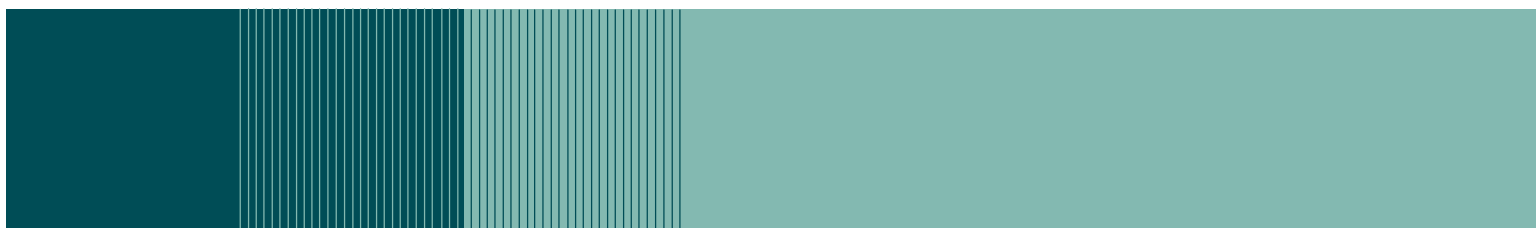April 2009

Accounting for Differences in the Timing of Emissions in Calculating Carbon Intensity for the California Low Carbon Fuels Standard

**Prepared for the
Renewable Fuels Association**

NERA
Economic Consulting

Project Team

David Harrison, Jr., Ph.D.
Albert L. Nichols, Ph.D.
Meghan McGuinness

NERA Economic Consulting
200 Clarendon Street, 11th Floor
Boston, Massachusetts 02116
Tel: +1 617 927 4500
Fax: +1 617 927 4501
www.nera.com

Contents

List of Figures

List of Tables

Executive Summary

The California Air Resources Board (CARB) has proposed regulations to implement a Low Carbon Fuels Standard (LCFS). In developing the LCFS, CARB must consider indirect emissions (in this case, increases in emissions due to land use changes) as well as direct emissions associated with different fuels. One of the issues addressed by CARB staff in the Initial Statement of Reasons (ISOR) is how to account for the fact that the emission profiles of the various fuels differ widely over time. In particular, the CARB staff estimates that land use changes associated with increased use of corn-based ethanol would generate substantial indirect CO_2 emissions in the early years of a project. In contrast, the reductions in direct emissions due to the use of ethanol rather than gasoline would be spread relatively evenly over many years. What formula is used to aggregate these various streams across time has a major effect on the potential credits given to corn-based ethanol as a substitute for gasoline in meeting a LCFS.

A. CARB Considers Four Alternative Timing Approaches in the Initial Statement of Reasons

In the ISOR, the CARB staff reviews four different methods for comparing uneven streams of emissions over time:

1. The *Annualized* method averages emissions over the life of the project and compares those averages.

2. The *Net Present Value* (NPV) method compares the present value of discounted emissions.

3. The *Fuel Warming Potential* (FWP) projects the impacts of emissions on the stock of CO_2 in the atmosphere over a fixed Impact Horizon and sums those impacts for comparison.

4. *The Economic Fuel Warming Potential* (FWPe) uses the same projections as the FWP, but discounts the stock impacts.

Note that the Annualized method is a special case of the NPV method with a discount rate of zero. Similarly, the FWP method is a special case of the FWPe method, again with a discount rate of zero.

These methods vary significantly in the relative weights they give CO_2 emissions in different years. The Annualized method weights emissions equally for all years in which they occur. At the other extreme, the FWPe gives relatively little weight to emissions in later years both because it discounts their impacts on the stock of CO_2 and because it tracks those emissions' effects on the atmospheric stock for fewer years, as we discuss below.

B. The Two Fuel Warming Potential Approaches are Arbitrary and Should Not be Used to Compute Carbon Intensity for Land Use Changes

The two FWP and FWPe methods, while claiming to provide a proxy measure of relative damages, in fact reflect an arbitrary choice of a fixed Impact Horizon over which effects are evaluated. This fixed Impact Horizon leads to calculating the effects of emissions in later years over fewer years, thus arbitrarily decreasing the relative importance of later-year emissions. With a 30-year Impact Horizon, for example, the atmospheric impacts of a unit emitted in year 1 are tracked over the full 30 years. However, a unit emitted in year 30 is tracked over only 1 year.

This truncation of the analysis for emissions in later years gives undue weight to emissions in the early years, when those for corn-based ethanol are greatest. We show that eliminating this differential truncation, so that the atmospheric effects of all emissions are tracked for the same length of time from the time they are emitted, makes the FWP equivalent to the Annualized method and the FWPe equivalent to the NPV approach. This equivalence holds true regardless of the length of time over which emissions are tracked following their release. In light of the arbitrary nature of the Impact Horizon and its uneven impacts, we recommend that CARB not rely on either of the two FWP approaches.

C. Calculations of Carbon Intensity Should Account for the Expectation that the Social Cost of Carbon Will Increase over Time

Discounting is normally applied to monetary measures of costs and benefits. If it is to be applied to emissions or other physical measures, it is not appropriate to apply the same discount rate used for dollars unless the dollar value per unit of the physical measure is constant over time. In the case of CO_2 emissions, there is a wide consensus among researchers who have studied the issue that the "Social Cost of Carbon" (SCC) is growing over time. This growth reflects several different factors, including growth in populations and income and rising atmospheric concentrations of CO_2 and other greenhouse gases. An IPCC report published in 2007, after reviewing the literature, concluded that "current knowledge suggests a 2.4 percent rate of growth."

In practice, adjusting for value means that whatever discount rate CARB finds is appropriate for monetary measures should be reduced by the estimated growth rate of the SCC. The ISOR provides estimates of carbon intensity using discount rates of 2 percent and 3 percent. Using the IPCC estimate of 2.4 percent, if the monetary discount rate is 2 percent, for example, the discount rate that should be applied is -0.4; i.e., later emissions should receive *more* weight than early emissions because of the greater damage they cause. If the monetary discount rate is 3 percent, the discount rate applied to emissions should be only 0.6 percent.

D. Illustrative Comparisons of Impacts of Alternative Methods on the Estimated Carbon Intensity of Land-Use Changes

For illustrative purposes, we use the various time-accounting methods to compute alternative estimates of ethanol's indirect emissions—the "Land Use Change Carbon Intensity" (LUC CI) for corn-based ethanol—using the ISOR's estimated profile of the LUC emissions. For each of three different general methods we computed the LUC CI's for discount rates in the range 0 to 3 percent—the range that bounds the values provided in the ISOR—as shown in Table E-1:

1. The "Annualized/NPV" method corresponds to the ISOR's Annualized method for a discount rate of 0 and to its NPV method for positive discount rates.

2. The Value-Adjusted method adjusts the discount rate to reflect a 2.4 percent annual growth in the SCC.

3. The FWP(e)-30 method corresponds to the ISOR's FWP method for a discount rate of 0 percent and to its FWPe method for positive discount rates with an Impact Horizon of 30 years.

For any given discount rate, the FWP(e) methods gives the highest estimates and the Value-Adjusted method the lowest.

Table E-1. LUC CIs with Alternative Methods for Accounting for Emission Timing (CO2e/MJ)

Discount Rate	Annualized/NPV	Value-Adjusted	FWP(e)-30
0%	29.9	22.9	47.5
1%	33.3	25.7	49.8
2%	36.9	28.7	52.2
3%	40.7	31.9	54.7

Note: Assumes 30-year project horizon and SCC growth of 2.4 percent for Value-Adjusted method. Annualized/NPV values are ISOR's Annualized Method for r=0 and its NPV method for r>0. FWP(e)-30 values are the FWP method for r=0 and FWPe for r>0, assuming 30-year Impact Horizon

Source: NERA calculations based on CARB (2009) and O'Hare et al. 2009.

