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Designing Cap and Trade to Correct for Non-Additional Offsets

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1. INTRODUCTION

An ideal cap-and-trade program for the control of greenhouse gas (GHG) emissions would include all sectors of the economy in order to capture opportunities for low-cost abatement from every sector. However, for sectors that are composed of many small dispersed emitters, the benefits of including low-cost abatement opportunities may be outweighed by the transactions costs of monitoring and enforcement. For example, agriculture accounts for about 15% of global GHG emissions, primarily in the form of nitrous oxide (N_2O) from fertilizer use and methane (CH_4) from livestock and rice production (IPCC 2007). But N_2O emissions from fertilizer use are spread across millions of farms and many more million acres of land and are difficult to measure. Methane emissions from livestock are even more dispersed and harder to measure, monitor and enforce.

Dispersed sources of GHG emissions in the agriculture and forestry sectors have not been capped in most existing and proposed greenhouse gas (GHG) cap-and-trade programs to date. This may be due to the high transaction costs alluded to above and political economic factors driven by small group coalitions (Olson, 1982). In most cases regulators have imposed a fixed limit on the emissions of GHGs on only some sectors of the economy (e.g. energy, industry, transportation). A notable exception is New Zealand, which covers emissions and sequestration (sinks) from forestry.

Instead of being capped, the agriculture and forestry sectors have typically been included through *offsets*. In a cap-and-trade system in which some sectors remain uncapped, an offset is a reduction in GHG emissions or an increase in carbon sequestration realized by an uncapped party that can purchased by a capped party to meet its compliance obligation. An offset can be functionally equivalent to an emission reduction in the capped sector because a GHG emission has the same environmental impact no matter where it originates. Offsets have been a component of almost all cap-and-trade initiatives and proposals to date. The European Union Emissions Trading System (EU-ETS), the world's largest cap-and-trade system, allows offsets from emission-reduction projects in developing countries not subject to emissions caps.[1] The Regional Greenhouse Gas Initiative (RGGI) in the northeastern United States caps emissions from the electric power sector, but allows for offsets originating in other sectors and regions. The state of California embarked in 2013 on a cap-and-trade program that includes trading of offsets from a variety of sources.

Offsets are included in cap-and-trade programs for a variety of reasons. The primary objective of offsets is to increase efficiency relative to the case where uncapped sources cannot sell offsets to the capped sector. By making less expensive mitigation available, especially at the beginning of a new mandatory GHG system, offsets can lower the overall cost of reaching the abatement level set by the policy cap. Results from economic modeling of federal U.S. cap-and-trade proposals have demonstrated marked decreases in carbon prices when offsets are included as an option (U.S. EPA, 2010). The generation of emission reductions in uncapped sectors may also provide economic and environmental co-benefits (e.g., the planting of native trees to offset emissions could enhance environmental quality by reducing water pollution and soil erosion (Pattanayak *et al.*, 2005)). On the distributional side, uncapped sectors could benefit from new revenue streams.

Non-additionality

Despite their advantages, however, offsets have some well-known imperfections that, if not addressed, can undermine the integrity of the entire cap-and-trade system. One such imperfection is *non-additionality.*[2] An offset is considered non-additional if the uncapped source receives credit for an emission reduction that has already occurred or would occur anyway. Consider that the uncapped sector can produce some amount of emission reduction under *business as usual* (BAU) without incurring any costs. This BAU reduction may be due to technological advances or market trends. For example, a landowner may allow a field of marginal cropland to be reclaimed by the

[1] These offsets are part of the Clean Development Mechanism (CDM) of the Kyoto Protocol. There are also credits from Joint Implementation projects, but those originate in other countries that face a cap on emissions and thus are in many ways different from offsets from uncapped sectors and countries, the focus of this paper.

[2] Other imperfections include leakage and non-permancence (Murray, Sohngen and Ross, 2007).

adjacent woods because farming the field is no longer profitable. The cessation of farming that land will reduce GHG emissions associated with fertilizing and tilling the field and sequester carbon as trees grow on it. However, since this natural reforestation of the field would have occurred even without the impetus of policy or program, the carbon being stored would be not be additional.

The existence of such "anyway" mitigation should be seen as a good thing overall, indicating that the cost of achieving emission reductions may be lower than was originally thought (Bushnell, 2010).[3] But if non-additional mitigation in an uncapped sector is allowed to substitute for real abatement in a capped sector, then the offsetting transaction increases emissions and results in a *de facto* violation of the cap.

Non-additional offsets can also result if baseline emissions, the basis against which emission reduction offsets are calculated, are erroneously set above BAU. Predicting an alternative and unobserved emissions trajectory into the future is difficult for a regulator as it relies on firms' private information, making estimates of BAU uncertain. This information asymmetry in baseline emissions can lead to a problem of adverse selection, in which the set of firms supplying offsets is weighted toward those that have been granted overly generous baselines by the regulator, as opposed to those that have truly reduced emissions below what they would otherwise have been (Montero, 2000). Setting a baseline equal to BAU is not necessary for capped entities since being regulated under a cap means that any emissions are directly constrained in absolute terms.[4] Error in allocating allowances in the capped sector has distributional impacts but does not undermine the

[3] An example of this is the recent switch in fuel source for the United States economy from oil and coal to natural gas, which put the U.S. on a trajectory to meet its emission reduction targets even in the absence of a cap-and-trade program.
[4] Note that the emissions target is typically set for a future period as a percentage deviation from some historic emissions level (e.g., the Kyoto Protocol targets are based on percentage deviations from 1990 emissions levels). That means that if emissions are trending downward under BAU for some technological or market reason, it will make achievement of the future target easier.

effectiveness of the GHG reduction program, while error in setting emission baselines in an offset sector affects both distribution and effectiveness (Cattaneo, 2010).

The problem of non-additionality is well known and is addressed in the protocols of existing offset initiatives. For example, the Clean Development Mechanism of the Kyoto Protocol (CDM-Executive Board, 2007) Verified Carbon Standard (VCS, 2010), the Climate Action Reserve (CAR, 2011), and U.S. climate legislation that passed the House of Representatives all state that individual emission reduction projects are eligible for offset credits only if they pass “additionality tests” to determine that the GHG emissions reduced (or carbon sequestered) would not have occurred in the absence of the project (Trexler *et al.*, 2006; Schneider, 2009).

This paper explores three types of additionality corrections, described in detail later in the paper: (1) direct additionality tests that attempt to screen out non-additional abatement at the project level, (2) a cap adjustment that tightens the abatement requirement to balance the aggregate quantity of non-additional abatement, and (3) imposition of a trading ratio that allows only a portion of the abatement produced by uncapped sources to be sold as offsets.

While each of the three correction approaches is able to overcome the problem of non-additionality, they have different aggregate costs and welfare impacts on the different sectors. The aggregate abatement cost is minimized by additionality tests, though the transaction costs associated with these tests are known to be substantial in practice. A cap adjustment is the most beneficial approach for offset suppliers, who gain greater opportunity to sell credits, and the most costly approach for capped sources, who face a tightening of the regulatory burden. A trading ratio is more costly to the capped sector than additionality tests but less costly than a cap adjustment, and has an ambiguous welfare impact on offset suppliers.

