

Economic Analysis of Projects in a Greenhouse World

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Abstract

Recent carbon market prices are substantially lower than mean or median estimates of the social cost of carbon in the literature. Intuition would therefore suggest that ‘investment errors’ are being made, in the sense that markets favor higher carbon-emitting projects, while global welfare would be larger with lower carbon-emitting projects. This intuition is correct in specific circumstances, but not others. For any comparison of two alternative projects, there is a carbon switching price that equalizes their net social benefits. From the perspective of maximizing global welfare, investment errors only occur when this switching price lies between the carbon

market price and the social cost of carbon. Data on the costs of high-carbon and low-carbon electric generation projects suggest that there is no financing gap using mean or median published figures, but for precautionary (95th percentile) choices of the social cost of carbon, there is a financing gap between carbon market prices and the switching price that would trigger investment in the global welfare-maximizing low-carbon project. A global carbon fund to finance this gap could be conceived, but stricter emission caps and reforms of carbon markets are likely to be a more efficient solution to the problem.

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1. Introduction

From the perspective of maximizing global welfare, the question of measuring the net benefits of an individual project which emits CO₂, or measuring the net benefits of choosing one project over another when the projects have differing streams of CO₂ emissions, is in principle more or less trivial: introduce the social cost of carbon as a project cost and measure the net benefit.² It is not so trivial in practice because, as we will see below, the social cost of carbon is determined by modeling the present value of damages from a marginal CO₂ emission today. Model choice and model parameters, in particular the discount rate, have a large influence on the estimate of the social cost of carbon.

The question of project choice in an individual country is more interesting, however, because under current climate governance (the UN Framework Convention on Climate Change – UNFCCC), some countries have an obligation to reach prescribed reductions in carbon emissions, and others do not. Some countries with emission caps (Annex I countries, in the language of the Kyoto Protocol to the UNFCCC convention) have created markets where emission permits representing a legal right to emit CO₂ can be traded, resulting in a carbon market price. In these countries projects which emit carbon face a financial cost for doing so, or incur opportunity costs if emission permits have been initially allocated free of charge.

Countries without emission caps (non-Annex I countries) participate in a market in carbon offsets that has been created, under the Clean Development Mechanism (CDM) of the Kyoto Protocol. By choosing projects with lower emission profiles than their alternatives, these

² Belli et al. (2001) look at including environmental externalities in project analysis, while Squire and van der Tak (1975) is a standard reference on project analysis.

countries can sell carbon offsets – a certified reduction in carbon emissions – to Annex I countries, who in turn can count these offsets against their carbon emission caps.

If markets for emission permits were global in scope (with all countries participating) and efficient, the price of an emission permit would equal the social cost of carbon and the question of project choice would again be trivial. The market prices would ensure that project choice in each country would maximize global welfare.

Since the world currently lacks this idealized carbon market, the prices observed in carbon markets at present would be equal to the social cost of carbon only by coincidence. As a result the preferences that an individual country has for one project over another, after accounting for the market value of CO₂ emissions, may diverge from the preferences of the hypothetical social planner who aims to maximize global welfare. It is this situation that we analyze in the paper.

We also analyze how the choice of discount rates can affect project choice at the country level, as well as the impact of including local pollution damages as a cost (or reduced damages as a co-benefit) on project choice at the country level. The key parameter in our analysis of project choice is the carbon switching price – the price for carbon at which the country is indifferent between two alternative projects.

We begin by presenting the data and recent literature on carbon market prices and the social cost of carbon. This is followed by a formal analysis of project choice in a greenhouse world, including the impacts of local co-benefits from projects and the choice of discount rate. We conclude by presenting estimates of the switching prices between alternative high carbon-emitting and low carbon-emitting electric generation technologies, using recent data on levelized costs.

2. Carbon markets and the social cost of carbon

It is difficult to speak of a single divergence between the market price of carbon and the social cost of carbon because there are multiple carbon markets and a wide range of modeled estimates

of the social cost of carbon. Rather than being encyclopedic on this topic, our aim is to present recent data on carbon market prices in the two major markets, and to summarize the most recent review of the social cost of carbon. As an example of the guidance that an individual country has provided on the social cost of carbon, we also present the results of a recent inter-agency working group assessment in the United States.

As mentioned in the Introduction, the primary market for carbon offsets is the CDM, created under the Kyoto Protocol of the UNFCCC. The unit of measurement is the Certified Emission Reduction (CER), a unit of carbon³ which has been certified to be a reduction of emissions from baseline by the CDM Executive Board. Primary CERs are generated as a result of a contract between a buyer and a project proponent who will deliver CERs to the buyer over the lifetime of the project. Primary CER prices are generally very low owing to high levels of project and counterparty risk. Once the buyer has taken delivery of a CER, however, it can be traded on the market for secondary CERs, and it is this price which we report below.