Note that the Value-Adjusted approach yields values of 28.7 and 31.0 for discount rates of 2 and 3 percent, respectively. These values are similar to the value of 29.9 achieved using the Annualized/NPV approach with a discount rate of 0 (i.e., no discounting), the approach apparently preferred by CARB staff.

I. Introduction and Overview

The California Air Resources Board (CARB) has proposed regulations to implement a Low Carbon Fuel Standard (LCFS) pursuant to Executive Order S-01-07 and Assembly Bill 32 (AB 32). In developing the LCFS, CARB is required to consider indirect as well as direct emissions associated with different fuels. Estimating the direct and indirect emissions of different fuels is a complex task that depends on numerous assumptions and assessments. The task is made more complicated by the fact that calculating the carbon intensity of various fuels involves comparing emissions profiles that differ in their timing. In this paper we focus on how emission profiles that vary over time can be aggregated to allow meaningful comparisons across fuels.

A. CARB's Estimated Profiles and Aggregation Methods

CARB staff has produced an Initial Statement of Reasons (ISOR) that provides an overview of the regulations and their implementation as well as analyses in support of the proposed rule. A principal component of the ISOR is an analysis of the Carbon Intensity (CI) of "alternative fuel pathways" that might be used in order to comply with the rule. These calculated CI values have implications for the level of credit that will be granted for use of the alternative fuel pathways under the rule, and ultimately how long a given alternative fuel pathway will remain a viable compliance option. For crop-based biofuels, calculations reported in the ISOR include the impact of indirect emissions, based on projections of increased land clearing and conversion (and the consequent release of CO_2 emissions) resulting from increased demand for ethanol. The ISOR refers to these indirect emissions from land clearing as Land Use Change (LUC) emissions.

These emissions have a very different temporal pattern than the reductions in direct emissions from substituting ethanol for gasoline. As estimated by CARB staff, the indirect emissions tend to be significant in early years and gradually fall to zero over about 20 years. In contrast, the direct emissions benefits per unit of fuel are smaller but constant over time. As a result, the calculation of carbon intensity requires a method for comparing emission streams that differ over time.

For any given profile of indirect emissions over time, the ISOR presents four different methods of calculating the indirect CI for comparison with the direct reductions in emissions achieved compared to gasoline:

1. *Annualize*. This approach averages emissions over the project life. It is the CARB staff's currently preferred approach.

2. *NPV* ("net present value"). This approach compares the discounted sums of emissions.

3. *FWP* ("Fuel Warming Potential"). This approach projects how emissions will influence the abundance of CO_2 in the atmosphere over time, based on the Bern model of the carbon cycle. It then sums those values over an "Impact Horizon."

4. *FWPe* ("economic FWP"). This approach uses the projections made with the FWP, but instead of summing the contributions to CO_2 in the atmosphere, it computes their discounted values.

B. Project Objectives and Organization of the Report

The objective of this project is to compare alternative methods for accounting for the different timing of indirect and direct emissions. The remainder of this report is organized into three major sections:

§ Section II provides an overview of the methods presented in the ISOR for aggregating emissions over time and shows graphically the implicit weights they give to emissions in different years. It also shows how the FWP methods give disproportionate weight to earlier emissions because they account for their atmospheric impacts over more years than they do for later years. Correcting that imbalance makes the FWP method equivalent to the Annualized method and the FWPe method equivalent to the NPV method.

§   Section III shows how taking account of the wide consensus that the marginal damages caused by CO_2 emissions (the "Social Cost of Carbon) will continue to increase for many decades affects the relative weights given to different years. For any given monetary discount rate (including zero), the appropriate discount rate for emissions is reduced substantially and in some cases even becomes negative, increasing the relative weight given to emissions in later years.

§   Section IV use the methods developed in the previous two sections to compute alternative estimates of the Land Use Change Carbon Intensity (LUC CI) for corn-based ethanol based on the CARB staff's estimated emissions profile using "representative" parameter values. It also offers brief concluding remarks.

II. Overview of the CARB Staff Analysis

This section provides an overview of the CARB analyses of timing considerations in calculating carbon intensity. We begin by presenting the CARB staff's estimated time profile of emissions from land use changes. Then we explain in more detail the alternative methods for aggregating emissions over time that the ISOR presents.

A. Summary of Indirect Emissions Analysis

CARB staff use life-cycle analysis to estimate the CI of ethanol and other fuel pathways that might be used under the LCFS. Complete life-cycle analysis requires the development of carbon intensity estimates for both "direct" emissions (resulting from fuel production, transport, storage, and use) and "indirect" emissions (resulting from market interactions associated with changes in fuel demand). CARB staff has developed estimates of indirect emissions only for land use changes for crop-based biofuels, asserting that this is the "one indirect effect that generates significant quantities of GHGs" (p. IV-17). We focus only on CARB staff's assessment of indirect emissions from corn-based ethanol. CARB staff used a computable general equilibrium (CGE) model to estimate the amount and types of land that would be converted as a result of increased ethanol demand, and then estimated the CO_2 emissions that would result.

The profile of emissions from land use changes depends heavily on a large number of assumptions. Because our focus is on alternative methods for weighting emissions over time, not the emissions themselves, we rely on the CARB staff's "representative" emissions profile from land-use changes that may be associated with corn-based ethanol. We understand, however, that the profile is subject to substantial uncertainty and is very sensitive to various assumptions, in particular how much land would be converted per unit of ethanol and the type of land converted.

As shown in Figure 1, the CARB staff's "representative" emission profile has the following characteristics:

§ a large initial flux in emissions due to the release of carbon from vegetation cleared from the land and assumed to be burned or left to decay;

§ release of carbon sequestered in the soil, with relatively high emissions over the first five years and then a lower rate of emissions over the next 15 years; and

§ forgone sequestration occurring over the entire Project Horizon (the period from initial production until corn-based ethanol is assumed to be displaced by other biofuels become more cost-effective).

Throughout this report we refer to "gasoline" and "corn-based ethanol," but the same metrics apply to diesel and other fossil motor fuels and to other biofuels.
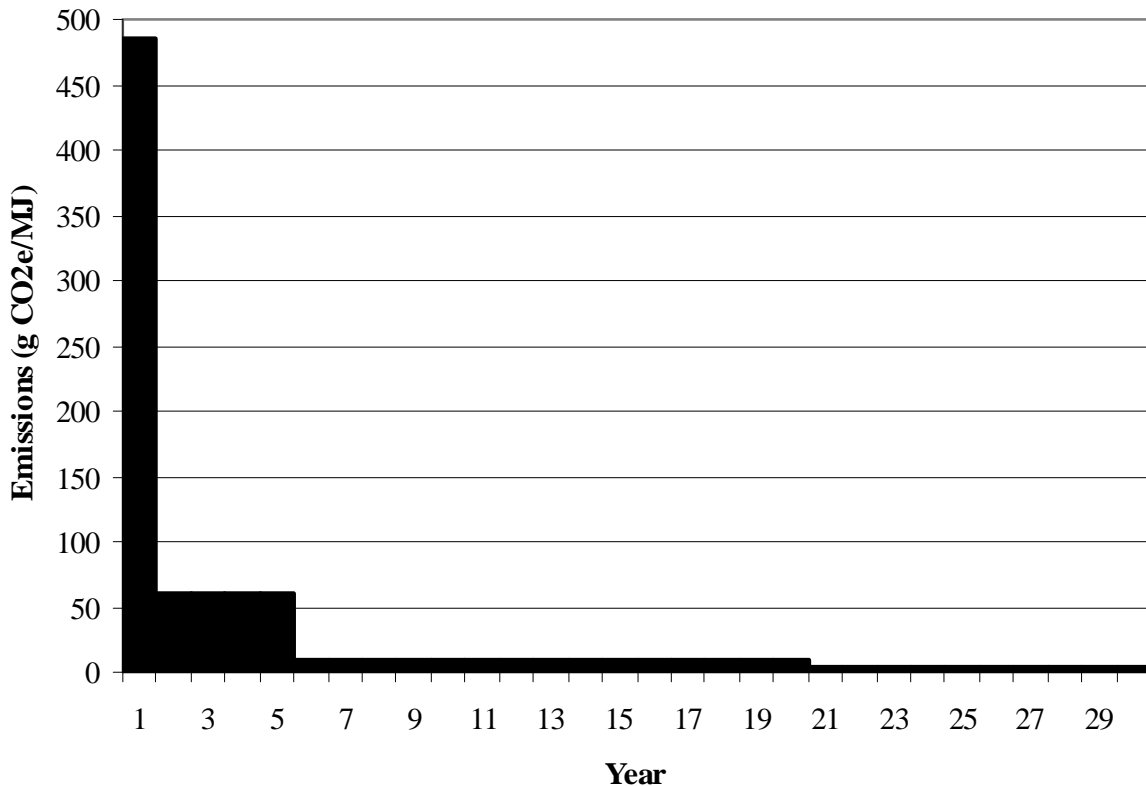
Note: Emissions are in gCO2e/MJ
Source: CARB 2009