This paper continues in Section 2 by presenting a simple analytical model of the economy in which all emitting sectors are included under an emissions cap. We show that high transactions costs in the uncapped sectors – we use the agriculture and forestry (AF) sectors as a specific example - can exceed the benefits of including these sectors under the cap. In Section 3 we present a model in which only the energy, industrial and transportation (EIT) sectors are included under the cap. Allowing offsets from the uncapped AF sectors lowers the cost of achieving the economy-wide reduction target. In Section 4 we introduce BAU emission reductions (zero-cost, non-additional abatement) in both sectors. We show that BAU emission reductions from offset sources in the uncapped sector can undermine the attainment of the economy-wide reduction target in a way that BAU emissions in the capped sector do not, by allowing real reductions from the capped sector to be traded for non-additional reductions in the uncapped sector. In Section 5 we use a partial equilibrium framework and welfare analysis to compare the environmental, cost and distributional impacts of the three potential policy approaches for addressing non-additionality identified above and detailed further below. In Section 6 we consider the case where the regulator does not have perfect information about BAU emissions at the firm- or sector-level. The paper concludes in Section 7 with a discussion of the practical implications of the three potential approaches.

2. AN ECONOMY-WIDE CAP, TRANSACTION COSTS, AND THE RATIONALE FOR LEAVING SOME SECTORS UNCAPPED

In the absence of transaction costs, an economy-wide cap-and-trade program would meet a national emissions target at the lowest possible abatement cost by capturing the most cost-effective abatement opportunities from all sectors. Transaction costs, however, can justify allowing some sectors to remain uncapped.

Figure 1 shows that abatement costs are minimized when all sectors are included under the emissions cap. Including both economic sectors under the cap, represented by the marginal abatement cost curves, MAC_{EIT} and MAC_{AF} respectively, allows the target to be achieved at total abatement cost *A.* If the cap had to be achieved by the EIT sector alone, it would raise total abatement costs to A+B, so the abatement efficiency gains of including the AF sector are represented by the area B.

However, relative to the EIT sector, emission sources and sinks from the AF sector are individually small, spatially dispersed, and costly to monitor and enforce. [5]This implies that including the AF sector could entail high transaction costs (which are not included in the marginal abatement cost curves in Figure 1). This can be illustrated by a model of transaction costs for emitters included in a capped system (Stavins, 1995), with the addition of firm-level fixed costs (e.g. planning, paperwork, permitting):

$$t_{ij} = \alpha_{ij} + f(x_{ij}, e_{ij}) \qquad [1]$$

where

$t_{ij} =$ cost of monitoring,reporting and verifying emissions for sector i, source j;

$\alpha_{ij} =$ fixed cost for each source in sector i; and

f(-) = a variable cost function of a source's economic output or capacity, x_{ij}, and a source's emissions levels, e_{ij}.

In the EIT sector a source may be a firm or plant, and in the AF sector a source may be a farm or forest property.

Let sector level transaction costs be represented as the sum of source-level costs.

$$T_i = \sum_{j=1}^{N_i} t_{ij} \qquad [2]$$

where N_i is the number of emission sources in sector *i*.

[5] As a point of comparison, in the U.S. in 2011 there were approximately 2,200 coal and gas electric power units (US EIA, 2013) generating about 2.2 billion tons of GHG emissions (US EPA, 2013), or about 1 million tons per power plant on average in relatively easy to measure form (at the stack). In contrast, there are approximately 2.2 million farms (US Census, 2012) generating 460 million tons of GHG emissions (about 200 tons per farm) from dispersed and difficult to measure processes such as field emissions of nitrous oxide (N_2O) from fertilizer application.

Sectors with many small emission sources such as AF are likely to have high transaction costs relative to sectors with fewer, larger sources, due in part to a large fixed cost component. Transaction costs associated with regulating the AF sector may exceed the cost savings from including the sector: $T_i > B$. In this case the emission reduction target may be met at lower overall cost by excluding the AF sector from the cap.[6]

However, even after considering monitoring and enforcement costs the AF sector may still include individual sources that offer relatively low-cost abatement opportunities, perhaps relatively large ones. We focus our attention on those offset possibilities through the remainder of the paper.

3. THE MARKET FOR OFFSETS

As described above, some sources in the uncapped sector can still produce low-cost abatement if incentivized to do so. Figure 2 illustrates a model of the market for offsets that forms the basis of analysis for the remainder of the paper. In this illustration, point *c* on the horizontal axis represents the aggregate emissions abatement target. Note that an *abatement target* is not the same as the emissions cap on the EIT sector; rather it is the emission reduction necessary to meet that cap. If all abatement has to be achieved only by the capped EIT sector, then the total cost of meeting the target would be the triangular area under the cost curve, ABCD.

Suppose however that the capped sector could meet a portion of its compliance obligations by purchasing emission reduction offsets from sources in the uncapped sector that can sell offset credits for a price higher than their cost of abatement plus transaction costs. The AF offset abatement cost function is represented by MAC_{AF}, which rises from right to left and, for the moment, we assume that all abatement by the sector is costly. The optimal abatement solution occurs at the intersection of the MAC curves for the capped sector and offsets. Here the abatement

[6] Lawmakers and regulators could also exclude small sources in capped sectors for the same cost considerations. Indeed, the Waxman-Markey climate bill that passed the U.S. House of Representatives in 2009 (HR 2454) excluded sources in the EIT sectors emitting less than 25,000 tons of carbon dioxide annually.

target is met by dividing abatement actions optimally between the capped sector and AF offsets: $c = q^*_{EIT} + q^*_{AF}$, where q variables represent the abatement from each sector. The use of offsets causes the marginal cost of the final unit of abatement to drop from P^0 to P^*. Moreover, the total cost of abatement to achieve c drops from ABCD to AB, for an aggregate savings of CD.

Mathematical derivation of the offset equilibrium

For the purpose of comparing outcomes across scenarios below, we derive the offset equilibrium based on the abatement cost functions introduced above. For computational ease, we stipulate linear marginal abatement costs:

$$MAC_{EIT} = m\, q_{EIT} \qquad [3]$$

$$MAC_{AF} \quad = n\, q_{AF} \qquad [4]$$

Abatement from the capped sector and offsets must add up to the aggregate target,

$$c = q_{EIT} + q_{AF} \qquad [5]$$

Via substitution, the equilibrium abatement outcomes can be expressed as follows:

$$q^*_{EIT} = \frac{n}{m+n} c \qquad [6a]$$

$$q^*_{AF} \quad = \frac{m}{m+n} c \qquad [6b]$$

at which the marginal cost (price) is defined by

$$P^* = m \frac{n}{m+n} c \qquad [7]$$

Figure 2 shows the total abatement cost (TAC) of achieving the abatement target is lowered from TAC^0=A+B+C+D to TAC^*=A+B). Analytically, these can be expressed

$$TAC^0 = \frac{m}{2}c^2 \quad [8a]$$

$$TAC^* = m\,\frac{n^2}{2(m+n)^2}\;c^2 \quad [8b]$$

Note that $TAC^* < TAC^0$.

4. THE NON-ADDITIONALITY PROBLEM

In the example above, any level of abatement from either sector incurred positive costs; there was no free emission reduction. However, in both the capped and offset sectors some sources may be able to reduce some level of emissions below historical levels at no cost. But the use of zero-cost abatement from the offset sector is problematic in a way that equivalent abatement from the capped sector is not. This is because non-additional reductions are being used in place of real emission reductions from the capped sector, preventing the overall economy-wide abatement target from being attained.

Figure 3 illustrates how non-additional offsets can undermine the integrity of the emissions cap. Here the EIT sector can costlessly reduce emissions by *a* even in the absence of a cap-and-trade program. Some quantity of offsets, *b*, is non-additional, either because the AF offset suppliers can costlessly reduce these emissions or as an artifact of erroneous baselines. In this scenario the EIT sector meets some portion of its compliance obligations through zero-cost, non-additional reductions (Figure 3 *i*). The EIT sector also meets some portion of its compliance obligations through low-cost abatement (Figure 3 *ii*). Furthermore, the EIT sector meets some portion of its compliance obligations by replacing its high-cost abatement with low-cost, additional abatement from the AF sector through the purchase of offsets (Figure 3 *iii*). Finally, the EIT sector meets some portion of its compliance obligations through the purchase of offsets from zero-cost, non-additional abatement from the AF sector (Figure 3 *iv*). Elements (i) through (iii) are not problematic, as they simply reduce the cost of abatement. Element (iv) creates a problem, however, as the purchase of non-additional offsets from the uncapped sector causes the cap to be violated by as much as quantity *b*, since total emission reductions by the economy may be as low as *c-b*, rather than *c*..