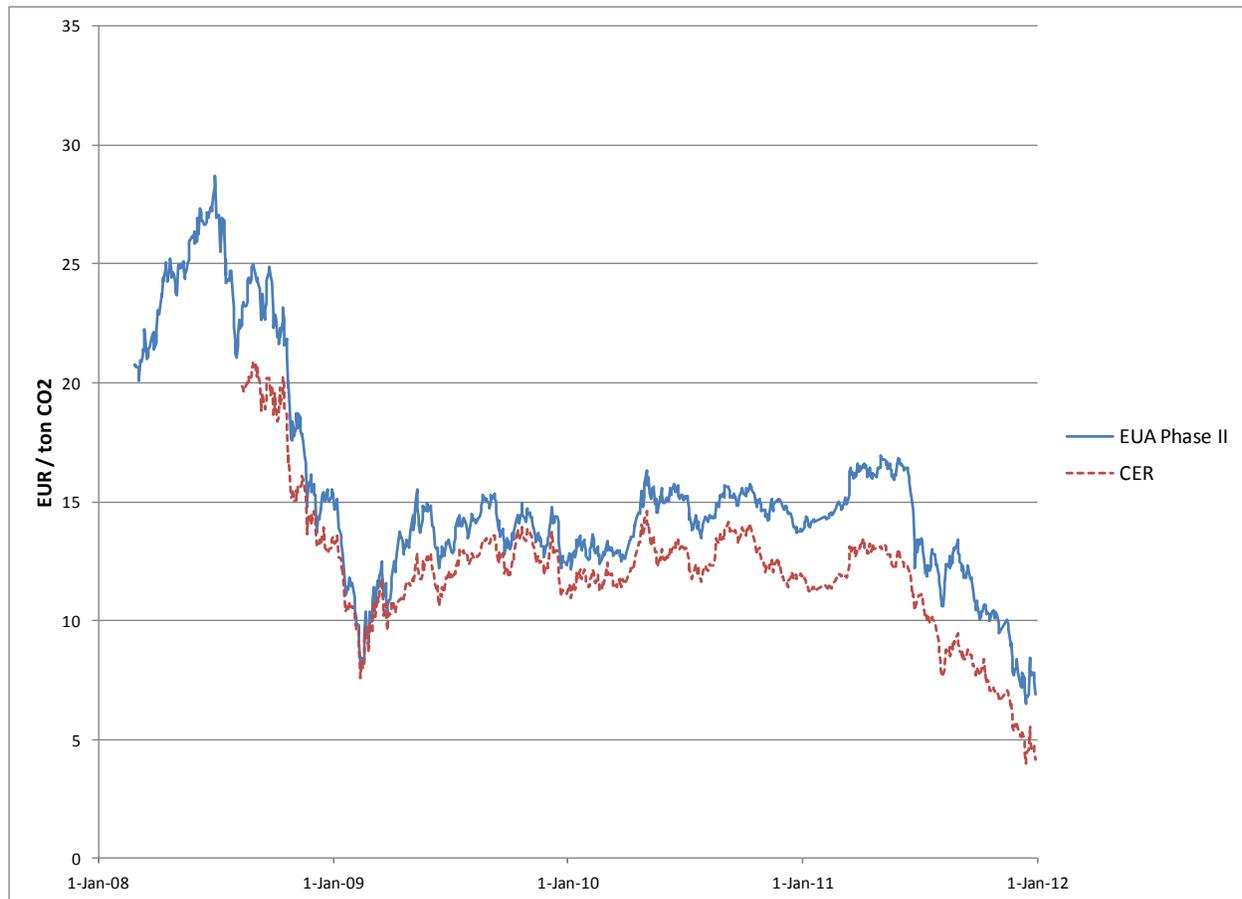
The world's largest carbon market is the EU Emission Trading Scheme (ETS), a market for emission allowances termed EUAs. Newly issued EUAs may be allocated by governments or put up to auction. Once held by emitters (currently large energy and industrial establishments), EUAs are freely tradable on exchanges, leading to readily observable market prices.

Figure 1 presents the evolution of carbon market prices, both secondary CERs and EUAs, since the start of Phase II of the EU ETS⁴.

³ Technically a CER is a unit of carbon-equivalent emissions, since other controlled greenhouse gases are tradable with weights determined by their global warming potential.

⁴ The second phase of the ETS, with its associated rules and regulations, runs from January 2008 to the end of 2012.

Figure 1. Spot Prices for EUAs and CERs



Source: BlueNext (2012)

From a peak near Euro 30/t CO₂, carbon traded roughly in the Euro 10 – 15 range before falling steadily toward Euro 5 at the beginning of 2012. Aside from the obvious volatility, the key trend visible in carbon market prices is the close correlation to the business cycle, with prices plunging during the global financial crisis in 2008, and dropping steadily in 2011 with the deteriorating fiscal situation in Europe. CERs trade at a discount to EUAs owing to regulated restrictions on swapping the former into the latter; this discount is widening owing to uncertainty about the continuity of offset markets beyond the end of the Kyoto Protocol commitment period (end-2012) and regulatory uncertainty around the future extent of swapping of CERs for EUAs.

Turning to the social cost of carbon, Tol (2009) summarizes recent figures based on 232 published estimates. Aside from basic issues concerning future population and economic

scenarios, key sources of variation in the estimates include the assumed climate sensitivity, the form of the damage function, and the discount rate employed. Tol summarizes these estimates in terms of the distribution of the full sample, in total and broken down according to the assumed pure rate of time preference, and by fitting a Fisher-Tippett distribution to the sample. Table 1 reports figures from Tol (2009), converting the damages to 2010 \$ / t CO₂. For the fitted distribution, the median estimates of the social cost of carbon vary from a value of \$13/t CO₂ to \$43, depending on the pure rate of time preference, with an overall median value of \$33/t CO₂.