Figure 1. CARB's Estimates of CO$_2$ Emissions from Land-Use Changes Associated with the Production of Corn-Based Ethanol

B. Aggregating Emissions Over Time

Because the time profile of indirect emissions is different than that for direct emissions, it is necessary to find a way of aggregating emissions over time so that the different streams associated with different fuels can be compared meaningfully in terms of their CIs. As noted above, the ISOR presents four different methods of aggregation. Application of each accounting method requires the choice of a "Project Horizon." The Project Horizon represents the number of years over which the analyst expects the production of the corn-based ethanol to continue. CARB staff argues that corn-based ethanol will not be competitive with other biofuels in the

long run because of relative costs and direct emissions. The ISOR considers project horizons of 20 and 30 years, with 30 years as the preferred horizon. As discussed above, the ISOR examines four different aggregation methods: (1) Annualized (averaged emissions), (2) NPV (discounted emissions); (3) FWP (carbon-cycle model); and (4) FWPe (FWP with discounting).

In addition to the Project Horizon, the two FWP methods require specifying an Impact Horizon, which is the period of time over which the global warming impacts of ethanol and the gasoline reference fuel are aggregated for comparison. The ISOR evaluates Impact Horizons ranging from 10 to 100 years, but focuses on results from 30 and 50 years. It does not make sense to use an Impact Horizon that is shorter than the Project Horizon and in general the impact horizon should extend well beyond the project horizon in light of the long residence of CO_2 in the atmosphere. The two methods that involve discounting (NPV and FWPe) require specifying a discount rate.

We now discuss the four methods in detail. We focus on the relative weight that each method gives to emissions in different years (w_t = emissions in year t), where the first year's weight is defined as $w_1 = 1.0$.

1. Annualized Method

The Annualized method simply averages LUC emissions over the Project Horizon; i.e., it takes the sum of the indirect emissions and divides them by the length of the Project Horizon. Thus, emissions in all years receive equal weight for any given Project Horizon; $w_t = 1$ for all t. However, annualized indirect emissions fall as the Project Horizon increases and the relatively high early indirect emissions are spread over more years.

2.   Net Present Value of Emissions

Taking the NPV of emissions assigns declining weights to emissions the farther in the future they occur. The relative weight for emissions in year t is simply $w_t = (1+r)^{-(t-1)}$, where r is the discount rate. Thus, the early sequestration losses assumed from land-use changes get more weight than the net emission reductions achieved in later years. The emissions in year 1, when CARB assumes land would be cleared, receive a weight of 1.0. At the 2 percent discount rate used by CARB in the main body of the ISOR, however, emissions in year 20 receive a relative weight of only 0.69 and those in year 30 receive a weight of 0.56. Thus, to offset each ton of emissions released in year 1, with a discount rate of 2 percent, emissions in year 20 would have to fall by more than 1.4 tons or emissions in year 30 would have to fall by almost 1.8 tons. Higher discount rates would lead to much more rapidly declining weights. With a rate of 3 percent, the discount rate used in Appendix C-4 of the ISOR for illustrative purposes, the weight for year 20 falls to 0.57 and that for year 30 falls to 0.42. The NPV approach also is sensitive to the project horizon, though less so than the averaging method. As with the averaging method, however, it does not vary with the Impact Horizon.[1]

The NPV approach is equivalent to annualizing LUC emissions with a positive interest rate. To calculate the annualized value of an uneven stream, one first takes the NPV of that stream. The annualized value is then the level stream over a specified number of years that yields the NPV of the original uneven stream. Mortgage payments are calculated in this way; monthly payments are set so that their NPV (discounted at the mortgage's interest rate) over the life of the loan is equal to the amount borrowed. If the annualized value is calculated using a discount rate

---

[1] The NPV approach would vary with the impact horizon only for impact horizons shorter than the project horizon, which, as we noted earlier, generally would not make sense.

of zero, it is the same as the CARB staff's "Annualized" approach, which is a simple average. For positive discount rates, however, the annualized value will be larger than the simple average.

Figure 2 plots the relative weights for the Annualized and the NPV methods, showing values for the NPV for discount rates of 1 and 3 percent in addition to the 2 percent rate used in the ISOR.
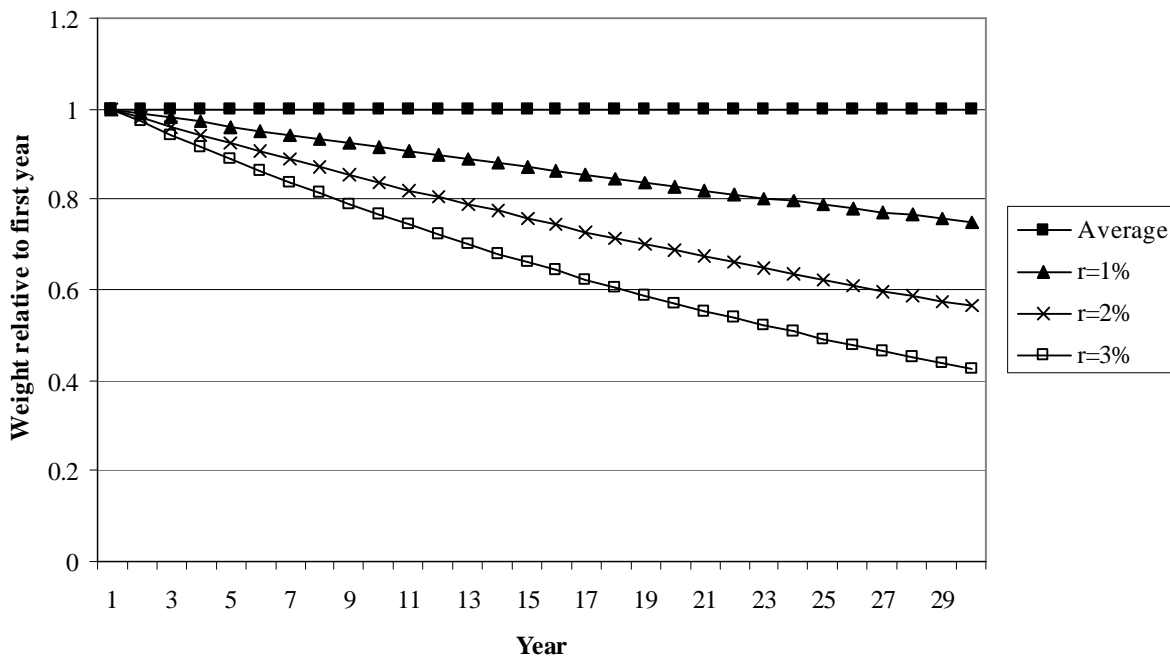
Source: NERA Calculations based on CARB (2009).

