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Antonio Bento, *Cornell University*
Ravi Kanbur, *Cornell University*
Benjamin Leard, *Cornell University*

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Antonio Bento[†], Ravi Kanbur and Benjamin Leard

**Abstract**

This paper presents an assessment of the relative efficacy of three key instruments - baselines, trade ratios and limits - which are under policy discussion in the design of carbon offset programs. We rank the instruments by their implications for total emissions, economic efficiency, and efficiency gain relative to a distributional transfer from capped to uncapped sectors. We find that the baseline is the best instrument for maximizing welfare as it directly reduces the share of offsets that are non-additional and that second-best policies do not sacrifice much welfare relative to the standard first-best policy prescription.

Keywords: Carbon offsets, cap and trade, additionality, distributional concerns
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† *Corresponding Author*: Antonio M. Bento, 432 Warren Hall, Cornell University. Ithaca, NY 14853. Phone: (607) 255-0626. Email: amb396@cornell.edu

# 1 Introduction

The design of markets for carbon offsets from unregulated sectors, to complement cap-and-trade programs in regulated sectors, is a central issue in environmental and climate policy. Such markets could, if designed appropriately, reduce the overall economic costs of climate change mitigation programs (Fell et al., 2011; Kollmuss et al., 2010). Allowing capped sectors to use offsets essentially broadens the affected sources that are able to reduce emissions. When capped and uncapped sources of emissions are open to trade emissions credits in the form of carbon offsets, a reduction target can be achieved at a lower cost relative to a program that does not let the uncapped sector opt in (Newell et al., 2013; Bushnell, 2012).

This form of cost containment, however, may break the cap established for regulated sources if the mitigation from uncapped sources would have happened in the absence of the program. The problem of non-additionality, or the awarding of carbon offsets to uncapped sources that do not perform mitigation, is a central source of criticism because of its adverse emissions consequences (Newell et al., 2013; Bushnell, 2012). The problem stems from the fact that programs cannot fully observe business-as-usual (BAU) emissions from uncapped sources, since these emissions are a hypothetical what if that never takes place if the source opts in. If the source would have reduced emissions anyway, then it is awarded non-additional offsets that are then sold to capped sources. The non-additional offsets contribute toward an increase in overall emissions, even if economic efficiency improves because of the additional offsets. This non-additionality, often discussed in terms of the integrity of the cap, is a major worry for key stakeholders, and thus for policy makers.

There is a well-known solution to this problem of cap integrity. Programs can deal with non-additionality by tightening the cap on the regulated sector sufficiently that total emissions remain unchanged (Montero, 2000). However, this policy involves a transfer of rents from the capped sector (if permits are grandfathered) to the uncapped sector. As we will see later on in this paper, this transfer can be very large for the proposed federal cap-and-trade program in the United States. Our numerical calibrations suggest a transfer of the order of 30 percent of the pre-offsets market rent in the capped sector. Not surprisingly, these transfers will be resisted strongly by firms in the regulated sector.

There are three key alternative methods being discussed in the offsets policy area for handling the problem of additionality, including (i) more stringent emissions baselines for sources in the uncapped sector; (ii) trade ratios for offsets relative to allowances, where a unit of offset supplied from the uncapped sector translates into less than one unit of emissions permitted in the capped sector; and (iii) a limit on the use of offsets for compliance in the capped sector. It should be obvious that each of these three instruments reduces the total supply of offsets, and hence the rent transfer from the capped sector. But the impact of each of these on the additional versus non-additional composition of offsets is not at all clear and requires careful analysis.

Further, the compositional effect relative to the distributional effect for each of these instruments needs to be quantified. This leads then to the question addressed in this paper – which instrument is best, for which objective?

Recent studies have taken some first steps in analyzing the welfare and distrubitional implications of opt in programs. Montero (2000) studies this problem in the context of the $SO_2$ opt-in provision where uncapped units were allowed to opt in and receive a quantity of allowances based on historical emissions. In a setting where units have private information on business-as-usual (BAU) emissions, the first best can be achieved by raising the allocation to uncapped units so that all of them opt in and lowering the permit allocation to capped units. Benthem and Kerr (2011) compare the efficacy of alternative methods for alleviating adverse selection in avoided deforestation programs. They find that increasing the scale of opt in projects alleviates (and, in the limit, can eliminate) the problem of adverse selection. This study, however, does not evaluate the relative welfare impacts of using alternative instruments and does not consider the simultaneous choice of carbon offset policy instruments. Milliard-Ball (2012) evaluates the effectiveness of sectoral crediting mechanisms using a similar model of adverse selection. He shows that there exists a significant trade-off between efficiency and rent transfers, and that uncertainty in BAU emissions makes these mechanisms very poor methods for reducing emissions. This study, however, focuses on national transportation sectors and does not consider the relative efficiency of alternative instruments for dealing with additionality among individual offsets projects.

Our paper extends the literature in several ways. First, we extend prior analyses of adverse selection in opt-in emissions trading programs by deriving analytical welfare formulas for instruments currently being adopted in cap-and-trade programs. Our formulas allow us to make general statements about the differences between the instruments and to provide clear policy recommendations based on these differences.