Table 1. Estimates of the social cost of carbon, 2010 \$ per ton of CO₂

	Sample				Fitted			
	All	0%	PRTP		All	0%	PRTP	
			1%	3%			1%	3%
Mean	39	87	32	7	56	55	45	19
Standard Deviation	91	162	53	7	101	58	55	23
Median	11	32	17	5	33	43	34	13
95th percentile	135	220	100	17	200	182	153	77
N	232	38	50	66				

Source: Selected figures from Tol (2009) converted to 2010 \$ / tCO₂;

PRTP: pure rate of time preference

In the US the Interagency Working Group on the Social Cost of Carbon (2010) produced estimates of the social cost of carbon for use in regulatory impact analysis by the executive branch of government. Rather than summarizing published literature, the working group produced their own simulations using the three major integrated assessment models⁵ with a common set of assumptions about population and economic growth, an assumed distribution for climate sensitivity, and three assumptions about the discount rate. The distributions of the social cost of carbon were averaged across models for each discount rate to arrive at the figures in Table 2. Because the total atmospheric stock of greenhouse gases is assumed to rise to 2050 in their simulations, there is a corresponding increase in the social cost of carbon. The mean estimates for 2010 lie between \$4.7/ton of CO₂ and \$35.1 /ton, depending on the discount rate.

⁵ DICE, PAGE and FUND – see Interagency Working Group on the Social Cost of Carbon (2010).

Table 2. US social cost of carbon estimates, 2007 \$ / t CO₂

	5% discount rate	3% discount rate	2.5% discount rate	95 th percentile of 3% discount rate distribution
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2030	9.7	32.8	50.0	100.0
2040	12.7	39.2	58.4	119.3
2050	15.7	44.9	65.0	136.2

Source: Interagency Working Group on the Social Cost of Carbon (2010)

The figures for the 3% discount rate in Table 2 should be fairly consistent with the figures for a pure rate of time preference of 1% in Table 1. These figures can, in turn, be compared with the carbon market prices shown in Figure 1. Starting with carbon market prices, we see EUA and CER prices lying in the range of Euro 10-15 per ton CO₂ over most of Phase II of the ETS. This corresponds, roughly, to \$14-21 per ton CO₂. In 2010, therefore, the US recommended social cost of carbon for a 3% discount rate is just at the upper limit of the predominant EUA price. In contrast, the figures for the social cost of carbon from the fitted distribution with 1% PRTP in Table 1 have a mean of \$45/t CO₂ and a median of \$34/t CO₂, distinctly above both the US recommended cost and the predominant EUA and CER prices.

These figures point at the dilemma facing policy makers choosing between high and low carbon emitting alternative projects: Carbon market prices are closely linked to the business cycle and existing carbon markets are not necessarily designed to maximize global welfare, which implies that they are not generally going to equal the social cost of carbon. Therefore the policy maker would have to establish criteria for choosing a social cost of carbon if they wanted to ensure that project choice contributed to maximizing global welfare (which may not be a concern of non-Annex I countries under the Kyoto Protocol, since they do not have emission caps). At a minimum these criteria would need to include assumptions about discount rates and the degree of precaution (as reflected in the choice of the percentile of the distribution of the social cost of carbon) to exercise. We return to these questions in the concluding section.

3. Project analysis with carbon pricing

In this section and the following two we provide a formal analysis of project analysis and project choice when carbon market prices cannot be assumed to equal the social cost of carbon. To clarify the central issues, we assume that the country making a choice between alternative projects cares only about local costs and benefits. This creates a potential divergence between local project choices compared with the decision that would be made by a hypothetical social planner aiming to maximize global net benefits from project choice.

There are many projects, such as electric power generation, where there are large flows of carbon emissions from fossil fuel use, but also less carbon-intensive alternatives. As Section 6 will highlight, the levelized costs for low-carbon electric generation projects are typically higher than for high-carbon projects. Carbon offset markets such as the CDM can help to finance low-carbon alternative projects, while emission permit markets such as the EU ETS can help to level the playing field between high-carbon and low-carbon alternatives. Because carbon creates a global externality, it is important to distinguish between global returns to project investments (which reflect global costs and benefits) and local returns (which reflect purely country-level costs and benefits).

To keep matters as simple as possible, we assume that there are two electric power projects under consideration: Project 1 (high-CO₂) has positive net benefits and a stream of unpriced carbon emissions over its lifetime; Project 2 (low-CO₂) also has positive net benefits, but these are lower than for Project 1, and the stream of unpriced carbon emissions for this project is also lower. We assume the lifetime of each generation facility is the same. For a fixed discount rate r , B is the present value of the flows of project benefits, C is the present value of costs, and e is the present value (in tons) of CO₂ emissions. The key assumptions are therefore:

$$B_1 - C_1 > B_2 - C_2 > 0 \tag{1}$$

$$e_1 > e_2 \geq 0 \tag{2}$$

We distinguish between two categories of net benefits in what follows. As long as carbon flows are unpriced, the net benefit of *implementing Project 1* is just $NB = B_1 - C_1$. The net benefit of *choosing Project 2 over Project 1* is $NB = (B_2 - C_2) - (B_1 - C_1)$.

As just noted, we assume that the country implementing the electric generation project cares only about local costs and benefits. The baseline project choice is therefore Project 1. In analyzing an electricity generation project, however, the country should also consider Project 2 as an alternative, including the value of emissions trading or the sale of carbon offsets generated by not implementing project 1. Which project the country prefers will depend on the net benefits of choosing one project over the other.