Figure 2. Relative Weights Given Emissions in Different Years: Averaging and NPV Methods

3.   Fuel Warming Potential

The FWP measure, developed by O'Hare et al. (2009) and presented in the ISOR, is substantially more complicated to compute. For a unit of CO_2 emitted in a given year, this model uses the Bern carbon-cycle model to project how much CO_2 will remain in the atmospheric stock over time; the farther one goes into the future from the year in which the emission occurred, the smaller the fraction of the original emission that remains in the atmosphere. The Bern model in

essence yields a decay function, D(i), which is the fraction of a unit of CO_2 remaining in the atmosphere i years after the unit is emitted. The FWP method totals the projected stock impacts from the year in which the emission occurs to the end of the Impact Horizon (H_I). We can then compute the relative weight for a given year by dividing the sum for that year by the sum for the first year:

$$w_t = \frac{\sum_{i=t}^{H_I} D(i-t+1)}{\sum_{i=1}^{H_I} D(i)}. \tag{1}$$

This expression may be rewritten in the following form:

$$w_t = \frac{\sum_{i=1}^{H_I-t+1} D(i)}{\sum_{i=1}^{H_I} D(i)}. \tag{2}$$

Note that because the FWP uses a fixed impact horizon, the impacts of later emissions are summed over fewer years. For example, consider Project and Impact horizons that are both equal to 30 years. For emissions that occur in the first year, their impact will be summed over the full 30 years of the Impact Horizon. For emissions that occur in year 30, however, their impact will be summed over only one year. Thus, later tons get less weight than early ones, with especially rapid fall-off as the year of the emission approaches the Impact Horizon. The relative weights are highly sensitive to the Impact Horizon, as shown in Figure 4, which plots the relative weights given to emissions in different years for alternative Impact Horizons ranging from 30 to 100 years and a Project Horizon of 30 years. The shorter the Impact Horizon, the less relative weight emissions in later years receive. As the Impact Horizon grows longer, all of the weights approach 1.0; with an infinite impact horizon, the FWP would be the same as the averaging method.
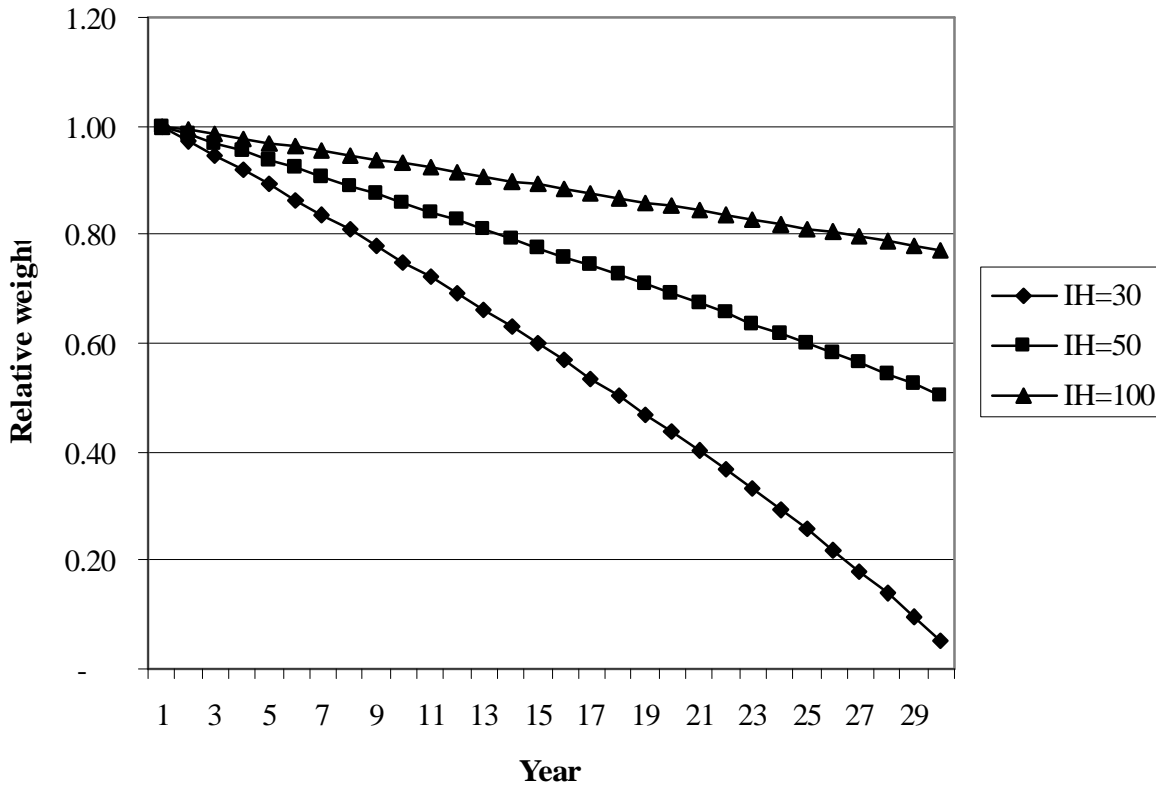
Source: NERA calculations based on CARB (2009).

Figure 3. Relative Weights under FWP Measure with Alternative Impact Horizons

4. "Economic" Fuel Warming Potential

Appendix C of the ISOR also presents a measure that it calls the "Economic Fuel Warming Potential," which it abbreviates as FWPe. It is simply the FWP with contributions discounted back to a common starting year:

$$
w_t = \frac{\sum_{i=t}^{H_I} D(i-t+1)(1+r)^{-i}}{\sum_{i=1}^{H_I} D(i)(1+r)^{-i}} = (1+r)^{-(t-1)} \frac{\sum_{i=1}^{H_I-t+1} D(i)(1+r)^{-i}}{\sum_{i=1}^{H_I} D(i)(1+r)^{-i}}. \tag{3}
$$

On the right-hand side, the term $(1+r)^{-(t-1)}$ is the discount factor reflecting the fact that a unit emitted in year t does not start affecting atmospheric concentrations until t-1 years after a unit

emitted in year 1 does. The ratio of the sums is similar to the ratio with the FWP, but with discounting applied.

With the FWPe approach, emissions in later years receive less weight relative to those in early years both because their implicit impacts are summed over fewer years (as with the FWP) and because they are discounted more heavily. As with the pure FWP, the FWPe is sensitive to the Impact Horizon, although the effect of the Impact Horizon is smaller on a proportional basis than with the FWP.[2] Figure 4 compares the weights assigned by the FWP and FWPe (with a discount rate of 2 percent) approaches for two different Impact Horizons, 30 and 50 years. The longer the Impact Horizon, the more slowly the weights decline over time. Conversely, the higher the discount rate, the more rapidly they decline. As we show in Appendix A, for any given discount rate, the longer the impact horizon, the closer the weights come to those obtained with the NPV method; in the limit, as the impact horizon approaches infinity, the FWP method approaches the Annualized method and the FWPe approaches the NPV method.