Second, we provide an assessment of three instruments for the level and composition of offsets, holding constant the cap on the regulated sector. We then use this to conduct an analysis of the efficiency and distributional implications of each instrument. Furthermore, we compare policies based on efficiency and on rent transfers, which lead to critical trade-offs that we explore analytically and numerically. This exercise contrasts with existing literature that focuses solely on the efficiency aspect of different offset policies.[1]

Third, we numerically calibrate the analytical model to analyze federal U.S. greenhouse gas (GHG) cap-and-trade legislation as described in the 2009 Waxman-Markey bill. With our numerical model we are able to compute the welfare and emissions impacts of alternative second-best policies. We are also able to

[1]While comparing the efficiency gains to the distributional implications is generally relevant for any environmental policy, it is especially important for designing markets for carbon offsets. In particular, the primary concern with the standard first-best mechanism presented in Montero (2000) is that there will be a potentially significant transfer of rents across sectors of the economy. If this rent transfer turns out to be small, then it may be feasible to implement in practice, which would make the discussion of second-best policies irrelevant.

compute the welfare cost associated with avoiding rents from being transferred across sectors to implement the first-best solution.

Our major findings are fourfold. Our first result suggests that coupling the instruments can achieve greater efficiency than using them individually. We find that the second-best policy couples a trade ratio less than one with a very stringent baseline. While a very stringent baseline eliminates most of the supply of non-additional offsets, it crowds out the supply of additional offsets. The trade ratio is set below one to increase the price of offsets and boost up the supply of additional offsets.

This mechanism may not be feasible as trade ratios less than one appear, independent of the other instrument choices, to increase aggregate emissions, as capped firms need less than one offset to account for one of its own emissions. Our second result addresses the question of how the policy maker should set the three instruments when it cannot select a ratio less than one. In this setting, the baseline is the best instrument for maximizing welfare. When the baseline is set at its optimum level, the trade ratio should be set at one and the offsets limit should be non-binding. The reason for this is that adjusting the baseline attacks the problem of non-additionality directly, while the other two instruments can only approach the issue indirectly.

Third, comparing the three instruments, our numerical calculations show that the welfare cost per unit of avoided redistribution from the capped sector is the lowest for the baseline. However, the numerical value of this ratio is below standard estimates for the marginal excess burden of public funds. This result suggests that if the policy maker chooses among the policy options of sacrificing welfare to avoid one dollar of transfers or allowing the rent transfer to take place but compensate capped firms through revenues generated from a labor tax, they should choose the former as it is less costly per dollar of transfers.

Fourth, when the baseline instrument is not fully reliable, as in the case of international offsets, then the other two instruments come into their own. In this case we show that the trade ratio instrument is superior to the limits instrument and that the efficient trade ratio is above one.

The plan of the paper is as follows. Section 3 sets out the basic analytical model and derives analytical results as the basis for the numerical model. Section 4 develops the calibration of the numerical model for the US and presents the main results. Section 5 provides further analysis and Section 6 concludes.

# 2 The Analytical Model

In this section we develop an analytical model to isolate the channels exploited by various instruments that regulate carbon offsets markets.

*2.1 Model Assumptions*

The model has two sectors: A *capped sector* and an *uncapped sector*. Each sector includes a unit mass of firms that are capable of reducing emissions.[2] A regulator controls emissions by establishing a cap-and-trade program requiring firms in the *capped sector* to hold a permit or an equivalent quantity of offsets for every unit of pollution they emit. The regulator encourages uncapped firms to opt into the program by allowing them to sell offsets to capped firms.[3]

The model lasts for two periods, denoted by period 0 and period 1. In period 0, firms have emissions $e_{0j}$, where $j = \{r, u\}$ denote the capped and uncapped sectors, respectively. In period 1, uncapped firms have business-as-usual (BAU) emissions $e^i$, which are expected to be $e_{0u}$, but they can be less than, equal to or greater than $e_0$. Similarly, capped firms have BAU emissions $e^i$ with expected BAU emissions equal to $e_{0r}$. In addition, firms are differentiated by marginal costs of emissions reductions, $c^i$. The values of $e^i$ and $c^i$ are firm $i's$ private information. The regulator does not observe $e^i$ or $c^i$ but observes density functions for each variable. In period 1 the regulator establishes a cap-and-trade program by grandfathering $A$ tradable permits to capped firms.[4] In the same period, the regulator sets emissions baselines for uncapped firms, $b^i$. Baselines attempt to measure BAU emissions of uncapped firms and are used to reward these firms for sequestration or emissions reductions.[5] Capped firms observe their permit allocation and make abatement decisions and uncapped firms observe their emissions baseline and make offset supply decisions. Firms make decisions after observing their own BAU emissions, marginal costs of emission reductions and market prices for permits and offsets.