5. THE EMISSIONS BASELINE AND OPTIONS FOR CORRECTING NON-ADDITIONALITY

One way to fix the non-additionality problem is to properly determine the emissions baselines for offset sources that sell credits to the capped sector. An emissions baseline is the quantity of emissions against which reductions (credits) are calculated. If the baseline accurately reflects BAU emissions and sinks, then any free (non-additional) abatement, such as that represented by *b* in Figure 3, would be included in the baseline and not count toward a reduction credit. Additionality would be assured.

However, determining the proper emissions baseline is inherently difficult because it cannot be observed directly. Rather, it is a prediction of a future in which the offset activity does not exist—a counterfactual world that cannot be proved or disproved. The baseline is set by the regulator who does not have perfect information and can only attempt to estimate it by extrapolating historic emissions rates or modeling technical change, market dynamics or other real but uncertain phenomena.

We consider three potential policy approaches can be used to ensure that the additional abatement provided by the offset sources is equal to the offset credits purchased by the capped sector—(1) direct additionality tests for each project, (2) an adjustment to the aggregate emissions cap, or (3) an offset trading ratio. We assume that the social value of ensuring that the cap is actually met is greater than the additional abatement costs that will be imposed on the capped and uncapped sectors, i.e., that the intended cap was set optimally. The question we ask, therefore, is not whether but how to ensure that the emission reduction target is met. As we show, any of the three approaches can achieve the reduction target in principle, but the distributional consequences for the capped and uncapped sectors differ depending on the approach used.

5.1 Option 1: Direct additionality tests to eliminate credits for business-as-usual (BAU) abatement at the project level

A variety of tests have been developed to filter out offsets from non-additional projects, often used in combination (CDM-Executive Board, 2007). Two broad categories of tests are *document justification* and *limiting entry*. Document justification requires each project to pass litmus tests — bottom-up evaluations that gauge projects individually on whether the project activities would be likely to occur without the inducement of an offset program. A common such test is a financial assessment that determines whether the proposed activity (e.g. afforestation) is more profitable than its closest alternatives (e.g. farming soybeans). Limiting entry tests set criteria that screen out offset projects with low probabilities of being additional based on secondary data. Limiting entry tests include "common practice" and "performance benchmark" that employ top-down standards informed by representative practice or performance in a given region or sector to serve as the baseline against which additionality is measured. When a project exceeds a pre-determined benchmark of performance or is better than common practice (i.e., BAU), then the difference between the emissions stream with the project emissions and the stream under BAU would be considered additional abatement.

Figure 4 illustrates a cap-and-trade program that permits the use of offsets and applies additionality tests that perfectly determine the BAU emissions baseline, thereby eliminating all non-additional abatement from the supply of offsets. The use of additionality tests shifts the offset supply curve to the right (which is inward given the right-to-left direction of the curve), so that all BAU emissions are included in the baseline and the supply curve reflects offset sources' true marginal cost of abating an additional unit of GHG emissions below BAU levels.

By removing the BAU abatement from use as offset credits, the equilibrium quantity of abatement produced by the capped sectors increases from $q_{EIT}*$ to q_{EIT}^{PT}, and the quantity of credits sold by offset sources decreases from $q_{AF}*$ (of which $q_{AF}* - b$ is additional and b is non-additional) to q_{AF}^{PT} (all of which is additional) so that the compliance cap is attained. Since mitigation in the capped sectors substitutes for a portion of the removed low-cost offset abatement, the allowance price rises from $p*$ to p^{PT}. The abatement cost for the capped sector rises from A to ABCD, while its total compliance costs including offset payments rises from ABCEFHJK (where A is capped sector abatement costs and the rectangle BCEFHJK represents the offset payments to the uncapped sector) to ABCDEFGHIJKL. In the offset sector, revenue for suppliers of additional offsets increases from BCEFH to EFGHIJKL, while revenue for suppliers of non-additional offsets decreases from JK to 0. Analytical formulations of welfare impacts are presented in Table 1.

Implementation challenges at the project level

The additionality test approach envisions tests that can perfectly distinguish emission reductions attributable to a mitigation project from those that would have happened anyway. Such tests have been found to be difficult, costly in practice, and subject to gaming by project proponents. As an indication of this problem in the field, Zhang and Wang (2011), find no statistical evidence that the CDM projects in China led to additional reductions in CO_2 emissions. This problem can be exacerbated by shifting rules and requirements for projects (Michaelowa, 2009). Moreover, efforts to assess additionality at the project level are complicated by the role of *leakage* (Murray et al, 2007). Actions taken by offset project participants to reduce emissions can shift activity and emissions elsewhere, undermining the direct emissions benefits of the project. This extent of leakage is impossible to estimate with project-by-project evaluations and requires market-level assessment (see Murray et al, 2004).

It is beyond the scope of this paper to empirically estimate the cost of addressing additionality and leakage at the project level . However, we note that in recent years offset protocols have gravitated from the project-level tests described above to more aggregated measures that both economize analysis across projects and can better control for market leakage. These aggregate approaches range from performance standards baselines that apply across all projects of a particular type (Climate Action Reserve, 2012) to jurisdictional offsets programs operating at national and subnational levels for particular sectors (Verified Carbon Standard, 2012; Governor's Climate and Forest Task Force, 2012)

Motivated by these concerns, the next two approaches operate from the premise that it may be more efficient to address the problem of non-additionality at higher levels of aggregation (e.g., at the sector level). Under these approaches, abatement lost due to non-additional offsets would be estimated at the aggregate level by the agency charged with overseeing the offset program. Thenthis estimate would be used to establish system-wide adjustments to ensure aggregate sector-level additionality. This quantification could be done prospectively based on predictive estimates or retrospectively using a selected past period and econometric models or other quantitative methods. There would be a degree of uncertainty surrounding these estimates, as discussed further below, but it should be no more uncertain than the direct project-level adjustment approach above, and could very likely be less uncertain if positive and negative discrepancies between estimated and true business-as-usual emissions are balanced out at the aggregate level.

The following approaches use the aggregate estimate of non-additionality to make system-wide adjustments that either: (i) adjust the aggregate emissions cap, or (ii) impose a trading ratio between abatement produced and offsets purchased.

5.2 Option 2: Adjust the cap to balance the inclusion of non-additional abatement

The *cap adjustment* approach takes the aggregate estimate of potential non-additional abatement just referenced and uses this to tighten the cap accordingly to require lower emissions (more abatement) from the capped sector.

Figure 5 illustrates the impact that a tightened cap would have on the offset market by shifting the level of abatement needed to meet a tighter cap outward by quantity *b*. It is assumed that the regulator can estimate the amount of zero-cost emission reductions available to the offset sector as a whole, even if it does not known the amount of zero-cost emission reductions available to individual entities within the sector. If the total economy-wide abatement obligation expands because of a tightened cap, then the capped sectors would abate more while at the same time purchasing more offset credits from the uncapped sector at a higher price. As was the case with the perfect additionality test above, the tightened cap causes the equilibrium amount of abatement produced by the capped sectors to increase from $q_{EIT}*$ (unadjusted) to q_{EIT}^{CA} so that the compliance cap is attained. Abatement by the offset sector now increases from the unadjusted value of $q_{AF}*$ (of which $q_{AF}* - b$ is additional and b is non-additional) to q_{AF}^{CA} (of which $q_{AF}^{CA} - b$ is additional and b is non-additional). Note in Figure 5 that the number of offsets sold under the cap adjustment approach q_{AF}^{CA} is greater than that sold under the perfect additionality test, q_{AF}^{PT} (Figure 4) even though the price is the same in both cases ($p^{CA} = p^{PT}$) . That is because the origin of the offset supply curve starts further right in Figure 5 the abatement target is pushed out and the non-additional abatement can be credited and sold.