The world perspective would aim to maximize the net global benefits from project choice. From this perspective, carbon markets are purely a transfer mechanism and so would not enter the project analysis. The critical parameter in measuring global benefits is the social cost of carbon: when the global damages from carbon emissions are taken into account, what are the net benefits for the world of choosing one project over the other?

To take these ideas further it will be useful to define four ‘carbon prices’ as shown in Table 3.

Table 3. Defining different carbon prices for use in project analysis

Social cost of carbon	p^d	The present value of global damages from a unit of carbon emitted today
Switching price	p^s	The price for carbon at which the country is indifferent between two specified projects
Hurdle price	p^h	The price for carbon at which a specific project is not profitable
Carbon market price	p^m	The price of carbon in emission trading or offset markets

For simplicity these prices are assumed to be constant over time. p^d , the estimate of global damages from carbon emissions, is assumed to be known with certainty. p^m can be observed in the carbon markets.

The hurdle price is defined such that, for Project 1,

$$B_1 - C_1 - p_1^h e_1 = 0,$$

which implies that,

$$p_1^h = \frac{B_1 - C_1}{e_1}. \quad (3)$$

The equivalent formula applies for Project 2. If the hurdle price of an individual project is below the social cost of carbon, then the project is not socially profitable from the world perspective.

In order to distinguish between the country and world perspectives on project choice, the crucial value is the switching price, defined such that,

$$B_1 - C_1 - p^s e_1 = B_2 - C_2 - p^s e_2, \quad (4)$$

which implies that,

$$p^s = \frac{(B_1 - C_1) - (B_2 - C_2)}{e_1 - e_2} \quad (5)$$

This is positive by assumption.

In an optimal world the carbon market price and the social cost of carbon would be equal. In practice, as seen in Section 2, carbon markets are imperfect and estimates of the social cost of

carbon are highly uncertain. This potential divergence has consequences for project analysis as we will show.

The analysis proceeds by measuring the net benefits (NB) of implementing the low carbon project, Project 2, minus the opportunity cost of not implementing the high carbon project, Project 1. For countries participating in an *offset* market the net benefit from implementing Project 2 consists of the difference between the costs and benefits of the two projects plus the value of selling carbon offsets – i.e. selling quantity $e_1 - e_2$ of emission reductions at the market price:

$$NB = (B_2 - C_2) - (B_1 - C_1) + p^m(e_1 - e_2).$$

For countries operating an *emission permit* market the cost of each project must include the cost of carbon emissions using market values for permits:

$$NB = (B_2 - C_2 - p^m e_2) - (B_1 - C_1 - p^m e_1) = (B_2 - C_2) - (B_1 - C_1) + p^m(e_1 - e_2).$$

We see that, although the market prices may be different, the expression for the net benefits of choosing Project 2 (low-CO2) over Project 1 (high-CO2) has the same form under either offset markets or emission permit trading schemes.

Finally, from the perspective of the *world* the cost of each project must include the social cost of carbon emissions:

$$NB = (B_2 - C_2 - p^d e_2) - (B_1 - C_1 - p^d e_1) = (B_2 - C_2) - (B_1 - C_1) + p^d(e_1 - e_2).$$

Table 4 summarizes the net benefits of choosing Project 2 (low-CO2) over Project 1 (high-CO2) from the country and world perspective.

Table 4. Net benefits of choosing Project 2 (low-CO2) over Project 1 (high-CO2)

Country perspective	$(B_2 - C_2) - (B_1 - C_1) + p^m(e_1 - e_2)$
World perspective	$(B_2 - C_2) - (B_1 - C_1) + p^d(e_1 - e_2)$

Obviously the net benefit of choosing Project 1 over Project 2 is just the negative of these expressions. From Table 4 and expression (4) defining the switching price we derive two basic results.

Result #1. If the carbon market price $p^m < p^s$ the country will choose Project 1 (high-CO2), while for $p^m > p^s$ the country will choose Project 2 (low-CO2) combined with a sale of carbon offsets (or a net saving on the cost of emission permits in the case of an emission trading scheme).

Result #2. If the social cost of carbon $p^d < p^s$ then the world will choose Project 1 (high-CO2), while for $p^d > p^s$ the world will choose Project 2 (low-CO2).

As should be clear, the ranking of these three prices determines the project choices from the country and the world perspective. Table 5 lays out the project choices for all possible rankings of the prices (excluding, for simplicity, any equalities).

Table 5. Country and world project preferences under different price rankings

Ranking of prices	Country preference	World preference
$p^s < p^m < p^d$	Project 2 (low-CO2)	Project 2 (low-CO2)
$p^s < p^d < p^m$	Project 2 (low-CO2)	Project 2 (low-CO2)
$p^m < p^s < p^d$	Project 1 (high-CO2)	Project 2 (low-CO2)
$p^d < p^s < p^m$	Project 2 (low-CO2)	Project 1 (high-CO2)
$p^m < p^d < p^s$	Project 1 (high-CO2)	Project 1 (high-CO2)
$p^d < p^m < p^s$	Project 1 (high-CO2)	Project 1 (high-CO2)

Table 5 shows that, while country and world preferences coincide for the majority of price rankings, this is not true when the switching price lies between the social cost of carbon and the carbon market price. This leads to two additional basic results.