---

[2] That is because the H_I -t+1 extra years counted for year 1 but not year t are discounted and thus receive less weight.
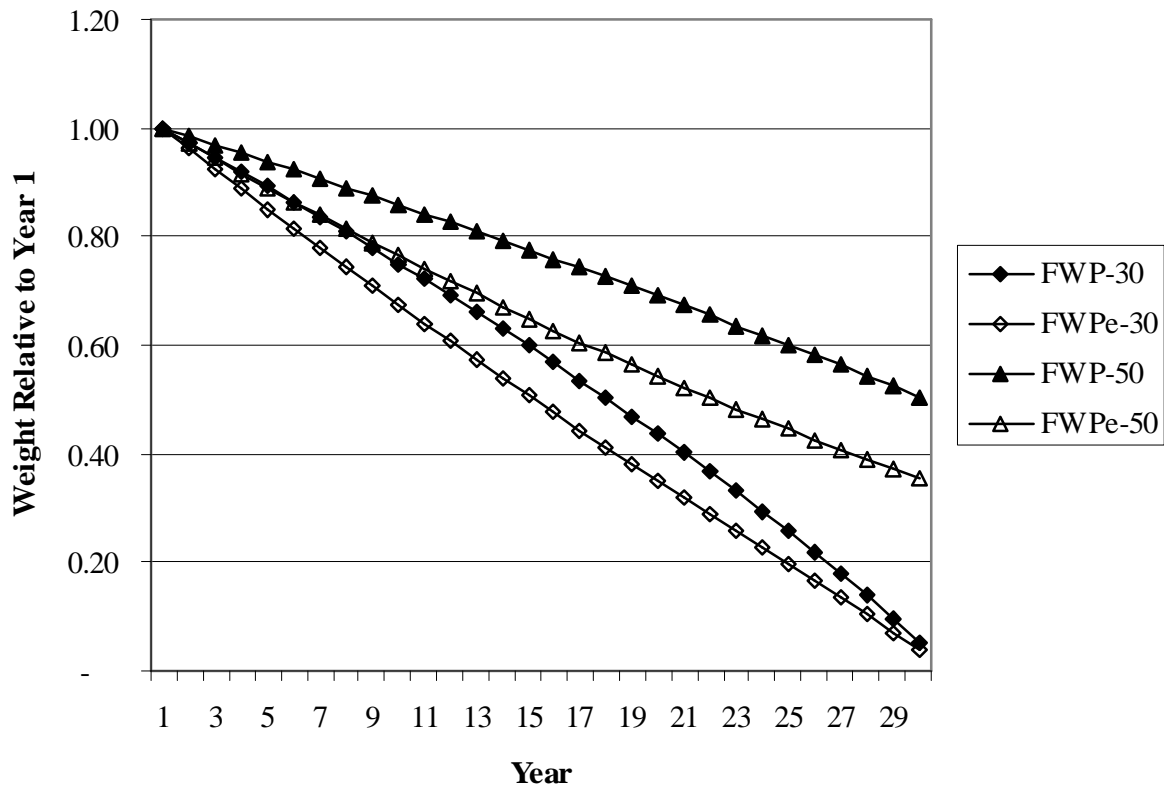
Note: FWPe weights reflect a 2 percent discount rate.
      "-n" in legend means an Impact Horizon of n years.
Source: NERA computations based on methods in O'Hare et al. (2009)

Figure 4. Comparison of Relative Weights for FWP and for FWPe with Impact Horizons of 30 and 50 Years and a Discount Rate of 2 Percent for FWPe

C. Modified Fuel Warming Potential and "Economic" Fuel Warming Potential

As discussed above, the FWP and FWPe give lesser weight to emissions in later years

simply because those methods evaluate the effects of those emissions in the atmosphere for

fewer years. Here we consider a modified version of the FWP(e), one that does not require using

a very long Impact Horizon. We propose that instead of using a fixed Impact Horizon, the

number of years over which emissions are evaluated after they occur should be constant, to avoid

uneven truncation effects. We call this period the Evaluation Horizon. That is, if the evaluation

horizon is 25 years, impacts of year 1 emissions are tracked (using the Bern equation) over 25 years, from year 1 through year 25 and the impacts of year 21 emissions also are tracked over 25 years, from year 21 through year 45. Similarly, if the Evaluation Horizon is 100 years, year 1 emissions are tracked over years 1-100 and year 21 emissions are tracked over years 21-120.

If one evaluates the FWP in this way, using a consistent evaluation period after a given emission occurs, it turns out that the length of the evaluation horizon does not affect the relative weights given emissions in different years; i.e., it does not matter whether one follows emissions in the atmosphere for 1 year after they are emitted or for 1000 years, so long as the Evaluation Horizon is the same for emissions in all years. Appendix A provides a formal proof of this fact.

With the modified FWP, all years receive equal weight: $w_t = 1$ for all t. Thus, if the FWP is modified to evaluate each unit of emissions for the same number of years following its release, the FWP is no different than the Annualized approach. Similarly, if one modifies the FWP$_e$ in the same manner, applying a uniform Evaluation Horizon after emissions occur, it yields the same weights as the NPV method, regardless of how long the Evaluation Horizon is. Thus, although the FWP and FWPe approaches may *appear* to be more sophisticated approaches than their emission-based counterparts, in fact they are no different once one equalizes the times over which the impacts of emissions are tracked after they occur. The temporal patterns of weights given by the original FWP and FWPe approaches are distorted by the uneven evaluation periods applied to emissions in different years because of an arbitrarily chosen Impact Horizon.

III. Accounting for Changing Marginal Damages

The methods presented in the previous section implicitly assume that the marginal value of controlling a unit of emissions is constant over time; i.e., they assume a ton emitted in 2029 causes the same marginal climate change damage as a ton emitted today, when those damages are valued at the time of the emissions. Discounting emissions accounts for the fact that we value a dollar received today more than one received in 20 years. However, as O'Hare et al. (2009) point out, discounting emissions (or other physical measures) using an economic discount rate intended for monetized costs and benefits is not appropriate if the dollar value of emissions is changing. In this section we analyze the impact on relative weights of accounting for projected changes in the marginal damages caused by emissions at different times. Although there is considerable uncertainty about the dollar value of damages caused by CO_2 emissions, commonly called the Social Cost of Carbon (SCC), there is a broad consensus in the literature that the SCC is growing and that the growth rate is significant relative to the discount rates commonly applied to long-term effects of climate change. As a result, taking account of these changes in the value of controlling a ton of CO_2 emissions can have a substantial effect on weights given to emissions over time.

A. Social Cost of Carbon is Likely to Rise over Time

Estimating the marginal damages caused by a ton of emissions in any year is a difficult task subject to many uncertainties. Integrated assessment modeling studies, however, have consistently found that the SCC will rise over time for decades to come. These models take account of the residence time of carbon in the atmosphere, as the FWP and FWPe do, but they also account for the fact that the underlying atmospheric concentrations to which emissions contribute at the margin will change, thus affecting marginal impacts on climate change, and that

the impacts of climate change will vary over time with changes in population, income, and other factors.

The SCC in year *t* is the present value of the stream of marginal damages caused by a ton of emissions in that year during the period it resides in the atmosphere. This SCC reflects many factors: how that ton of emissions will affect the atmospheric stock of GHGs in subsequent years, how those changes in the stock will translate into changes in climate, and finally the marginal damages caused by those changes in climate. Finally, the present value in year *t* of that stream of marginal damages resulting from a ton of emissions must be computed. That present value represents the SCC for year *t*.

There are several reasons why one would expect the SCC to increase over time. First, even with substantial cuts in emissions—especially if they are limited to a subset of developed nations—the atmospheric concentration is likely to continue to grow for many decades, if not a century or more, before a steady-state concentration is reached.[3] This will be the case regardless of what LCFS regulation CARB imposes. Second, within broad limits, the later a ton is emitted, the more it will contribute to higher concentrations because a smaller fraction will have been removed from the atmosphere. Third marginal damages from climate change are likely to increase with the level of climate change. Fourth, marginal damages are likely to increase over time due to growth in population and income (Pearce 2003). As population increases, more individuals are exposed to any negative ecological, health, or economic effects associated with climate change. Similarly, as average worldwide incomes increase, the costs associated with economic disruptions become larger. Thus, it seems likely that the SCC will increase for many decades, well beyond the project horizons assumed in the analyses presented in the ISOR.