The cost of abatement within the capped sector rises from A to ABCD, while its total compliance costs including offset payments rises from ABCEFHJKM to ABCDEFGHIJKLMN. In the uncapped sector, revenue for suppliers of additional offsets increases from BCEFH to EFGHIJKL, while revenue for suppliers of non-additional offsets increases from JK to MN. Analytical formulations of welfare impacts are presented in Table 1.

An interesting question arises if the option to purchase offsets is paired with an adjustment to the cap: Would the capped sector be better off without the option to purchase offsets at all? The capped sector benefits from trading through the ability to purchase offsets, but it suffers because of the more stringent cap on total emissions. In our model, the welfare benefit to the capped sources from allowing the use of offsets while tightening the cap is MN–O. As shown analytically in Appendix I, this value can actually be negative when there is a high level of non-additional abatement in the uncapped sector. That is, the increased cost to the capped sector resulting from the tightened cap will exceed the benefit from the use of offsets.

5.3 Option 3: Impose a trading ratio between offsets and uncapped-sector emission reductions

A third approach for addressing non-additionality is to calculate the offset sector's abatement at face value and then adjust the credits that can be used as offsets by the capped sector via a *trading ratio*. This approach has been proposed for the CDM (Chung, 2007; Schneider 2009) and was a feature of legislative proposals in the United States (e.g., Waxman-Markey American Clean Energy Security Act [H.R. 2454, 2009]). A trading ratio would require that $t = 1 + s$ units of abatement must be generated and verified for every credit issued — $t \geq 1$ is the trading ratio; $s \geq 0$ is the *surplus requirement*. The net outcome in the market would be the same whether the trading ratio is applied to the supply side (in which case offset producers could only sell a fraction of their abatement as credits) or the demand side (in which case offsets buyers could only apply a fraction of the offsets they purchase). Like the cap-adjustment approach, this policy measure makes no attempt to distinguish BAU abatement from abatement that is truly additional; all offset credits are affected equally.

Note that a trading ratio is not equivalent to a tax on offset purchases. A trading ratio increases the price and reduces the quantity of offsets purchased, just as a tax on offsets would. However, because of the surplus requirement, a trading ratio results in extra, or *super-additional*, abatement while a tax would not. Unlike a tax on offsets, a trading ratio can ensure that the cap integrity is not violated by balancing the inclusion of non-additional offsets with the production of super-additional abatement.

The application of a trading ratio, using the abatement cost framework from the previous examples, is illustrated in Figure 6. As with the cap adjustment, it is assumed that the regulator knows the amount of zero-cost emission reductions available to the offset sector as a whole, *b*, even if it does not known the amount of zero-cost emission reductions available to individual entities within the sector. The capped sector's demand is for offsets, rather than for abatement in the uncapped sectors *per se*, and remains unchanged with the imposition of a trading ratio. The supply-side trading ratio converts the supply curve for "raw" abatement to a supply curve for offsets. When the trading ratio $t > 1$, sellers must generate t times as many units of abatement as they are allowed to sell as offset credits, $q^{A}{}_{AF}{}^{TR}=tq^{O}{}_{AF}{}^{TR}$, while the price received by suppliers per unit of abatement, $p^{A\text{-}TR}$, is a fraction of the price paid by buyers per unit of useable offset credit, $p^{O\text{-}TR}$; $p^{A\text{-}TR} = p^{O\text{-}TR}/t$. Hence the offset supply curve, $MAC^{O}{}_{AF}$, is obtained by shifting the abatement cost curve $MAC^{A}{}_{AF}$ to the right, which is inward given the direction of the supply curve by a factor of $1/t$ and upward by a factor of t, which increases the slope overallby a factor of t^2.

A trading ratio always raises the price of offsets paid by purchasers and decreases the quantity of offsets purchased. However, a trading ratio may either increase or decrease the price received by offset suppliers for a unit of abatement, and similarly may either increase or decrease the quantity of abatement produced by the offset sources. Thus the impact of a trading ratio on the producer surplus received by offset suppliers is ambiguous. These propositions are proven in Appendix II.

If the regulator seeks to exactly balance the inclusion of non-additional abatement with the production of super-additional abatement using a trading ratio, then the optimal ratio is $t^* = \frac{m(c-a)+bm}{m(c-a)-bn}$. The derivation of this ratio is presented in Appendix III. In this case, the imposition of an optimal trading ratio causes the equilibrium amount of abatement produced by the capped sectors to increase from $q_{EIT}*$ to q_{EIT}^{TR} so that the compliance cap is attained. Abatement by the offset sector changes from $q_{AF}*$ (of which $q_{AF}*-b$ is additional and b is non-additional) to $q^A{}_{AF}{}^{TR}$ $=t\, q^O{}_{AF}{}^{TR}$ (of which $q^A{}_{AF}{}^{TR} -b$ is additional and b is non-additional); this change may be either an increase or a decrease. The price received by offset suppliers for a unit of abatement changes from $p*$ to $p^{A\text{-}TR} = p^{O\text{-}TR}/t$; this change may be either an increase or a decrease.

The cost of abatement within the capped sector rises from A to ABCDE, and its total cost including offset payments rises from ABCDFGIKLN to ABCDEFGHIJKLMNO. Revenue for suppliers of additional offsets changes from CDFGI to FGHIJKLM; this change may be either an increase or a decrease. Meanwhile revenue for suppliers of non-additional offsets changes from KLN to NO; this change may be either an increase or a decrease.

6. UNCERTAINTY ABOUT THE OFFSET SECTOR'S AGGREGATE EMISSION REDUCTIONS UNDER BAU

In our analysis above, we have derived policies and policy implications assuming that all of the parameters governing the system were known to regulators with certainty. In this section we relax this assumption to consider the case of a policy maker who is unable to observe the actual quantity of non-additional abatement from the AF sector, b, but must instead make policy based on an estimate of the parameter, $\hat{b}$. Since additionality tests attempt to eliminate the uncertainty over b, we focus here on the cap adjustment and trading ratio policies, which attempt to adjust other parts of the system for the b that is thought to exist.

When b is uncertain and policy choices are based on $\hat{b}$, analytical expressions of the policy outcomes are cumbersome and provide little intuition. Hence, we use Monte Carlo simulations to explore the relative effectiveness of the two policies under uncertainty. In the analysis, 50 scenarios were chosen based on random draws of values for the parameters a, c, m, and n from set distributions.[7] Then for each scenario 10,000 values were drawn for $b \in [0,5]$. Since the actual value of b is not observed by the policy maker, each policy was made using the average value of b, $\hat{b} = 2.5$. For each random draw, the effectiveness and welfare consequences of both policies were calculated, looking at both the mean and the variance of outcomes across the 10,000 simulations.

Table 2 summarizes the results of this analysis by comparing the ratio of the simulation results under the cap adjustment policy and the trading ratio policy. For example, the first row of the table shows that on average, the levels of total abatement under the two policies are nearly the same. However, the variation across the 10,000 simulations in total abatement achieved was 31% greater with the cap adjustment policy than with the trading ratio. The total abatement cost for the cap adjustment is slightly lower than for the trading ratio, because the trading ratio creates a gap between the marginal abatement costs for the two sectors. However, in all 50 scenarios there was more variation in the cap adjustment than under a trading ratio. Hence, we see that although the cap adjustment is more efficient on average, the trading ratio has a self-regulating feature that consistently reduces the variation in welfare outcomes that arises because of the unknown value of b.