Result #3. If $p^m < p^s < p^d$ then the country's preference, Project 1 (high-CO2), is less beneficial than Project 2 (low-CO2) from a world perspective.

Result #4. If $p^d < p^s < p^m$ then the country's preference, Project 2 (low-CO2), is less beneficial than Project 1 (high-CO2) from a world perspective.

These results have important policy implications. First, if there is reason to believe that the carbon market price is “too high” (higher than the social cost of carbon), then “investment mistakes” can be made – if the switching price lies between the social cost of carbon and the carbon market price, the country would choose the low carbon project while the world would be better off with the high carbon project. Second, if the carbon market price is below the social cost of carbon but the switching price lies between them, then there is a potential financing gap⁶ – the country will choose the high carbon project because the carbon market price is “too low”, while the world would be better off if the country chose the low carbon project.

We established above that there is a formal symmetry between the calculation of net benefits of choosing a given project over another under permit trading and offset markets, but in practice there are differences between the two market structures which may affect country preferences. Carbon offset trades are generally international transactions, exports of offsets by the seller – this is certainly the case under the CDM. As a result, sales of carbon offsets are clearly a benefit from the country perspective. In contrast, trade in emission permits may be purely within a country, or may cross national boundaries (as is the case for the EU ETS).

If all sales of emission permits are exports, then the analysis above of country preferences stands – exports of permits provide an economic benefit to the country which will determine country

⁶ Obviously this language about ‘investment mistakes’ and ‘financing gaps’ is written from the perspective of a social planner aiming to maximize global net benefits from project choice.

preferences for one project over the other. In a single-country (autarchic) emission trading scheme, however, trades of emission permits are purely a transfer from the government perspective (this parallels the argument concerning world preferences for project choice) and therefore would not affect project choice. The government would always prefer Project 1 (high-CO₂) because it yields greater net benefits when carbon market values are excluded (recall expression 1). But this argument ignores the reason that the country has implemented emission trading in the first place – it has implemented an emission cap either for altruistic reasons or as a result of signing a treaty or convention. From this perspective, using the carbon market price in project selection makes sense. However, if the reasons for establishing the carbon market were altruistic there would be some logic to using the social cost of carbon as the carbon price in project analysis. This would ensure that the country's preferences for one project over another would coincide with world preference rankings.

We now turn to two additional topics affecting project choice: the impact of including local co-benefits from project implementation, and the choice of discount rate.

4. Accounting for local co-benefits

At least for the case of a simple binary choice between low carbon and high carbon projects, Section 3 has established the central role played by the switching price. In this section we establish that including local co-benefits in the project analysis will tend to lower the switching price between projects.

As a general rule, high CO₂-emitting projects also tend to be large emitters of local air pollutants such as SO_x, NO_x and PM₁₀ – without stringent environmental controls, emissions of these pollutants, linked to the combustion of fossil fuels, will affect human health and damage other assets as well. In contrast, low CO₂-emitting projects are typically much less likely to emit large quantities of local air pollutants.

To analyze the issue of local co-benefits we define present values d_1 of damages from local pollution emitted by project 1 over the project lifetime and d_2 emitted by project 2 which satisfy,

$$d_1 > d_2 \geq 0 \tag{6}$$

With this restriction, choosing the low carbon project rather than the high carbon project yields a co-benefit in the form of reduced local pollution damages.

We again define the switching price for carbon p^s such that,

$$B_1 - C_1 - d_1 - p^s e_1 = B_2 - C_2 - d_2 - p^s e_2 \tag{7}$$

which has solution,

$$p^s = \frac{(B_1 - C_1 - d_1) - (B_2 - C_2 - d_2)}{e_1 - e_2} \tag{8}$$

From expressions (6) and (8) we can therefore derive the following result.

Result #5. If high carbon projects produce more local pollution damages than low carbon projects, the switching price for carbon falls when local pollution damages are taken into account.

Referring back to Table 5, we see that this reduction in the switching price could result in pushing the project analysis from a situation where both the country and the world prefer Project 1 (high-CO2) to one where the preferences diverge because the switching price lies between the social cost of carbon and the carbon market price.⁷ Of course, the switching price could fall to the point where it is less than both the other two prices, in which case both the country and the world prefer Project 2 (low-CO2) – this could be the outcome when co-benefits are very large, for example in a country with lax environmental standards. In fact, the switching price could be negative if the difference in local pollution damages between the two projects is sufficiently

⁷ Recall that the global planner in this analysis is only interested in the social cost of carbon, not the benefits to certain subsets of the population from local pollution reduction. If the planner's objective were modified to incorporate co-benefits, this divergence would disappear.

large.⁸ This would indicate that Project 2 (low-CO₂) is the preferred project for the country independent of any carbon market transactions.

As is obvious from the definition of the hurdle price (expression 3), if any project causes local pollution damages, this will lower the hurdle price of carbon.

5. Choice of discount rate

There are in principle two discount rates that enter into the economic analysis of carbon-emitting projects – the discount rate used for the project analysis itself, and the rate used to calculate the social cost of carbon. There has been a vexed debate on the latter question, nicely summarized in Hepburn and Beckerman (2007). In practice, if the social cost of carbon is chosen from the distribution of studies using a pure rate of time preference of 1% in Table 1, there is unlikely to be a major inconsistency between the pricing of project costs and benefits and the social cost of carbon.