---

[3]　See, for example, Webster et al. (2003).

B. Estimates of the Social Cost of Carbon from the Literature

Numerous studies report estimates of the SCC, but relatively few address the rate at which the SCC will grow over time. In addition, to the extent to which studies report an expected growth rate over time (or point estimates of the SCC in multiple years), the varied assumptions and methodologies used in different studies make it challenging to reconcile estimates made by different groups. Studies vary in the emissions scenarios assumed (generally either business as usual or optimal control of emissions), the time horizon evaluated, the discount rate, whether equity weights are used (which give greater weight to impacts in less-developed regions), and the scope of damages considered, among other factors.

For all of their differences, however, those studies that have estimated the SCC for different years consistently have produced estimates of the SCC that increase over time. Clarkson and Deyes (2002) provide a survey of studies that develop point estimates for the SCC, including five that estimate the SCC in multiple time periods and find that it increases over time.[4] Pearce (2003) builds upon the research in Clarkson and Deyes, focusing on estimates developed without equity weights and incorporating three additional studies that also find that point estimates of the SCC increase over time.[5] Finally, the Final Report of the UK Government's *Social Costs of Carbon Review* (Watkiss et al. 2006) commissioned additional analyses of the SCC over time using two different integrated assessment models, and likewise

---

[4] The time periods range from 1991-2000 to 2021-2030. The relevant studies are Cline (1992), Maddison (1994), Nordhaus (1994), Fankhauser (1995), and Tol (1999).

[5] Pearce considers the same time periods and many of the same studies as Clarkson and Deyes. The additional studies considered include Peck and Teisberg (1992), Roughgarden and Schneider (1999) and Nordhaus and Boyer (2000).

finds that the SCC increases over time, though the rate at which this occurs varies over time and between models.[6]

In interpreting the wide range of findings outlined above, the IPCC Fourth Assessment Report notes that "current knowledge suggests a 2.4% rate of growth." (Yohe et al. 2007, p. 822). We use this number for illustrative purposes.

C. Applying the Growth Rate of the Social Cost of Carbon

Discounting normally is applied to monetized costs and benefits (or damages), and it is not appropriate to apply a monetary discount rate to physical quantities unless the economic marginal value of the physical measure remains the same over time. If the marginal value of the physical unit is growing at a constant rate over time, however, there is a simple relationship between the financial discount rate and the rate that should be applied to the underlying physical measure.

Let SCC_t be the marginal damages from a unit emitted in year t, reflecting the discounted sum of its damages over its residence in the atmosphere. The present value of one unit of emissions in year t is then $SCC_t/(1+r)^t$. If SCC_t is growing at the rate s, then we can rewrite its present value as $SCC_0 (1+s)^t/(1+r)^t$, or $SCC_0[(1+s)/(1+r)]^t$. In computing relative weights for different years, the SCC_0 term drops out because it appears in all years; i.e., in developing relative weights, the absolute value of SCC_0 is not needed. The weight given to a unit emitted in year t relative to a unit emitted in year 0 is $[(1+s)/(1+r)]^t$. We obtain the same result if we use a discount rate for emissions that is equal to $(r-s)/(1+s)$, which is approximately the same as $r-s$ for small values of s. Thus, for example, if the monetary discount rate is 3 percent and the growth rate of the SCC is $s = 2.4$ percent, the equivalent discount rate for emissions is about 0.6

---

[6] The analyses commissioned by the UK DEFRA evaluate SCC estimates over a time horizon of 60 years.

percent.[7] If the monetary discount rate is 2 percent, the rate used in the ISOR, the equivalent discount rate for emissions is -0.4 percent; i.e., later emissions receive *more* weight than current emissions because the SCC is rising faster than the discount rate.

Figure 5 plots relative weights for a range of monetary discount rates assuming 2.4 percent annual growth in the SCC. If the growth rate exceeds the discount rate, the weights rise over time. If the discount rate exceeds the growth rate of the SCC, the weights fall with time, but at a significantly slower rate than if the growth in the SCC was not incorporated in the calculation.
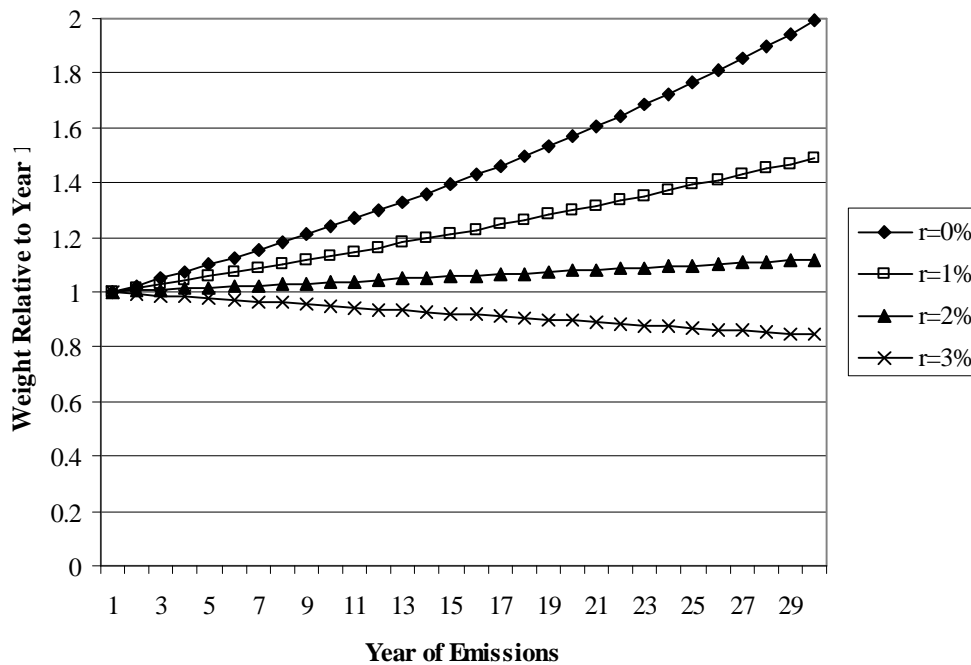
Note: Assumes that the SCC is growing at 2.4% per year, so the effective discount rate applied to emissions is (*r*-2.4%)/(1.024).
Source: NERA calculations

Figure 5. Relative Weights for Value-Adjusted Emissions and Alternative Monetary Discount Rates

---

[7] More precisely, it is (*r-s*)/(1+*s*), or (0.03-0.024)/(1.024) = 5.86 percent for *r*=3 percent and *s*=2.4 percent.