[7] The ranges chosen for the parameters were as follows: $a \in [0,3]$, $c \in [10,20]$, $n \in [0.5,3]$, $m \in [0.5,3]$.

As was the case with no uncertainty, the capped EIT sector is consistently better off when the trading ratio is used and the AF offset sector is consistently better off under a cap adjustment. What is striking about the results in Table 2 is that the degree to which the net revenue of the AF sector is greater under the cap adjustment. While the specific values are only illustrative, it does suggest that the AF sector may have a strong interest in attempting to influence policy makers to adopt a cap adjustment approach.

7. POLICY IMPLICATIONS

The number of countries and states implementing or considering cap-and-trade systems for reducing greenhouse gas emissions continues to grow.[8] The designers of such systems will continue to find the use of offsets desirable for cost containment, but will want to consider approaches that can overcome offsets' potential imperfections. We have examined three policy design approaches that might be used to correct for non-additional offsets in a GHG mitigation market. Additionality tests directly address integrity issues but require a great deal of information. System-level approaches presume a shortfall in meeting mitigation goals in the uncapped sector and then compensate for it, either by tightening the stringency of the aggregate cap, or by imposing a trading ratio that requires more abatement from the uncapped sector than they are allowed to sell as offsets.

By shifting the rules governing the market for offsets, all three approaches are able to ensure that the target level of system-wide abatement is achieved. However, distributional effects differ substantially across the three options. The capped sector's compliance costs (abatement costs plus offset payments) vary across the three approaches, with all three requiring higher capped-sector spending than the no-adjustment case to ameliorate the welfare distortion due to imperfect offsets.

[8] The emphasis in this paper has been on offsets in compliance markets, but the voluntary carbon market is growing as well, especially as compliance markets face continuing political hurdles. Conte and Kotchen (2010) show that the price of voluntary carbon offsets can be affected by the standards they apply and thus the non-additionality approaches described in this paper are relevant in those contexts as well.

Compared to a compliance cap with no offsets, pairing offsets with either additionality tests or a trading ratio always lower the capped sector's cost of achieving the abatement requirement, while pairing offsets with a cap adjustment may actually raise the capped sector's cost in some cases. If adjusting the cap is the only option for addressing additionality, then the capped sector may prefer forgoing offsets entirely to a tightened cap.

For offset suppliers, the welfare gained from the sale of offsets (revenue less abatement cost) varies with the approach considered. The additionality test would result in a smaller offset market than in the no-adjustment case. Those selling non-additional abatement in the offsets market would lose producer surplus relative to the no-adjustment option, while those selling additional abatement would gain producer surplus through higher prices. In contrast, a cap adjustment would result in a considerably larger offset market, with increased producer surplus for sellers of both additional and non-additional abatement. Compared to a market policy that makes no adjustment for imperfect additionality, a trading ratio could either decrease or increase the uncapped sectors' producer surplus, depending on the relative responsiveness of the marginal abatement curves in the uncapped and capped sectors to changes in price.

A regulator's preferred approach for addressing non-additionality may depend on whether the welfare gains in the offset sector are accruing domestically (as in Waxman-Markey or the California cap-and-trade program) or overseas (e.g. through the UNFCCC Clean Development Mechanism or a market for a future market for credits for reduced emissions from deforestation and forest degradation, or REDD+). If the offset sector is domestic, a cap adjustment or trading ratio may be preferred for political reasons. If the offset sector is foreign, the domestic regulator may prefer to impose additionality tests. The dichotomy may apply to domestic offsets as well, when legislators favor distributional consequences across capped and uncapped domestic sources that benefit those economic sectors that are prominent within their district.

Using large transfers to achieve environmental objectives has the potential to produce rent-seeking behavior (van Kooten, 2009). In the case of offsets, for instance, this could mean that potential offset suppliers might lobby for favorable treatment (e.g., full cap adjustment in lieu of trading ratios or additionality tests). Such transfers might increase the political difficulty of eventually moving an uncapped sector to a capped sector, which as we show here would ultimately be a more efficient way to address economy-wide reductions if transaction costs can be reduced. If one objective is to minimize welfare transfers so as to avoid rent-seeking behavior of offset sectors, then the trading ratio approach may be preferred to an overall cap adjustment. On the other hand, if a political objective is to gain support of offset suppliers, rent-seeking caveats notwithstanding, the cap adjustment approach may be preferred.

In many ways, the most attractive scenario would be one in which BAU abatement could be completely and costlessly removed from the offset market, eliminating windfall gains for non-additional offsets. Offset standards in the voluntary market up to now have pursued this approach by imposing strict additionality tests and baseline monitoring requirements on candidate projects. But eliminating all non-additional reductions on a project-by-project basis is difficult and costly, and the results are not ultimately provable. Even under the most feasible project-level analysis, some non-additional offsets are likely be credited. Therefore, system-wide adjustments for dealing with additionality — such as a cap adjustment or offset trading ratio — should be seriously considered as alternatives or complements.

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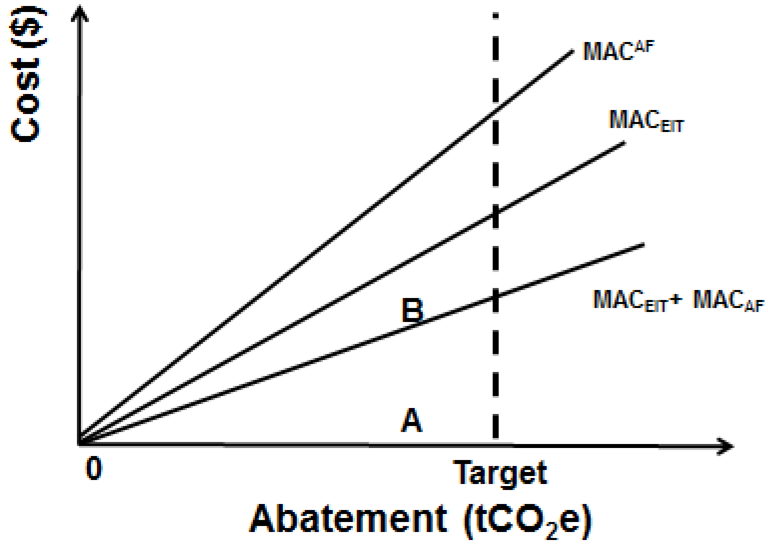