The opportunity cost of capital is a logical starting point in deciding upon the discount rate for project analysis. The capital markets are telling us what is foregone when the marginal project is financed and this should determine which projects are socially profitable. This is the logic underlying the default discount rate of 10% used by the World Bank (for example) in project analysis – this is an approximation to a global opportunity cost of capital, and the Bank applies this uniformly across projects in different countries in order to provide a level playing field for project analysis.

This choice of discount rate invites the usual set of objections about market-based discount rates:

- Capital markets reflect purely private preferences for consumption over the relatively short term, including individual rates of impatience and risk preferences.

⁸ Markandya *et al.* (2009) model just such an outcome for India.

- While it is rational for individuals to be impatient, it is not clear that this should be the case for governments.
- Risks to society as a whole are much lower than risks to individuals within the society.

These arguments have merit and in fact most high income countries use a *social* discount rate, lower than the opportunity cost of capital, in analyzing pension schemes. However, one reason for development institutions to use a relatively high discount rate is simply to ration the finance that they can provide. The capital base of development banks is limited, as is the annual quantity of concessional ODA⁹ finance. This form of rationing has the benefit of biasing project choice toward those projects with relatively high economic rates of return, but at the cost of more heavily discounting longer-term future costs and benefits.

Suggesting that low carbon-emitting projects should qualify for economic analysis based upon lower social discount rates would seem to be a slippery slope. In the limit all project proponents would prefer to argue for the ‘special’ properties of their project, which would merit the use of a lower rate of discounting the future. Markandya and Pearce (1991) suggest getting the valuations right (including, in this instance, the social cost of carbon or a carbon market price) rather than pleading for special discount rates, a theme that is echoed in Sterner and Persson (2007).

Hurdle prices, switching prices, and the discount rate. Under reasonable assumptions it turns out that the hurdle price varies inversely with the discount rate r . Define the sum of discount factors Z from period 1 to period N as follows:

$$Z = \sum_{i=1}^N \frac{1}{(1+r)^i}.$$

It is clear that $Z \propto \frac{1}{r}$.

⁹ Official Development Assistance

Assuming that capital costs K occur at time 0, and that a constant stream of benefits, operating costs and emissions $(\bar{B}, \bar{C}, \bar{e})$ occurs over the lifetime of the project (starting in period 1), then the net benefit of the project is given by,

$$NB = -K + (\bar{B} - \bar{C})Z,$$

while the sum of the discounted flow of emissions is given by $\bar{e} \cdot Z$. The hurdle price p^h solves the equation,

$$-K + (\bar{B} - \bar{C})Z - p^h \bar{e}Z = 0$$

and is therefore given by,

$$p^h = -\frac{K}{\bar{e} \cdot Z} + \frac{\bar{B} - \bar{C}}{\bar{e}}. \tag{9}$$

We therefore have the following result.

Result #6. $p^h \propto \frac{1}{r}$, so the higher the discount rate, the lower the hurdle price.

The switching price between projects 1 and 2 is also sensitive to the discount rate. The switching price equalizes the net benefits of each project, and is therefore given by the solution to the following equation:

$$-K_1 + (\bar{B}_1 - \bar{C}_1)Z - p^s \bar{e}_1 Z = -K_2 + (\bar{B}_2 - \bar{C}_2)Z - p^s \bar{e}_2 Z,$$

so that,

$$p^s = \frac{K_2 - K_1}{(\bar{e}_1 - \bar{e}_2)Z} + \frac{(\bar{B}_1 - \bar{C}_1) - (\bar{B}_2 - \bar{C}_2)}{\bar{e}_1 - \bar{e}_2} \quad (10)$$

Since low-carbon technologies are generally more capital intensive than high-carbon technologies, we have the following result.

Result #7. If the low-CO2 project is more capital intensive than the high-CO2 project (i.e. $K_2 > K_1$), then the switching price will increase as the discount rate increases.

6. Empirical estimates of hurdle and switching prices for electric power generation

To further assess our results derived in sections 2-5, we present selected estimates of hurdle and switching prices for electric power generation. The analysis is necessarily ‘stylized,’ abstracting from important questions of base versus peak load dispatch and other critical aspects of ‘real world’ energy systems. Similarly, we use levelized costs to normalize different project lifetimes as well as to provide the numeraire for comparison – prices, costs and emissions are all expressed per kilowatt-hour (or multiples thereof).

Following expression (3), hurdle prices are calculated as

$$p^h = \frac{p^e - lcoe}{e}$$

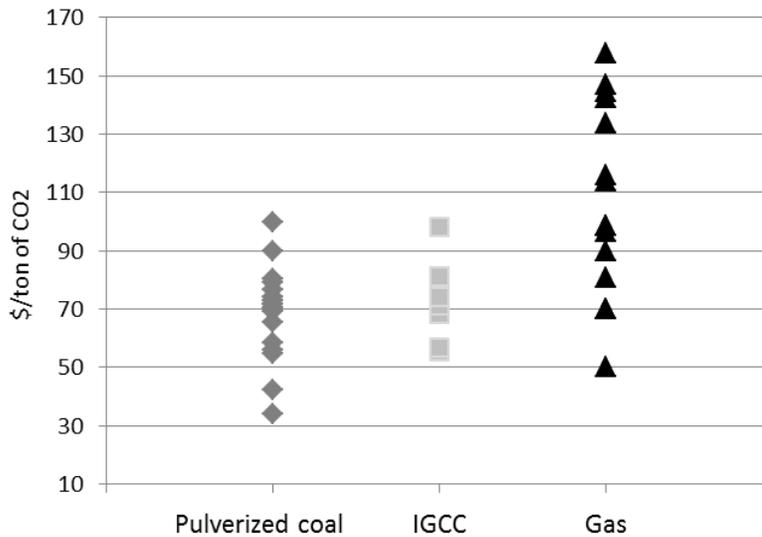
where p^e is the electricity price, $lcoe$ is the levelized cost of electricity generation and e is CO2 emissions.