We assume that BAU emissions are drawn from a sector-specific probability density function with support $e^i \in [\underline{e}_j, \overline{e}_j]$ where each $e^i$ is independently and identically distributed according to the cumulative distribution function $Y_j(e)$ with mean $e_{0j}$. Marginal costs are constant and satisfy $c^i \in [\underline{c}_j, \overline{c}_j]$ and are independently and identically distributed according to the cumulative distribution function $Z_j(c)$. To keep the model analytically tractable, we assume that the distributions are independent.[6] In addition to lowering emissions, uncapped firms can sequester emissions. We assume that each uncapped firm has the same

[2]Emissions reductions either occur through abatement or sequestration. Reductions from abatement result from actions that lower the release of emissions into the atmosphere. Carbon sequestration is the process of capturing and storing emissions.

[3]There are several reasons why some sources are capped while others are not. The most prominent reason is because monitoring and verification costs for some sectors are substantially higher than they are in other sectors (Sigman, 2010). Other reasons include legal and political constraints and property rights issues (Hahn and Richards, 2010). Governing bodies generally have power to prevent harms (by preventing carbon emissions through abatement) but they cannot force the private production of benefits (by forcing emissions sequestration). The property rights issue involves international participation. While the United States may be willing to develop an emissions target, other countries may not. The US cannot force the participation of other countries, but it can encourage them to participate through an offsets program.

[4]We do not consider the possibility that permits are auctioned. In the most recent U.S. climate bill and in many existing cap-and-trade programs including Caifornia's program within the Global Warming Solutions Act, a large fraction of permits are freely allocated at the beginning of the programs.

[5]Setting a baseline is required for any opt-in policy. The credited reductions are determined by the agent's behavior in relation to the baseline. See Baumol and Oates (1988) for a formal theoretical treatment.

[6]Correlations between marginal abatement costs between capped and uncapped sectors will most likely lead to higher compliance costs as demonstrated in Fell et al. (2011). A large positive correlation leads to an increase in compliance costs of about nine percent.

sequestration potential of $\alpha \leq 0$.[7]

*Capped Firm Problem*

In period 0, capped firm $i$ is grandfathered permits $a_0^i$.[8] The rent generated from the grandfathering equals $p_e a_0^i$, where $p_e$ is the equilibrium permit price. In period 1, firm $i$ uses permits to comply with the cap-and-trade program or the firm sells them to other firms.[9] In addition, the firm can buy offsets, $f$, or abate its emissions, $e$. Firm $i$ minimizes compliance costs by solving

$$\min_{0 \leq e \leq e^i,\ a \geq -a_0^i,\ f \geq 0} \left\{ p_a a + p_f f + c^i(e^i - e) \right\} \quad \text{subject to} \tag{1}$$

$$a + a_0^i + f \geq e. \tag{2}$$

The choice variable $a$ defines the firm's net permit sales. If $a < 0$, the firm is a net seller of permits, and if $a > 0$, it is a net buyer.[10] Permits are bought and sold at the equilibrium permit price, $p_a$, while offsets are bought at the equilibrium price $p_f$. The first-order conditions imply that the prices are equal in equilibrium:[11]

$$p_a = p_f. \tag{3}$$

*Uncapped Firm Problem*

Uncapped firms can opt into the cap-and-trade program by voluntarily selling offsets to capped firms. For an uncapped firm to generate an offset, the regulator sets an emissions baseline for the firm. As the regulator cannot observe firm-specific BAU emissions, assigning baselines collapses to the decision of setting a common baseline for all uncapped firms.[12] We denote the common baseline by $b$.

Uncapped firm $i$ makes two decisions. First, the firm decides whether to opt in to the program. Second,

[7]We represent sequestration of emissions as a negative quantity so that net emissions equals the sum of emissions and sequestration.

[8]The integral summation of individual firm permit allocations equals the aggregate permit allocation, $\int a_0^i di = A$.

[9]We abstract from dynamic aspects of cap-and-trade programs by considering a single compliance period. These aspects include permit banking and borrowing across compliance periods. Allowance banking and borrowing allow capped firms to smooth abatement costs over time by shifting emissions reduction responsibilities from one year to another. This mechanism has the effect of flattening the time path of emissions reductions and permit prices. See Rubin (1996) for a theoretical treatment of banking and borrowing. Fell and Morgenstern (2010) estimate the cost-savings from allowing firms to bank and borrow permits.

[10]Firm $i$'s solution is to abate its emissions if it has a marginal cost of abatement that is less than the equilibrium permit price. In the absence of market power and transaction costs, the program will minimize compliance costs among capped firms (Montgomery, 1972). Furthermore, the initial allocation of permits, $a_0^i$, will not influence the equilibrium, a manifestation of Coase's theorem (Coase, 1960). For studies that consider market power and transaction costs, see Hahn (1984) and Stavins (1995).

[11]In Section 2, we will show that this equilibrium condition is distorted when the regulator introduces alternative instruments to regulate the supply of offsets.