Figure 1: Cost savings from including low-cost abatement from all sectors

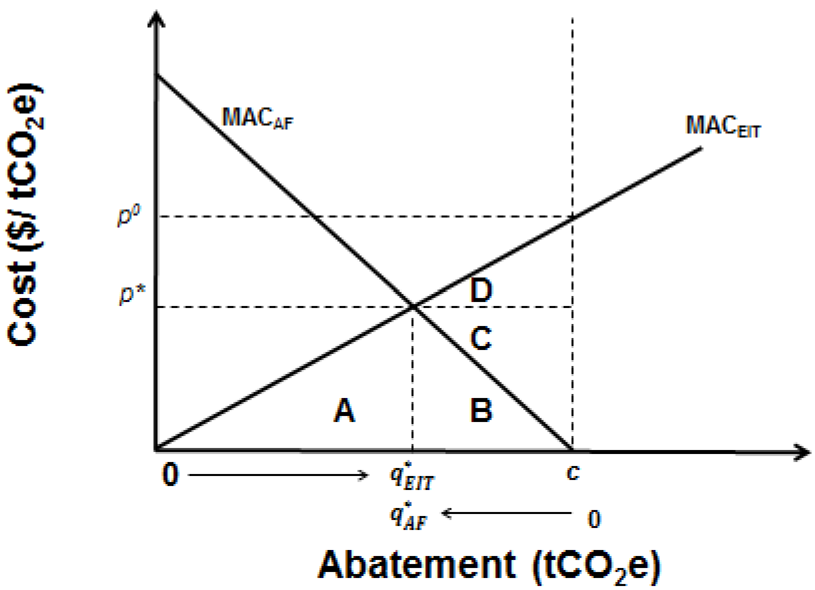

Figure 2: Efficiency gains from offsets

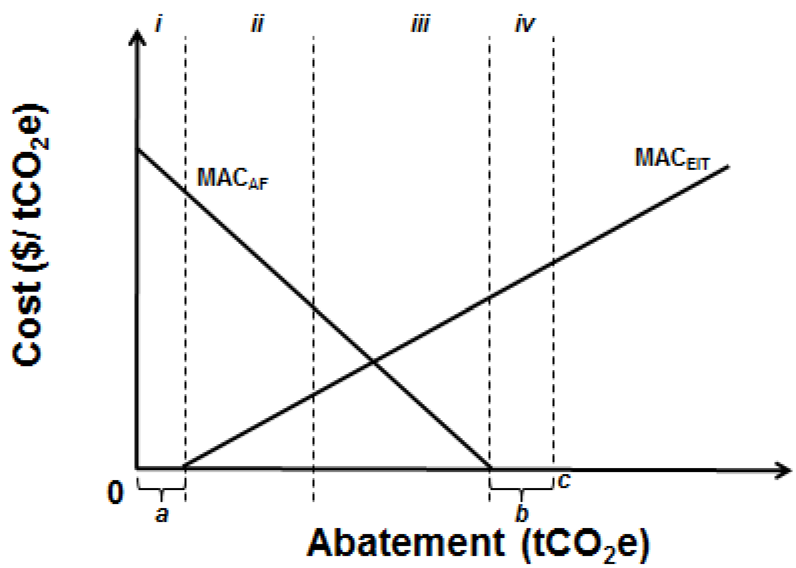

Figure 3: Effects of including zero-cost abatement from each sector

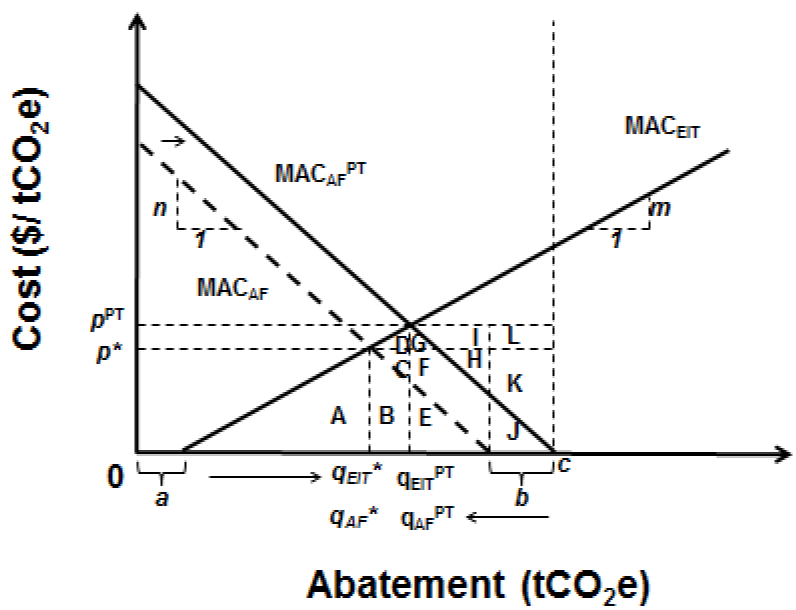

Figure 4: Effects of using additionality tests to exclude non-additional offsets

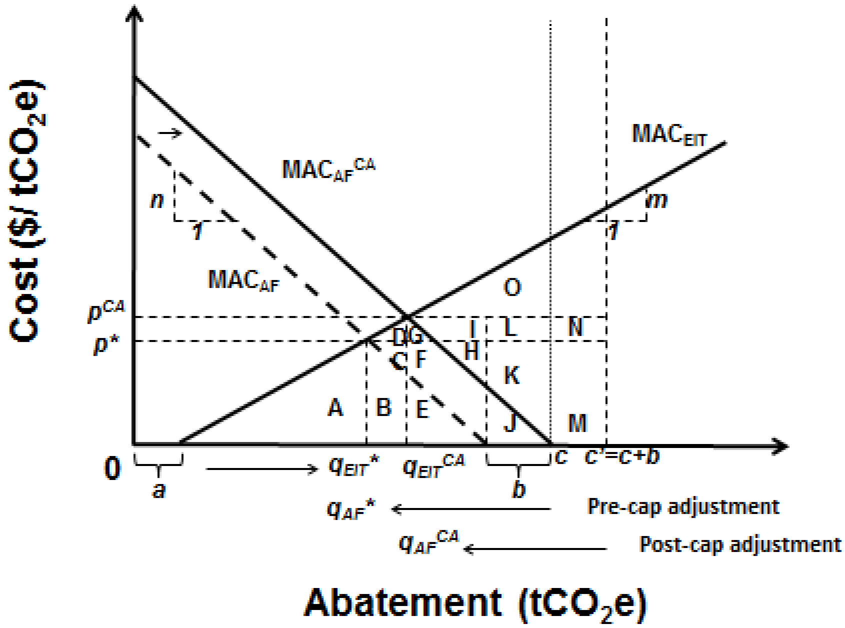

Figure 5: Effects of using a cap adjustment to balance the inclusion of non-additional offsets

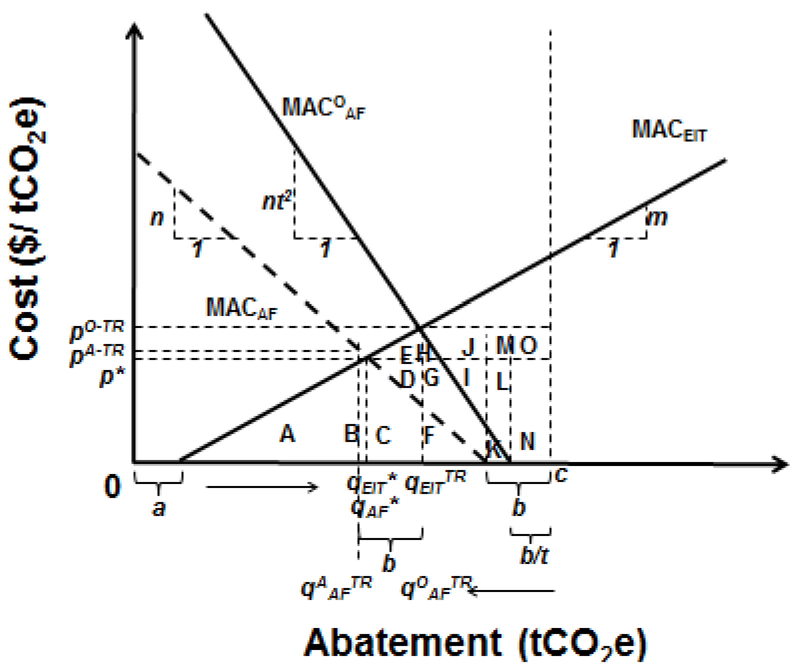

Figure 6: Effects of using a trading ratio to balance the inclusion of non-additional offsets

Table 1: Analytical representations of environmental and economic consequences of all policy options