Figure 2 depicts the ranges for hurdle prices derived from recent studies. While emission factors for each technology were taken from ESMAP (2007) and the Royal Academy of Engineering (2004), electricity prices were derived from IEA (2012). The levelized cost estimates are based on an overview of a large number of recent studies presented in IEA (2010).¹⁰ Obviously, using

¹⁰ For clarity, the assumptions are also shown in table 6. Prices in IEA (2010) are post-tax.

different studies that are based on different designs implies that the levelized costs are not fully comparable due to different assumptions (e.g. on fuel input prices, different locations, slightly different technologies) underlying the different studies. But this heterogeneity gives us a sense of the range of hurdle prices which might be observed.

Figure 2: Estimates of hurdle prices for an electricity price of \$110/MWh



Note: An electricity price of 110 USD/MWh (OECD mean in 2010) is assumed.
 Authors' calculations based on data from IEA (2010).

Figure 2 shows that the estimated hurdle price for pulverized coal lies roughly between \$30 and \$100/t CO₂, while the estimates for integrated gasification combined cycle (IGCC)¹¹ vary less and range between around \$50 and \$100/t CO₂. In contrast, the estimates for gas are more dispersed and generally higher (\$50-\$160/t CO₂).

To examine the impact of different electricity price assumptions on hurdle prices, we use data from only the two most comprehensive studies (EC (2008) and IEA (2005)) presented in IEA (2012), which implies that the levelized costs for different technologies are more comparable. Not surprisingly, the hurdle prices change significantly when different electricity prices are assumed, as Table 6 shows.

¹¹ A technology that turns coal into gas.

Table 6: Mean hurdle prices with varying electricity price assumptions

Technology	Lcoe \$/MWh	Emission factor tons/MWh	Hurdle price \$/ ton of CO2			
			a*	b	c	d
Pulverized coal	55	0,82	67	248	73	-10
IGCC	57	0,70	75	287	82	-15
Gas	64	0,46	101	427	111	-38

*a: OECD mean electricity price (110); b: OECD max (258); c: non-OECD mean (115); d: non-OECD min (47), in \$/MWh. All prices are post-tax.

Authors' calculations based on data from EC (2008) & IEA (2005).

Using the 2010 mean OECD electricity price results in hurdle prices between \$67/t CO2 for pulverized coal and \$101/t CO2 for gas. These hurdle prices are well above the fitted median social cost of carbon estimates from Tol (2009), as shown in Table 1 above, as well as the Interagency Working Group's (2010) mean estimates, for all assumed pure rates of time preference and discount rates (Table 2 above). Suppose instead we view Tol's (2009) 95th percentile estimates of the social cost of carbon in Table 1 as 'precautionary' values – values that, if used in project analysis, would reduce the risk of catastrophic climate change. Comparing this figure with a 1% PRTP, \$153/ton of CO2, to the carbon hurdle prices above, we see that pulverized coal at the mean OECD electricity price would not be socially profitable using the 95th percentile social cost of carbon. The 95th percentile from the Interagency Working Group's (2010) mean estimates, \$64.90/ton of CO2, can be viewed as essentially the same as the hurdle price above.

Turning to the switching price estimates, we adapt expression (5) to calculate switching prices as

$$p_{i,j}^s = \frac{lcoe_j - lcoe_i}{e_i - e_j}$$

Note that electricity prices do not figure in this expression, because they are assumed to be same for each project.¹² Using data from EC (2008) and IEA (2005), Table 7 presents mean estimates of the switching prices between the different technologies, including renewables – biomass, hydro, wind and solar.¹³

Table 7: Mean estimates of switching prices (two most comprehensive studies)

Technology from to	Switching price \$/t CO ₂		
	Pulverized coal	IGCC	Gas
Pulverized coal	.	.	.
IGCC	17	.	.
Gas	25	29	.
Biomass	91	104	145
Onshore wind	69	78	104
Offshore wind	84	96	132
Hydro	121	139	198
Solar PV	1174	1373	2096
Solar thermal	273	317	472

Authors' calculations based on data from EC (2008) & IEA (2005).

Table 7 shows that the mean values of the switching prices for the renewable technologies versus the fossil fuel technologies lie well above the mean and median values of the fitted distribution of the social cost of carbon in Tol (2009), as well as the 2010 mean values in the Interagency Working Group (2010). However, if precautionary (95th percentile) values of the social cost of carbon for a pure rate of time preference of 1% are chosen from the fitted distribution in Tol (2009), then biomass, wind and hydroelectric technologies are preferred (from the world perspective) to the coal-based technologies.

¹² This is usually a reasonable assumption in the context of a single project, but it is a very strong assumption when one considers larger portfolios of projects to lower national emissions volumes or their growth rates.