[12]We adopt this assumption for simplicity. Our results are insensitive to this assumption since the regulator only observes the aggregate distribution of BAU emissions. In practice the regulator can assign baselines at various scales, including assigning a baseline for an entire sector. See Kollmuss et al. (2010) for more details.

it makes an emissions choice. If firm $i$ opts in, it solves

$$\pi^i = \max_{\alpha \le e \le e^i} \left\{ p_f(b-e) - c^i(e^i - e) \right\}. \tag{4}$$

Firm $i$ opts in if $\pi^i \ge 0$. If $\pi^i < 0$, then firm $i$ does not opt in and chooses $e = e^i$. The general behavior of uncapped firms is illustrated in Figure 1. The horizontal axis measures marginal abatement costs of capped firms. The vertical axis measures BAU emissions of uncapped firms. Firms that are represented by area $A_1$ do not produce offsets because their BAU emissions are too high above the baseline. Firms in area $A_2$ do not supply offsets because they have marginal costs of abatement that exceed the marginal return of supplying an offset, $p_f$. The curve separating areas $A_1$ and $A_3$, $e^i(c^i)$, represents firms that are indifferent to supplying offsets. The curve is obtained by substituting $e = \alpha$, setting the objective function in (4) equal to zero and isolating $e^i$:

$$e^i = \frac{p_f(b-\alpha) + c^i\alpha}{c^i}. \tag{5}$$

*Composition of Offsets and Emissions*

The remaining areas in Figure 1 include firms that produce offsets. We define two types of offsets: additional and non-additional. An offset is *additional* if it corresponds to actual reductions in emissions. Additional offsets are sold by firms in regions $A_3$ and $A_4$, as the firms in these regions sell offsets that are created by reducing emissions. An offset is *non-additional* if it does not correspond to emissions reductions. These types of offsets are sold by suppliers with BAU emissions below the baseline that are able to claim offsets up to the baseline without actually reducing emissions. Non-additional offsets are sold by firms in regions $A_4$ and $A_5$.[13]

There exists a quantity of emissions reductions that does not create offsets. Firms in area $A_3$ contribute to this type of reduction, which we call *under-credited emissions* reductions and denote by $E_{SA}$.[14] The quantity of under-credited emissions reductions by a firm in region $A_3$ is given by the difference between the firm's BAU emissions and its baseline, $e^i - b > 0$.[15]

*2.2 Welfare*

We define welfare as the difference between the benefits and costs of emissions reductions. Benefits of emissions reductions are defined by the function $B(\cdot)$ and satisfy $B'(\cdot) > 0$. Costs of emissions reductions

[13] Firms in area $A_4$ sell both additional and non-additional offsets. These are firms that are over-credited with non-additional offsets as the baseline is above their BAU emissions. These firms, however, also mitigate emissions because their marginal cost of mitigation is less than the equilibrium offsets price. The firms earn additional offsets from these mitigated emissions.

[14] Under-credited emissions reductions are defined as a negative quantity of emissions, $E_{SA} < 0$. The existence of these reductions has the effect of lowering aggregate emissions. In a companion paper, Bento et al. (2012) use a simulation analysis to investigate the relative magnitude of under-credited emissions reductions to non-additional offsets for different levels of offset prices and baseline stringencies.

[15] Schneider (2009) discusses how various policy instruments, including adjusting baselines below BAU, can be used to achieve emissions reductions beyond those credited as offsets.

consist of abatement costs of capped firms $C_r(\cdot)$ and uncapped firms $C_u$.[16] Welfare is expressed by

$$W = B(\overline{q} - E_{NA} - E_{SA}) - C_r(\overline{q} - E_{NA} - q_u - E_{SA}) - C_u, \tag{6}$$

where $\overline{q} = e_0^r - A$ is the reduction target for capped firms, $E_NA$ is the quantity of non-additional offsets sold to the capped sector, $E_SA$ is the quantity of under-credited emissions reductions and $q_u$ is the quantity of mitigation performed by uncapped sources. The first-best solution equalizes marginal benefits and marginal costs of emissions reductions across sectors. Montero (2000) studies a similar problem in the context of phase in emissions trading programs such as Phase 1 of the Acid Rain Program where some sources of emissions can opt in and become regulated.[17]. He demonstrates that the first-best solution can be achieved by adjusting the opt-in allocation to the point where all unregulated units opt in and by adjusting the capped unit permit allocation to account for the supply of over-allocated permits. In our model, the first best can be achieved with a similar strategy, where the baseline is set to the point where all uncapped firms opt in and where the permit allocation is adjusted to account for the supply of non-additional offsets. The baseline is set at the upper bound of the uncapped sector BAU emissions distribution ($b = \overline{e}_u$) so that every uncapped firm opts in. The high baseline generates a supply of non-additional offsets, $E_{NA}$, that reduces aggregate emissions reductions from the program. To account for this quantity, the regulator increases the reduction target $\overline{q}$ from $\overline{q} = q^*$ to $\overline{q} = q^* + E_{NA}$,where $q^*$ would have been the reduction target had all offsets been additional.[18]

*Distributional Consequences of the First-Best Solution*

The mechanism for achieving the first-best solution outline above leads to a significant transfer of rents from the capped to the uncapped sector. The larger reduction target on capped firms is analogous to a smaller permit allocation. The value of the permit allocation to capped firms, $V = p_a A$, is reduced by $p_a E_{NA}$ to achieve the first best.

Therefore one should be concerned that the regulator may not be able to adjust the permit allocation to capped firms because of distributional constraints.[19] In fact, no policy to date has attempted to implement a program that would account for non-additional offsets by transferring rents across sectors. Instead of adjusting the initial permit allocation to account for non-additional offsets, the regulator can regulate the

[16]See Appendix A for definitions of the welfare components.