			All sectors capped	EIT sector only, no offsets	Imperfect Offsets	Approach 1: Offsets + Additionality Test	Approach 2: Offsets + Cap Adjustment	Approach 3: Offsets + Trading Ratio
Quantity	Abatement, EIT		$\frac{am+(c-b)n}{m+n}$	c	$\frac{am+(c-b)n}{m+n}$	$\frac{am+cn}{m+n}$	$\frac{am+cn}{m+n}$	$\frac{nt(ct-b)+ma}{m+nt^2}$
	Abatement, AF (additional)		$\frac{bn+(c-a)m}{m+n}$	n.a.	$\frac{(c-b-a)m}{m+n}$	$\frac{(c-a)m}{m+n}$	$\frac{(c-a)m}{m+n}$	$\frac{mt(c-a)-bm}{m+nt^2}$
	Abatement, AF (non-additional)		n.a.[1]	n.a.	b	0	b	b
	Total real abatement		c	c	c-b	c	c	$\frac{nt(ct-b)+ma+mt(c-a)-bm}{m+nt^2}$ (= c when $t^*=\frac{m(c-a)+bm}{m(c-a)-bn}$)
Price			$\frac{(c-b-a)mn}{m+n}$	$(c-a)m$	$\frac{(c-b-a)mn}{m+n}$	$\frac{(c-a)mn}{m+n}$	$\frac{(c-a)mn}{m+n}$	$p_O=\frac{mnt[(c-a)t-b]}{m+nt^2}$ $p_A=\frac{mn[(c-a)t-b]}{m+nt^2}$
Welfare	EIT	Cost of abatement	$\frac{(c-b-a)^2mn^2}{2(m+n)^2}$	$\frac{(c-a)^2m}{2}$	$\frac{(c-b-a)^2mn^2}{2(m+n)^2}$	$\frac{(c-a)^2mn^2}{2(m+n)^2}$	$\frac{(c-a)^2mn^2}{2(m+n)^2}$	$\frac{m[nt((c-a)t-b)]^2}{2(m+nt^2)^2}$
		Cost of offsets	n.a.	n.a.	$\frac{mn(c-b-a)(cm-am+bn)}{(m+n)^2}$	$\frac{(c-a)^2m^2n}{(m+n)^2}$	$\frac{mn(c-a)(bm-am+bn+cm)}{(m+n)^2}$	$\frac{mnt[(c-a)m+bnt][(c-a)t-b]}{(m+nt^2)^2}$
		Total cost to EIT sector	$\frac{(c-b-a)^2mn^2}{2(m+n)^2}$	$\frac{(c-a)^2m}{2}$	$\frac{(c-b-a)mn[(c-b-a)n+2(cm-am+bn)]}{2(m+n)^2}$	$\frac{(c-a)^2mn(2m+n)}{2(m+n)^2}$	$\frac{mn(c-a)[(c-a)n+2(bm-am+bn+cm)]}{2(m+n)^2}$	$\frac{mnt[(c-a)t-b][(c-a)(2m+nt^2)+bnt]}{2(m+nt^2)^2}$
	AF (additional)	Cost of abatement	$\frac{(c-b-a)^2m^2n}{2(m+n)^2}$	n.a.	$\frac{(c-b-a)^2m^2n}{2(m+n)^2}$	$\frac{(c-a)^2m^2n}{2(m+n)^2}$	$\frac{(c-a)^2m^2n}{2(m+n)^2}$	$\frac{m^2n[(c-a)t-b]^2}{2(m+nt^2)^2}$
		Revenue from offsets	n.a.	n.a.	$\frac{(c-b-a)^2m^2n}{(m+n)^2}$	$\frac{(c-a)^2m^2n}{(m+n)^2}$	$\frac{(c-a)^2m^2n}{(m+n)^2}$	$\frac{m^2n[(c-a)t-b]^2}{2(m+nt^2)^2}$
		Net revenue	$\frac{(c-b-a)^2m^2n}{2(m+n)^2}$	n.a.	$\frac{(c-b-a)^2m^2n}{2(m+n)^2}$	$\frac{(c-a)^2m^2n}{2(m+n)^2}$	$\frac{(c-a)^2m^2n}{2(m+n)^2}$	$\frac{m^2n[(c-a)t-b]^2}{2(m+nt^2)^2}$
	AF (non-additional)	Cost of abatement	n.a.	n.a.	0	0	0	0
		Revenue from offsets	n.a.	n.a.	$\frac{(c-b-a)bmn}{m+n}$	0	$\frac{b(c-a)}{m+n}$ $\frac{(c-a)bmn}{m+n}$	$\frac{mn[(c-a)t-b]}{b(m+nt^2)}$
		Net revenue	n.a.	n.a.	$\frac{(c-b-a)bmn}{m+n}$	0	$\frac{(c-a)bmn}{m+n}$	$\frac{mn[(c-a)t-b]}{b(m+nt^2)}$
	EIT+AF	Total cost of abatement	$\frac{(c-b-a)^2mn}{2(m+n)}$	$\frac{(c-a)^2m}{2}$	$\frac{(c-b-a)^2mn}{2(m+n)}$	$\frac{(c-a)^2mn}{2(m+n)}$	$\frac{(c-a)^2mn}{2(m+n)}$	$\frac{mn[(c-a)t-b]^2}{2(m+nt^2)}$

Table 2: Ratios of performance under Cap Adjustment Policy to the Trading Ratio Policy when non-additional abatement is not known with certainty

		Minimum	Maximum	Average
Total Abatement	mean	0.999	1.001	1.000
	std. deviation	1.033	2.490	1.312
Total abatement cost	mean	0.932	0.997	0.980
	std. deviation	1.031	2.311	1.277
Total cost to the EIT sectors	mean	1.025	1.198	1.088
	std. deviation	1.094	8.541	2.215
Net Revenue for the AF sectors	mean	1.062	5.362	1.740
	std. deviation	1.098	13.286	2.651

APPENDIX I

This appendix derives the level of non-additional abatement in the uncapped sector above which the increased cost to the capped sector resulting from a tightened cap will exceed the benefit from allowing the use of offsets:

$m(c-a)^2 - \frac{mn(c-a)[(c-a)n+2(bm-am+bn+cm)]}{2(m+n)^2} < 0$ (From Table 1)

$2(c-a)(m+n)^2 < n[(c-a)n + 2(bm - am + bn + cm)]$

$2(c-a)(m+n)^2 - n^2(c-a) - 2mn(c-a) < 2bn(m+n)$

$$b > \frac{(c-a)[2(m+n)^2 - n^2 - 2mn]}{2n(m+n)}$$

$$b > \frac{(c-a)[2m^2 + 2mn + n^2]}{2n(m+n)}$$

APPENDIX II

This appendix provides the mathematical derivation of the four propositions in Section 5.3 on the general relationship between the trading ratio and abatement and offset prices and quantities. Please see main text for the original equations for these variables.

Proposition 1: Imposing a trading ratio always increases the price of offsets purchased from the uncapped sector.

We show that p^{O-TR} - p^* for all $t>1$.

$\frac{mnt[(c-a)-b]}{m+nt^2} - \frac{mn(c-b-a)}{m+n} >^? 0$ (From Table 1)

$(m+n)t[(c-a)t-b]-(m+nt^2)(c-b-a) >^? 0$

$mt^2(c-a)+nt^2(c-a)-bmt-bnt-m(c-a)-nt^2(c-a)+bm+bnt^2 >^? 0$

$mt^2(c-a)-bmt-bnt-m(c-a)+bm+bnt^2 >^? 0$

$m(c-a)(t^2-1)-bm(t-1)+bn(t^2-1) >^? 0$

$m(c-a)(t-1)(t+1)-bm(t-1)+bn(t-1)(t+1) >^? 0$

$m(t-1)[(c-a)t+(c-b-a)]+bn(t-1)(t+1) >^? 0$

Since $t>1$, $c>a$, $c>a+b$, the above inequality holds true and therefore $p^{O-TR} - p^* > 0$ for all $t > 1$.