IV. Illustrative Comparisons of Land Use Change Carbon Intensity Values and Concluding Comments

In this section we compute LUC CIs based on the CARB staff "representative" LUC emissions using the alternative methods of accounting for the timing of emissions discussed in Sections II and III. We also offer some brief concluding remarks.
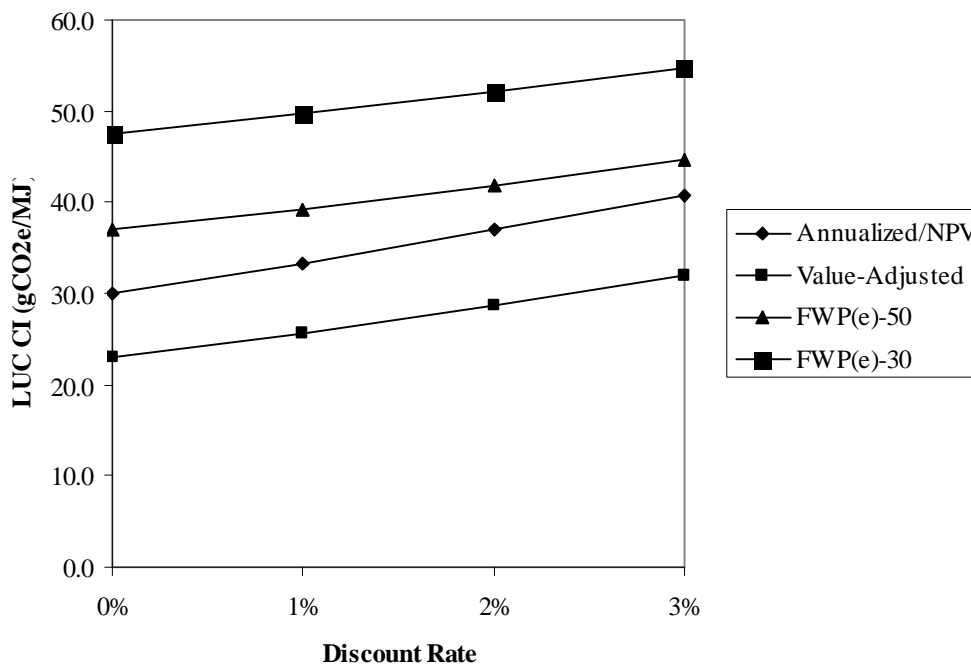
A. Comparison of Land Use Change Carbon Intensity Values Using CARB Staff's Emission Estimates and Different Methods for Accounting for the Timing of Emissions

In computing the LUC CIs for the CARB staff's LUC emission estimates, we consider three general methods of accounting for the timing of emissions:

1. Annualized/NPV: Weights based on the discounted sum of emissions. This is the ISOR's Annualized method for r=0 percent and its NPV method for r>0 percent.

2. FWP(e): Weights based on FWP method (when r=0 percent) or FWPe method (when r>0 percent). We consider two Impact Horizons, 30 (FWP(e)-30) and 50 (FWP(e)-50) years.

3. Value-adjusted method: Weights based on discounted sums of emissions with discount rate adjusted for growth rate of SCC (2.4 percent for illustrative purposes).

Figure 6 plots the results, varying the discount rate over the range considered in the ISOR, from 0 to 3 percent. As the figure shows, for any given discount rate, the FWPe yields the highest LUC CI and the Value-adjusted method yields the lowest value. The emissions-only method yields intermediate values. For any given method, the LUC CI is lowest with a discount rate of zero and rises as the discount rate increases. The FWP(e) values are substantially higher with a shorter Impact Horizon.

Note: Assumes 30-year project horizon and SCC growth of 2.4% for Value-Adjusted method.
Annualized/NPV line is ISOR's Annualized Method for r=0 and its NPV method for r>0.
FWP(e) lines are FWP method for r=0 and FWPe for r>0.
Line labeled FWP(e)-50 assumes a 50-year impact horizon and FWP(e)-30 assumes a 30-year impact horizon

Source: NERA calculations based on CARB (2009) and O'Hare et al. 2009.

Figure 6. Impact of Discount Rate on Alternative Methods of Computing LUC CI

Table 1 reports the same information as Figure 6, but in tabular form.

Table 1. LUC CIs with Alternative Methods for Accounting for Emission Timing

Discount Rate	Annualized/NPV	Value-Adjusted	FWP(e)-50	FWP(e)-30
0%	29.9	22.9	37.0	47.5
1%	33.3	25.7	39.3	49.8
2%	36.9	28.7	41.8	52.2
3%	40.7	31.9	44.7	54.7

Note: Assumes 30-year project horizon and SCC growth of 2.4% for Value-Adjusted method.
Annualized/NPV line is ISOR's Annualized Method for r=0 and its NPV method for r>0.
FWP(e) lines are FWP method for r=0 and FWPe for r>0.
FWP(e)-50 assumes a 50-year impact horizon and FWP(e)-30 assumes a 30-year impact horizon

Source: NERA calculations based on CARB (2009) and O'Hare et al. 2009..

B. Concluding Remarks

The method used to aggregate emissions across time can have a large impact on the estimated indirect emissions due to land use changes associated with corn-based ethanol. We recommend that CARB staff reject the use of the FWP and the FWPe methods because they reflect an arbitrary truncation effect. Early emissions can receive dramatically more weight than later ones because their impacts in the atmosphere are tracked and accumulated by the method for more years after they are released. The magnitude of this effect depends on the arbitrarily chosen length of an Impact Horizon. Correcting for the truncation effect with the FWP and FWPe makes them equivalent to the simpler Annualized and NPV approaches, respectively, that are based on emissions.

The Annualized and NPV approaches are superior to the FWP and FWPe, respectively, but like those methods they fail to account for the fact that there is a broad consensus that the marginal damages caused by a ton of CO_2 emissions will grow over time, so that, for example, it will be worth more in 20 years to reduce emissions by a ton in that year than it is worth to control a ton today. This means that in aggregating emissions that occur in different future years, the weights should reflect those higher relative values, as well as whatever discount rate CARB determines is appropriate for monetized benefits.

The practical effect of accounting for changes over time in the SCC is to reduce the monetary discount rate by the growth rate in marginal damages to arrive at a discount rate appropriate for physical emissions. If one uses either of the two discount rates for benefits highlighted in the ISOR (2 or 3 percent) and the growth rate in the SCC suggested in a recent IPPC report (2.4 percent), this approach yields emission discount rates of between -0.6 percent (with r=2 percent) and +0.4 percent (with r=3 percent), bracketing the emission discount rate of

zero implicit in the CARB staff's preferred Annualized or averaging approach. This means that

the indirect emissions values for ethanol calculated taking into account increasing marginal

damages and the ISOR discount rates of 2 and 3 percent bracket the value obtained using the

CARB staff's preferred Annualized (averaging) approach.

References

California Air Resources Board (CARB). 2009. Proposed Regulation to Implement the Low Carbon Fuel Standard. Staff Report: Initial Statement of Reasons. Volumes I and II. March 5. Online: http://www.arb.ca.gov/fuels/lcfs/lcfs.htm.

Clarkson, R. and K. Deyes. 2002. Estimating the Social Cost of Carbon Emissions. UK Government Economic Service Working Paper 140. Online: http://www.hm-treasury.gov.uk/d/SCC.pdf.

Cline, W. 1992. *The Economics of Global Warming*. Washington, DC: Institute for International Economics.

Fankhauser, S. 1995. *The Economics of the Greenhouse*. London: Earthscan.

Maddison. D. 1994. Economics and the Environment: The Shadow Price of Greenhouse Gases and Aerosols. Surrey Energy Economics Discussion Papers, SEEDS, 76.

Nordhaus, W. 1994. *Managing the Global Commons: The Economics of Climate Change*. MIT Press: Cambridge, MA.

Nordhaus, W. and J. Boyer. 2000. *Warming the World: Economic Models of Global Warming.* Cambridge, MA: MIT Press.

O'Hare, M., R.J. Plevin, J.I. Martin, A.D. Jones, A. Kendall, and E. Hopson. 2009. Proper Accounting for Time Increases Crop-Based Biofuels' Greenhouse Gas Deficit Versus Petroleum. *Environmental Research Letters* 4:1-7,

Pearce, D. 2003. The Social Cost of Carbon and its Policy Implications. *Oxford Review of Economic Policy*. 19:362-384.

Peck, S. and T. Teisberg.1992. Global Warming Uncertainties and the Value of Information: an Analysis Using CETA. *Resource and Energy Economics*: 15:71-97.

Roughgarden, T., and Schneider S. 1999. Climate Change Policy: Quantifying Uncertainties for Damages and Optimal Carbon Taxes. *Energy Policy* 27:415-429.

Tol, R. 1999. The Marginal Costs of Greenhouse Gas Emissions. *The Energy Journal*. 20:61-81.