[17]In a related paper Montero estimates the welfare effects of the opt in provision of the Acid Rain Program. He finds that a majority of opt in units were over-allocated permits, leading to a small increase in the aggregate emissions cap (Montero, 1999).

[18]The result that the first-best solution can be achieved in the presence of asymmetric information has been established in previous work (Spulber, 1988; Kwerel, 1977). Similar to the setting described in Montero (2000), the regulator requires two instruments to achieve the first-best, or one instrument per market failure.

[19]Distributional concerns have traditionally played a major role in the design of cap-and-trade programs and more generally the choice between policy instruments. As an example, distributional concerns are the primary reason that pollution permits are typically grandfathered instead of auctioned. Studies have explored how distributional constraints influence the cost effectiveness of alternative instruments (Bovenberg et al., 2005, 2008) and how grandfathered permits are necessary to keep capped firm profits unchanged (Goulder et al., 2010).

market for carbon offsets directly through a variety of alternative instruments. The use of these instruments will not be as efficient as the first-best prescription. Or in other words, the inability of the regular to adjust the permit allocation put us in a second-best setting.

We define the cost of this distributional constraint as the welfare cost per dollar of avoided transfer, which is given by the formula

$$\frac{\Delta W}{\Delta V} = \frac{W_{FB} - W_{SB}}{V_{SB} - V_{FB}}. \tag{7}$$

The term $\Delta W$ is defined as the non-marginal difference in welfare between first-best setting ($W_{FB}$) and a second-best setting ($W_{SB}$, when the permit allocation is fixed). The term $\Delta V$ is defined as the difference in rents to the capped sector between first- and second-best settings ($V_{FB}$ and $V_{SB}$, respectively).

Moving to the second-best setting by restricting the permit allocation may lead to combinations of alternative instruments being chosen to maximize welfare. In the next sections, we provide formulae that decompose the channels of efficiency by three alternative instruments: more stringent baselines, a trade ratio and a limit on the use of offsets. We refer the reader to Appendix A for formal derivations.

*2.3 The Choice of Instruments in a Second-Best Setting*

*The Baseline*

Consider a marginal reduction of the baseline assigned to uncapped firms. The welfare effects of an incremental adjustment of the baseline are given by

$$\begin{aligned} \frac{\partial W}{\partial b} = & \underbrace{-[B'(\cdot) - p_a]\frac{\partial E_{NA}}{\partial b}}_{\mathrm{dW}^{NA}} - \underbrace{[B'(\cdot) - p_a]\frac{\partial E_{SA}}{\partial b}}_{\mathrm{dW}^{SA_b}} \\ & + \underbrace{\int_{\underline{c}_u}^{p_f} \frac{\partial}{\partial b} \int_{\underline{e}_u}^{\tilde{c}} (p_a - c)(e - \alpha) dY_u dZ_u}_{\mathrm{dW}^{A_b}}, \end{aligned} \tag{8}$$

where $\tilde{c} = \min\left\{\overline{e}_u, \frac{p_f b}{c}\right\}$. Equation (8) three sources of welfare associated with a marginal reduction of the baseline. First, $\mathrm{dW}^{NA}$ is the *non-additional offsets effect*. This is the efficiency cost of non-additional offsets. It is equal to the product of the marginal change in non-additional offsets and the wedge between marginal benefits and marginal costs of emissions reductions of capped firms. A lower baseline implies a smaller mass of firms supplying non-additional offsets and a lower quantity of non-additional offsets awarded to uncapped firms. The lower supply of non-additional offsets can be illustrated with Figure 1. Areas $A_4$ and $A_5$ shrink as the baseline is adjusted down. The combined effect is a reduction in the supply of non-additional offsets. This increases capped firm compliance costs as the cap is effectively tightened when there are fewer non-additional offsets supplied. Emissions benefits are higher as a consequence of the tighter cap. These two effects are represented by the wedge between capped firm marginal benefits and marginal costs of emissions reductions. The second component, $\mathrm{dW}^{SA_b}$, is the *under-credited emissions baseline effect*. This is the efficiency cost of uncapped firms providing under-credited emissions reductions. It is equal to the product of the marginal change in under-credited emissions reductions and the wedge between marginal benefits and marginal costs of emissions reductions of capped firms. A lower baseline may increase or decrease the mass of firms contributing to under-credited emissions reductions. Based on Figure 1, the top of area $A_1$ shrinks as the profit indifference line $e^i(c^i)$ pivots down. Simultaneously the bottom of area $A_1$ expands as the baseline is pushed down. An increase in under-credited emissions reductions lowers the supply of additional offsets and increases total emissions reductions. A lower supply of additional offsets increases compliance costs as fewer cheap reductions are purchased from the uncapped sector. Emissions benefits are higher as a result of greater emissions reductions. These two effects are represented by the wedge between capped firm marginal benefits and costs of emissions reductions.

