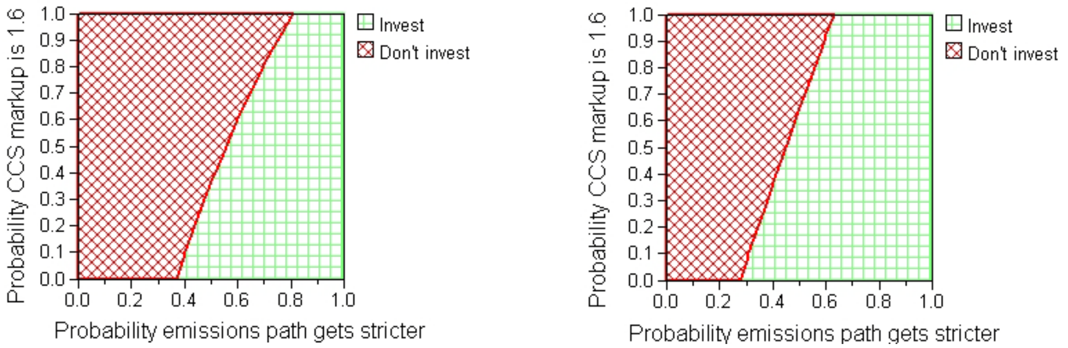
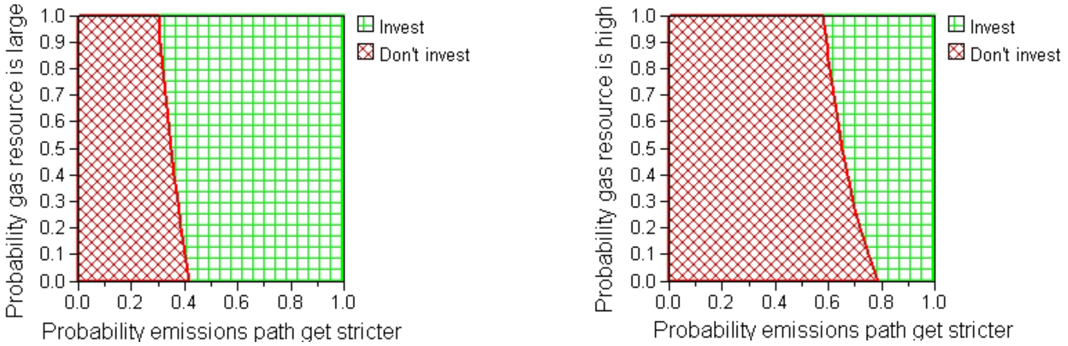
[2] An increase of 0.063% ((-1.412) – (-1.475)) to the welfare of the No Policy case.

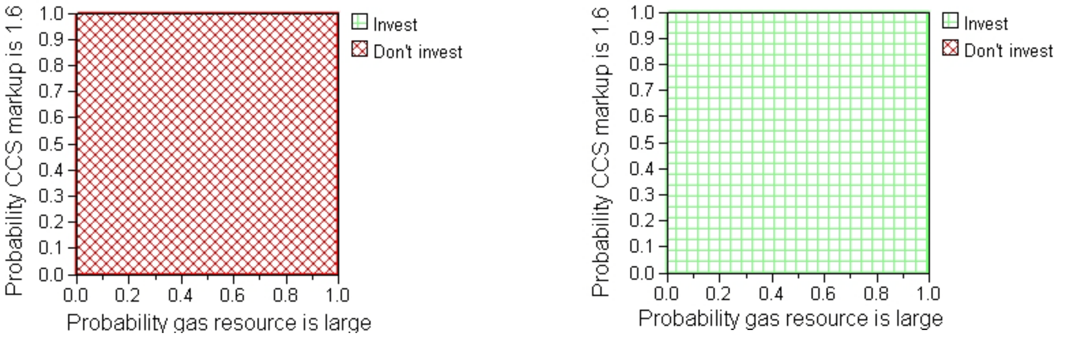
[3] A decrease of 0.051% ((-1.105) – (-1.054)) to the welfare of the No Policy case.


Probability gas resource is large is 0.1

Probability gas resource is large is 0.9


Probability of CCS MU being 1.6 is 0.1

Probability of CCS MU being 1.6 is 0.9


Probability emissions path gets stricter is 0.1

Probability emissions path gets stricter is 0.9

Figure 6 Probability space diagrams demonstrating the probabilities for circumstances when we should choose to invest or not. Top row: Probability of large gas resource supply held constant, Middle row: Uncertainty of CCS cost held constant, Bottom row: Stringency of emissions path held constant.

3. Conclusions

We have shown that when examining the question of whether to invest money in CCS today to improve social welfare over the next century, the investment choice depends on future circumstances, and there are indeed circumstances where it is beneficial to invest. This analysis introduces a new framework for informing investment decisions under uncertainty. In order for this framework to be more useful in informing policymakers' decisions on technology investment (and it should be policymakers since the metric used for analysis is social welfare, not return on investment), it should not be applied to CCS alone, but should be extended to analyze optimal investment portfolios across all energy technologies. In this way, we could give ourselves many options of using different energy technologies in the future at reduced costs, since we do not know today which we will want to use in the future. A further beneficial extension would be to add more decision options over time, rather than specifying a single investment schedule from 2015 to 2050 that cannot be amended. We would then be able to resolve some of the uncertainties, such as technology costs, as we build capacity and learn, and alter the investment portfolio by shifting investments from technologies that appear less viable to the technologies that we find are more cost-effective.

This analysis explores the circumstances under which early CCS investments would be beneficial to society, but does not discuss who, or by what means, these investments should be made. There are many instruments for technology investments such as mandates, subsidies, carbon pricing and R&D incentives to name a few. The analysis presented introduces a framework for considering whether the investments should be made, but policymakers must decide which investment tool is most appropriate, and use these mechanisms to ensure the correct level of investment.

This analysis requires making assumptions about the likelihoods of future possibilities, and assumes that it is possible to quantify them. However, as much as we educate ourselves, ultimately our estimates of the likelihood of the uncertainties considered are subjective to our own beliefs about the future, and there are no ‘true’ objective probabilities. Therefore, in making investment decisions, policymakers should use the analysis framework presented to help inform their investment decisions, and to compare the results of sensitivity analysis with their subjective beliefs about the probabilities of the uncertainties.

The result that the existence of uncertainties and learning-by-doing can, under some circumstances, show that early investments are beneficial to society is important, since these elements are often neglected in many studies designed to inform plans for building out future energy technologies. With the appropriate extensions, this framework can provide useful insights as to whether policymakers should encourage particular investments and induce innovation to mitigate climate change at the lowest possible cost to society.

4. Acknowledgements

This paper is based on research conducted at MIT from September 2008-May 2010. We would like to thank the MIT Carbon Sequestration Initiative and the MIT Joint Program on the Science and Policy of Global Change for their financial support of this research effort. A more detailed account of this research effort can be found in Eleanor Ereira’s MS Thesis [6].

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