Watkiss, P., Anthoff, D., Downing, T., Hepburn, C., Hope, C., Hunt, A. & Tol, R. S. J. 2006. *The Social Costs of Carbon (SCC) Review—Methodological Approaches for Using SCC Estimates in Policy Assessment.* Final report to UK Department for Environment, Food, and Rural Affairs. Online: http://www.defra.gov.uk/environment/climatechange/research/carboncost/pdf/aeat-scc-report.pdf.

Webster, M. D., Forest, C., Reilly, J., Babiker, M., Kicklighter, D., Mayer, M., Prinn, R., Sarofim, M., Sokolov, A., Stone, P., Wang, C. (2003). Uncertainty Analysis of Climate Change and Policy Response. *Climatic Change* 61: 295-320.

Appendix A.   Impact of Constant Evaluation Horizon on FWP(e)

This appendix shows how the FWP(e) approach is affected by the Impact Horizon and how the approach would be modified through use of a common Evaluation Horizon.

A. The FWP(e) Weights and the Impact Horizon

The FWP and FWPe methods defined by CARB have a fixed Impact Horizon. The FWP is simply a special case of the FWPe with a discount rate of zero. Under the FWPe, the weight given emissions in year t relative to year 1 is given by:

$$w_t = \frac{\sum_{i=t}^{H_I} D(i-t+1)(1+r)^{-(i-1)}}{\sum_{i=1}^{H_I} D(i)(1+r)^{-(i-1)}},$$

where $D(i)$ is the fraction of CO_2 remaining in the atmosphere t years after it is emitted and H_I is the Impact Horizon. Note that $D(i)$ depends only on the number of years since an emission occurred, and not when the emission occurred within the Project Horizon. Rearranging terms yields:

$$w_t = (1+r)^{-(t-1)} \frac{\sum_{i=1}^{H_I-t+1} D(i)(1+r)^{-i}}{\sum_{i=1}^{H_I} D(i)(1+r)^{-i}}.$$

Note that in addition to the discount factor, the two summations in the ratio have the same first (H_I-t+1) terms, the numerator lacks the last t terms that are in the denominator. This difference reflects the fact the method tracks the fate of emissions in the atmosphere for a longer time with early emissions than later ones.

To see how w_t changes as the Impact Horizon lengthens, we can rewrite w_t in the following form:

$$w_t = (1+r)^{-(t-1)} \left\{ 1 - (1+r)^{-(H_I - t)} \left[\frac{\sum_{i=1}^{t-1} D(H_I + i - t)(1+r)^{-i}}{\sum_{i=1}^{H_I} D(i)(1+r)^{-i}} \right] \right\}$$

As H_I approaches infinity, the term in square brackets approaches 0, because the number of terms in the summation in the numerator remains constant at t-1, but each terms gets smaller because the t-1 years of atmospheric concentrations not included in the FWPe are increasingly far away from the time of emissions, and hence will have decayed more. In contrast, the sum in the denominator continues to grow with H_I. Moreover, if the discount rate is positive, the ratio shrinks even faster and it is multiplied by a discount factor, $(1+r)^{-(H_I - t)}$, that approaches zero as H_I grows. As a result, as H_I approaches infinity, w_t approaches $(1+r)^{-(t-1)}$, which is the same weight given by the NPV method. If r=0 (i.e., with the FWP), w_t approaches 1 as H_I approaches infinity, the same as the Annualized method.

Figure A-1 compares the relative weights for emissions in year 30 for alternative Impact Horizons. The FWP weight converges slowly to the Annualized weight. With an Impact Horizon of 100 years, it is 77 percent as large as the Annualized weight. With an impact horizon of 500 years, it is 96 percent as large. The FWPe converges more rapidly to the NPV weight as the Impact Horizon lengthens, reaching 91 percent of the NPV value with a horizon of 100 years and 99 percent of the NPV value with a horizon of 200 years or more.
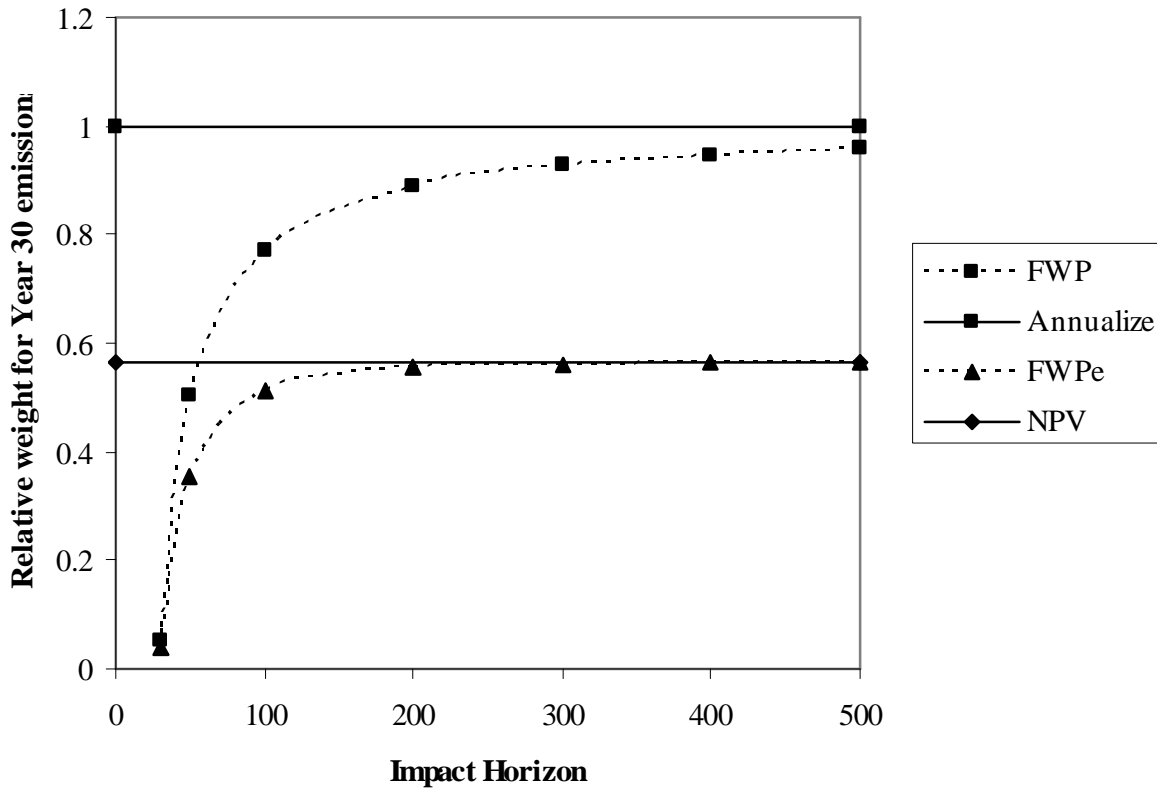
Note: FWPe and NPV weights computed using a discount rate of 2 percent.
Source: NERA calculations

Figure A-1. Weights for Year-30 Emissions with Alternative Impact Horizons

B. Applying a Constant Evaluation Horizon to the FWP(e) Method

If we modify the method to evaluate CO_2 in the atmosphere for a constant number of

years (H_E) after they occur, the ratio is:

$$w_t = \frac{\sum_{i=t}^{t+H_E-1} D(i-t+1)(1+r)^{-(i-1)}}{\sum_{i=1}^{H_E} D(i)(1+r)^{-(i-1)}}$$

Rearranging terms yields:

$$w_t = \frac{(1+r)^{-(t-1)} \sum_{i=1}^{H_E} D(i)(1+r)^{-i}}{\sum_{i=1}^{H_E} D(i)(1+r)^{-i}} = (1+r)^{-(t-1)} .$$

Note that this weight does not vary with the length of the Evaluation Horizon (H_E) and that it is the same as the NPV method.