The non-additional offsets effect and the under-credited emissions baseline effect influence emissions and the supply of offsets to capped firms, but do not influence the efficiency gain from allowing capped firms to pay uncapped firms to reduce emissions. This efficiency effect is captured in the last term, $\mathrm{dW}^{A_b}$, denoted as the *additional offsets baseline effect*. It is equal to the marginal change in the difference between marginal costs of emissions reductions of capped and uncapped firms for the mass of uncapped firms reducing emissions. Reducing the baseline discourages the production of additional offsets as it lowers the compensation that all uncapped firms receive.

*The Trade Ratio*

Next consider the impact of imposing an offset trade ratio between offsets and permits, denoted by $r$. The trade ratio converts one offsets into $\frac{1}{r}$ fungible pollution permits. A ratio greater than one implies that a capped firm must hold more than one offset to cover one unit of emissions. A major difference between a more stringent baseline and the trade ratio is that the latter cannot discourage the supply of non-additional offsets because these are defined as the difference between the baseline and BAU emissions. To decompose the welfare effects of a trade ratio, we first explore how it impacts the problem of capped firms. A trade ratio alters the permit constraint (2) of each capped firm to

$$a + \frac{f}{r} + a_0^i = e^i. \tag{9}$$

The first-order conditions of the capped firm problem implies

$$p_f = \frac{p_a}{r}. \tag{10}$$

Unlike the baseline, the trade ratio creates a wedge between the prices of offsets and permits. Holding the permit price constant, a ratio greater than one depresses the offsets price. The resulting welfare effects of adjusting the trade ratio are given by

$$
\begin{aligned}
\frac{\partial W}{\partial r} &= \underbrace{[B'(\cdot) - p_a]f}_{\mathrm{dW}^r} - \underbrace{[B'(\cdot) - p_a]\frac{\partial E_{SA}}{\partial r}}_{\mathrm{dW}^{SA_r}} \\
&\quad \underbrace{+ \frac{\partial p_f}{\partial r}\int_{\underline{e}_u}^{b}(p_a - p_f)(e-\alpha)dY_u + \int_{\underline{c}_u}^{p_f}\frac{\partial}{\partial r}\int_{\underline{e}_u}^{\tilde{c}}(p_a - c)(e-\alpha)dY_u dZ_u}_{\mathrm{dW}^{A_r}}\,.
\end{aligned}
\tag{11}
$$

Comparing (11) to (8) reveals three key differences between the trade ratio and the baseline. First, the trade ratio fails to exploit the non-additional offsets effect used by the baseline policy. That is, the trade ratio fails to directly discourage the production of non-additional offsets. In place of the non-additional offsets effect is a *capped firm trade ratio effect*, denoted by $\mathrm{dW}^r$. This is the efficiency cost of requiring capped firms to hold more than one offset per unit of emissions. Raising the trade ratio above one reduces aggregate emissions as one unit of emissions reductions from the uncapped sector converts to less than one unit of fungible pollution permits in the capped sector.[20] Second, although the trade ratio also exploits *under-credited emissions trade ratio effect* denoted by $\mathrm{dW}^{SA_r}$ that looks identical to the under-credited emissions baseline effect, the effects are fundamentally different different. While adjusting the baseline has an ambiguous effect on under-credited emissions reductions, in contrast a larger trade ratio reduces under-credited emissions reductions. As a consequence, fewer under-credited emissions reductions increases overall emissions. Therefore we cannot apriori infer the effect of a higher trade ratio on aggregate emissions. Third, the trade ratio discourages the opt-in decision of uncapped firms. This can be seen through the *additional offsets trade ratio effect,* $\mathrm{dW}^{A_r}$. A trade ratio larger than one reduces the offsets price below the permit price, reducing the incentive for uncapped firms to opt in, represented by the first term in $\mathrm{dW}^{A_r}$. The second term is similar to the *additional offsets baseline effect* in (8). It is equal to the marginal change in the difference between marginal costs of emissions reductions of capped and uncapped firms for the mass of uncapped firms reducing emissions. Increasing the trade ratio discourages the production of additional offsets as it lowers the offset production revenue to uncapped firms.

*The Offsets Limit*

Finally consider a limit of $L$ on the use of offsets by capped firms. An offsets limit adds a constraint to

[20] This holds true whenever there is a positive supply of additional offsets. If all offsets are non-addiitonal, then discounting will have no effect on aggregate emissions.

the capped firm problem:

$$f \leq L. \tag{12}$$

With this additional constraint, the capped firm first-order conditions imply a relationship between the prices:

$$p_f = p_a - \beta. \tag{13}$$

The term $\beta$ is the multiplier on the limit constraint. A binding limit ($\beta > 0$) drives a wedge between the permit price and the offsets price. For a fixed permit price, a binding limit reduces the offsets price. The offsets price is reduced until the total supply of offsets equals the limit. Like the trade ratio, this feature of the limit has the effect of reducing the supply of additional offsets while not discouraging the supply of non-addiitonal offsets. This is because the supply of non-additional offsets is independent of the offsets price. The welfare effects of adjusting a binding limit are given by

$$\begin{aligned} \frac{\partial W}{\partial L} = & \underbrace{-[B'(\cdot) - p_a]\frac{\partial E_{SA}}{\partial L}}_{\mathrm{dW}^{SA_L}} \\ & + \underbrace{\frac{\partial p_f}{\partial L}\int_{\underline{e}_u}^{b}(p_a - p_f)(e-\alpha)dY_u + \int_{\underline{c}_u}^{p_f}\frac{\partial}{\partial L}\int_{\underline{e}_u}^{\tilde{c}}(p_a - c)(e-\alpha)dY_u dZ_u}_{\mathrm{dW}^{A_L}}. \end{aligned} \tag{14}$$