¹³ Using the mean values hides considerable total variation, however. If the least costly renewable technologies are compared with the most costly fossil fuel technologies, then biomass, wind and hydro technologies have 0 or negative switching prices versus the two coal technologies, indicating that these technologies would be preferred (from the world perspective) even for a \$0 social cost of carbon. Note as well that the levelized cost methodology masks the sensitivity of switching prices to discount rates in the case of capital-intensive renewable technologies, as shown in expression (10).

While these mean switching prices are high relative to mean or median estimates of the social cost of carbon, there are at least three additional factors to consider. First, the social cost of carbon will rise over time as atmospheric concentrations of CO₂ rise – this will particularly be the case if significant international efforts to reduce carbon emissions are not forthcoming in the near future. Even without technical advance in renewable technologies, a rising social cost of carbon would eventually render them cost-competitive when that cost is included. Second, the costs of renewable technologies have been falling rapidly in recent years, while the costs of fossil technologies have been rising, and this may not be fully reflected in the cost estimates underlying Table 7. Finally, we have not included any value of co-benefits from reduced local air pollution with renewable technologies which, as shown in expression (8), will reduce switching prices.

7. Conclusions

Intuition would tell us that the likely divergence between inefficient carbon market prices and uncertain social costs of carbon should lead to ‘investment errors,’ in the sense that countries will choose projects which are not consistent with maximizing global welfare in a greenhouse world. If inefficiency biases carbon markets toward low carbon prices, intuition would again say that the likely result is that countries will choose high carbon-emitting projects when the global welfare maximizing choice would be in favor of low carbon-emitting projects.

Our central result shows that this intuition is correct in specific circumstances, but not in others. Errors in the choice of alternative projects will only be made when a key parameter, the carbon switching price, lies between the carbon market price and the social cost of carbon. We derive this result by analyzing a country choosing between alternative high carbon-emitting and low carbon-emitting projects based only upon local project costs and benefits, and the costs and benefits of carbon market trades. By assuming that the ‘world preference’ in project choice would be to maximize global social welfare, we show that world preferences and country preferences only diverge when the switching price lies between the carbon market price and the social cost of carbon. If the switching price does not lie between the carbon market price and the social cost of carbon, then country preferences and world preferences for project choice are always identical.

Two categories of investment errors can be foreseen. If the carbon market price is higher than the switching price, which is in turn higher than the social cost of carbon, then the country would prefer the low carbon-emitting project, while global welfare would be maximized by choosing the high carbon-emitting project. As the empirical analysis of the levelized costs of a variety of electric generation technologies suggests, however, the more likely investment error occurs when the social cost of carbon exceeds the switching price, which in turn exceeds the carbon market price. In this case the country would choose the high carbon-emitting project while global welfare would be maximized by choosing the low carbon-emitting project.

The policy implication of this more likely investment error is that there is a financing gap which the carbon markets are not filling. A hypothetical global carbon fund, charged with maximizing global welfare, could identify situations where this particular investment error is likely to be made and ‘top up’ the financing in order to align country preferences with world preferences. But it seems logical that stricter emission caps and reforms of the carbon markets would be a more efficient solution to the financing problem.

While the concept of a carbon switching price is not new – it is a staple feature in the literature on low-carbon technologies – we have established the critical role that it plays in aligning country preferences and world preferences for project choice. We have also identified two important influences on the switching price. First, accounting for the domestic co-benefits from the low or zero emissions of local pollutants associated with low carbon-emitting projects will lower the carbon switching price, which is a move in the direction of better alignment of country preferences with world preferences. Conversely, owing to the generally higher capital costs of low carbon-emitting projects compared to high carbon emitters, increases in the discount rate will tend to increase switching prices.

Our stylized look at the empirical data on costs of alternative fossil and non-fossil electric generation technologies strongly suggests that carbon market prices are currently below the switching prices for the low-carbon alternative projects compared to the fossil fuel projects we analyze. As a result, carbon markets alone will not drive investment decisions toward the low-

carbon alternatives. If a global social planner were using a precautionary choice of the social cost of carbon (i.e. the high values observed at the 95th percentile of the distribution of estimated social costs of carbon), then the current state of technology (as measured by levelized costs of generation) has placed the world in the ‘financing gap’ situation highlighted above: the carbon market price is less than the switching price, which is in turn less than the social cost of carbon. As a result, low carbon-emitting projects that would maximize global welfare are not being chosen because the carbon market price is too low. This result only holds, however, for precautionary values of the social cost of carbon. Central (mean or median) values of the social cost of carbon would generally favor high carbon-emitting projects with the current state of technology – but, as noted, comparing the lowest-cost low carbon-emitting projects with the highest cost high carbon-emitting projects would favor the low-carbon project even at a social cost of carbon of 0\$.

Finally, our empirical analysis of hurdle prices for fossil fuel electric generation suggests that if precautionary values of the social cost of carbon were used as the carbon price, coal-based electricity would be on the very margin of social profitability in OECD countries. We also show that hurdle prices will typically fall as the discount rate rises, and that including local pollution damages in the economic analysis will also lower hurdle prices.

Going forward, there is reason to expect the empirics of project choice to change. The costs of low-carbon projects will continue to drop as investments in new knowledge and scaling up of deployments have an impact on costs. At the same time the costs of high-carbon projects may continue to rise as a result of fossil fuel costs and environmental regulation. And, on a less-hopeful note, the estimates of the social cost of carbon will rise as countries continue to delay agreement on limiting global carbon emissions.

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