Proposition 2: Imposing a trading ratio always decreases the quantity of offsets purchased from the uncapped sector.

By the proof of Proposition 1 we know that a trading ratio t>1 always increases the price of offsets. If the cap remains unchanged, this immediately implies that the trading ratio leads to a reduction in the quantity of offsets purchased.

We show that $q^O{}_{AF}{}^{TR} < q_{AF}^*$ for all $t>1$.

$\left(c - \frac{am+cnt^2-bnt}{m+nt^2}\right) - (c - \frac{am+(c-b)n}{m+n}) <^? 0$ (From Table 1)

$\frac{am+cnt^2-bnt}{m+nt^2} - \frac{am+(c-b)n}{m+n} >^? 0$

$am^2+cmnt^2-bmnt+amn+cn^2t^2-bn^2t-am^2-amnt^2-(c-b)mn-(c-b)n^2t^2 >^? 0$

$cmnt^2-bmnt+amn-bn^2t-amnt^2-cmn+bmn+bn^2t^2 >^? 0$

$cmn(t^2-1)-bmn(t-1)-amn(t^2-1)+bn^2t(t-1) >^? 0$

$mn(t-1)[(c-a)t+(c-a-b)]+bn^2t(t-1) >^? 0$

Since $t>1$, $c>a$, $c>a+b$, the above inequality holds true and therefore $q^0{}_{AF}{}^{TR} - q_{AF}{}^* > 0$ for all $t>1$.

Proposition 3: Imposing a trading ratio may either increase or decrease price paid for unit of abatement in the uncapped sector.

We find the conditions under which imposing a trading ratio increases the price paid for unit of abatement in the uncapped sector: $p^{A\text{-}TR} > p^*$.

$$\frac{1}{t} * \frac{mnt[(c-a)-b]}{m+nt^2} - \frac{mn(c-b-a)}{m+n} > 0$$

$$(m+n)[(c-a)t-b] - (m+nt^2)(c-b-a) > 0$$

$$mt(c-a) + nt(c-a) - bm - bn - m(c-a) - nt^2(c-a) + bm + bnt^2 > 0$$

$$mt(c-a) + nt(c-a) - bn - m(c-a) - nt^2(c-a) + bnt^2 > 0$$

$$m(c-a)(t-1) - nt(t-1)(c-a) + bn(t-1)(t+1) > 0$$

$$m(c-a) - nt(c-a) + bn(t+1) > 0$$

$$m(c-a) + bn > (c-a-b)nt$$

$$t < \frac{m(c-a)+bn}{n(c-a)-bn}$$

It is easily shown that this inequality does not hold for all possible parameter values. Thus, a trading ratio is more likely to increase the price paid for unit of abatement in the uncapped sector when *m* is large relative to *n*, or when *b* is large relative to *c-a*. A trading ratio is more likely to decrease the price paid for unit of abatement in the uncapped sector when *m* is small relative to *n*, or when *b* is small relative to *c-a*.

Proposition 4: Imposing a trading ratio may either increase or decrease the quantity of abatement produced by the uncapped sector.

By Proposition 3, we know that imposing a trading ratio can either increase or decrease the abatement price. Since the abatement supply curve is monotonically upward sloping, it follows that imposing a trading ratio can either increase or decrease the quantity of abatement.

We find the conditions under which imposing a trading ratio increases the quantity of abatement produced the uncapped sector: $q^0{}_{AF}{}^{TR} > q_{AF}{}^*$.

$$t\left(c - \frac{b}{t} - \frac{am+cnt^2-bnt}{m+nt^2}\right) - \left(c - b - \frac{am+(c-b)n}{m+n}\right) > 0 \qquad \text{(From Table 1)}$$

$$c(t-1) + \frac{am+(c-b)n}{m+n} - \frac{amt+cnt^3-bnt^2}{m+nt^2} > 0$$

$$c(t-1)(m+n)(m+nt^2) + (am+(c-b)n)(m+nt^2) - (amt+cnt^3-bnt^2)(m+n) > 0$$

$$cm^2t + cmnt^3 + cmnt + cn^2t^3 - cm^2 - cmnt^2 - cmn - cn^2t^2 + am^2 + amnt^2 + cmn + cn^2t^2 - bmn - bn^2t^2 - am^2t - amnt - cmnt^3 - cn^2t^3 + bmnt^2 + bn^2t^2 > 0$$

$$cm^2t + cmnt - cm^2 - cmnt^2 + am^2 + amnt^2 - bmn - am^2t - amnt + bmnt^2 > 0$$

$$cm^2(t-1) - cmnt(t-1) - am^2(t-1) + amnt(t-1) + bmn(t-1)(t+1) > 0$$

$$m(t-1)[cm - cnt - am + ant + bnt + bn] > 0$$

$$m(c-a) + bn > (c-a-b)nt$$

$$t < \frac{m(c-a) + bn}{n(c-a) - bn}$$

As above, a trading ratio is more likely to increase the quantity of abatement in the uncapped sector when *m* is large relative to *n*, or when *b* is large relative to *c*-*a*. A trading ratio is more likely to decrease the quantity of abatement in the uncapped sector when *m* is small relative to *n*, or when *b* is small relative to *c*-*a*.

APPENDIX III

This appendix derives the "optimal" trading ratio, at which non-additional abatement in the uncapped sector is exactly balanced by super-additional abatement occurring due to the surplus requirement.

The equilibrium price of offsets occurs where abatement produced in the capped sector plus offsets purchased from the uncapped sector sum to the cap. That is where,

$$q_{EIT}{}^{TR} = c - q^{O}{}_{AF}{}^{TR}$$

$$a + \frac{p}{m} = c - \frac{b}{t} - \frac{p}{nt^2}$$

$$p(\frac{1}{m} + \frac{1}{nt^2}) = c - \frac{b}{t} - a$$

$$p^* = \frac{mnt[(c-a)t - b]}{m + nt^2}$$

Thus the quantity of abatement produced by the capped sector in equilibrium is

$$q_{EIT}{}^{TR} = a + \frac{p^*}{m} = a + \frac{nt[(c-a)t - b]}{m + nt^2} = \frac{am - bnt + cnt^2}{m + nt^2}$$

The quantity of offsets purchased from the uncapped sector is

$$q^{O}{}_{AF}{}^{TR} = \frac{b}{t} + \frac{p}{nt^2} = \frac{b}{t} + \frac{m[(c-a)t-b]}{t(m+nt^2)}$$

And the quantity of abatement produced by the uncapped sector is

$$q^{A}{}_{AF}{}^{TR} = t * \quad q^{O}{}_{AF}{}^{TR} = b + \frac{m[(c-a)t-b]}{(m+nt^2)}$$

The quantity of additional abatement produced by the uncapped sector is $q^{A}{}_{AF}{}^{TR} - b = \frac{m[(c-a)t-b]}{(m+nt^2)}$.

The optimal trading ratio, *t**, is that for which the quantity of abatement produced by the capped sector and the quantity of additional abatement produced by the uncapped sector sum to the cap:

$$\frac{am - bnt + cnt^2}{m + nt^2} + \frac{m[(c-a)t - b]}{(m + nt^2)} = c$$

$$am - bnt + cnt^2 + m[(c-a)t - b] = c(m + nt^2)$$

$$t(cm - am - bn) = cm + bm - am$$

$$t^* = \frac{m(c-a) + bm}{m(c-a) - bn}$$