A comparison of (14) to (8) reveals that the limit, similar to the trade ratio, does not influence welfare through discouraging the supply of non-additional offsets as the *non-additional offsets effect* is missing. As it is the case with the previous two instruments, however, the limit influences welfare through adjusting the quantity of under-credited emissions reductions, denoted by the *under-credited emissions limit effect* $\mathrm{dW}^{SA_L}$. The limit discourages uncapped firms from participating, which lowers the quantity of under-credited emissions reductions, an effect that is similar $\mathrm{dW}^{SA_r}$.

The second welfare effect seen in (14) which we term the *additional offsets limit effect* and is denoted by $\mathrm{dW}^{A_L}$. A comparison of (14) to (11) demonstrates that the limit and the trade ratio discourage the production of additional offsets through the same two channels. In contrast to the trade ratio, establishing a binding limit on offsets, however, unambiguously does not reduce emissions, but instead raises emissions relative to a policy with a non-binding limit. The under-credited emissions limit effect is the only component in (14) that has welfare adjustments from emissions changes. A more stringent limit raises emissions because it lowers the quantity of under-credited emissions reductions and does not require capped firms to hold more offsets per unit of emissions.

*2.6 Summary*

We summarize the differences across the instruments in Table 1. We compare how the instruments influence the supply of non-additional offsets, the supply of additional offsets, the supply of under-credited emissions reductions and total emissions. From the welfare formulas, we see that the baseline is the only instrument that reduces the supply of non-additional offsets.[21] The trade ratio can reduce emissions if the capped firm trade ratio effect dominates the supper-additional trade ratio effect. A more stringent offsets limit raises emissions. As the offsets limit depresses the offsets price, the quantity of under-credited emissions reductions falls, inducing an increase in total emissions.

Since the the welfare cost per dollar of avoided transfer equation (7) is non-marginal, we cannot assess the magnitude of welfare losses from restricting the use of the emissions cap by comparing the welfare formulas above. Therefore we rely on numerical simulations to rank the instruments along several dimensions, including the composition of offsets, total emissions, and welfare.

# 3 The Numerical Model

We now supplement the analytical model with a numerical model calibrated to represent a United States cap-and-trade program with carbon offsets. The purpose of the numerical model is to quantify exact welfare assessments in contrast with the marginal effects presented above. This is relevant for comparing the efficacy of the three instruments, providing magnitudes of the trade-offs between efficiency and rent transfers and evaluating optimal instrument choices under the second-best setting. We now provide a brief description of the model calibration procedure. A complete description of the model is in Appendix B.

*3.1 Model Calibration*

The purpose of the numerical model is to yield generic insights that are applicable to a range of climate mitigation programs. Even though our objective is to quantify general relationships, we choose a specific set of parameter values to calibrate the model. Our central values represent abatement costs and benefits from a federal cap-and-trade program in the United States. In particular, we calibrate the analytical model with short-run (2015-2020) estimates of emission reduction costs, BAU emissions and marginal benefits of emissions reductions obtained from the literature.[22] We use short-run estimates for two reasons. First, short-run forecasts less likely to suffer from forecasting error. Second, the problem of non-additionality is most pronounced in the short run because the price of offsets is expected to be lowest in the short run.[23] To

[21] This is true unless the limit or trade ratio are selected so that there is no supply offsets, which would occur if $\delta = +\infty$ or $L = 0$.

[22] Alternatively we can calibrate the model with medium- or long-run estimates to quantify the effects of the model for a longer time span. We leave this exercise for future work that incorporates dynamics.

[23] What we mean by the problem of non-additionality is the ratio of non-additional to additional offsets. When the price of offsets is low, the supply of additional offsets is low, making the ratio of non-additional to additional offsets large.

illustrate how alternative assumptions on costs and benefits may effect efficient policy decisions, we consider significant departures from these central case values in the sensitivity analysis.

The capped sector represents industries likely to be covered under a federal greenhouse gas (GHG) cap-and-trade program. We base our representation on the industries that would have been covered under the H.R. 2454 American Clean Energy and Security Act, henceforth the Waxman-Markey bill, which include coal-fired power plants, petroleum refineries, natural gas refineries, iron and steel production, cement manufacture, among others. The capped sector is regulated by a cap-and-trade program. We model the capped sector as a representative firm that takes equilibrium prices as given. This is a standard assumption used to evaluate compliance costs of cap-and-trade programs (Fell and Morgenstern, 2010). The capped sector is allocated a fixed quantity of emissions permits that are equal to capped sector business-as-usual (BAU) emissions minus a reduction target. The uncapped sector represents major sources of mitigation that will likely not be capped in a federal climate policy. These sources include forestry and agriculture.

*Data*

We use estimates from the Environmental Protection Agency (EPA) analysis of Waxman-Markey of BAU emissions for the capped and uncapped sectors (EPA, 2009a). Capped sector marginal costs of emissions reductions are calibrated to match extrapolated values from the EPA's simulation of the Intertemporal General Equilibrium Model (IGEM) for the year 2016, while uncapped sector marginal costs of abatement are selected based on the EPA Updated Forestry and Agriculture marginal abatement cost curves (EPA, 2009b).

*Parameters*

The distributions of BAU emissions and marginal costs of emissions reductions are assumed to be uniform. We calibrate the heterogeneity of BAU emissions in the uncapped sector so that the percentage of offsets that are non-additional at a carbon price of 25 dollars is 40 percent. This value approximately matches evidence from the largest carbon offsets program in the world, the Clean Development Mechanism. The marginal benefits of emissions reductions, known as the Social Cost of Carbon (SCC), is set at 25 dollars per ton of $CO_2$ equivalent, representing estimated damages between 2015-2020 (EPA, 2010). Table 2 summarizes the values used to calibrate the model and Table 3 shows implied parameter values. The calibrated model approximately matches the predicted compliance cost savings from including offsets in the Waxman-Markey cap-and-trade program. Appendix B provides more details on the calibration procedure and data used to identify the parameters of the model.

*3.2 Numerical Results*

This section presents results from the numerical model. To compare the offsets instruments, we calculate the welfare effect of imposing an emissions cap under different assumptions on the set of instruments available to the policy maker. We emphasize the welfare effects relative to a series of benchmark settings that we consider in the next section.

To facilitate comparisons, we simulate the model without offsets as a benchmark. Our emphasis is on qualitative, rather than quantitative, differences across policies. The quantitative differences can vary depending on our assumptions for marginal abatement costs and benefits and the heterogeneity in uncapped firm BAU emissions. Note that our analysis abstracts from other sources of emissions changes that may plague offsets markets, including leakage and permanence.[24]

*Benchmark Simulations*

We first examine benchmark simulations that help facilitate comparisons of the three offsets instruments. Table 4 presents simulation results for our benchmark settings. The first setting represents a cap-and-trade program that does not include offsets. Under this setting, the allocation of permits is endogenously chosen to maximize welfare. Welfare - defined as emission reduction benefits minus costs - is 10.8 billion dollars.

Next we simulate the model assuming that the policy maker has full information on BAU emissions. Under this assumption, the policy maker assigns baselines equal to BAU emissions of uncapped firms, $b_i = e_i$. In these simulations, adverse selection is not present and only additional offsets are awarded to the uncapped sector and supplied to capped firms. When the allocation of permits remains at the no offsets optimum, including offsets increases welfare by 36 percent. The welfare change is attributed to a reduction in compliance costs, as cheaper reductions from the uncapped sector replace more expensive reductions in the capped sector. When the allocation of permits is re-optimized when offsets are included, the welfare change increases to 56 percent. This increase represents the first-best allocation of emission reductions.

The next set of simulations assumes that the policy maker has imperfect information on BAU emissions. These settings represent the numerical version of our analytical model. With imperfect information, the policy maker assigns a single baseline to each uncapped firm. We consider two benchmark cases in the presence of imperfect information. First, we consider the case where the allocation of permits equal the no offsets optimum and the baseline equals the expected value of BAU emissions. This setting achieves a 15 percent increase in welfare relative to the no offsets program, a value which is significantly lower than the full information settings. This is because adverse selection is present. Firms in areas $A_4$ and $A_5$ are supplying non-additional offsets, which increases aggregate emissions and lowers the benefits from the program. Second, we consider the case where the policy maker can select both the allocation of permits and the baseline. With both instruments, the policy maker can achieve the first best outcome. The increase in welfare of 56 percent matches the welfare change in the full information setting that allows the policy

[24]While leakage and permanence may have relevant impacts on the welfare effects of offsets programs, we do not focus on them in our paper. Previous literature suggests that liability and insurance programs are superior instruments for handling leakage and permanence (Murray et al., 2007).

maker to re-optimize the permit allocation. Comparing capped sector rents across the settings, however, demonstrates the distributional consequence of the imperfect information first-best outcome. Capped sector rents in the imperfect information first-best outcome are 69.8 billion dollars compared to 105.2 billion dollars in the no offsets case. While the first-best solution achieves a significant increase in welfare, along with it comes a rent transfer equal to roughly 30 percent of rents under the no offsets setting.

*Instrument choice*

In the analytical model, we consider one instrument at a time to isolate key welfare effects. In the numerical model we consider the welfare implications of allowing the regulator to choose the instruments simultaneously. This allows us to determine whether some instruments may be coupled together to achieve higher welfare gains relative to cases when instruments are optimized one by one. Moreover, we determine whether some instruments welfare-dominate others by restricting them one at a time.

Table 5 shows optimal instrument choices under different assumptions on the policy maker instrument choice set. Without offsets, the optimal allocation of permits is $4,207$ $MMTCO_2e$. The remaining settings include offsets in the case when the regulator has imperfect information on BAU emissions. To achieve the first best under imperfect information, the baseline is set equal to the upper bound of BAU emissions ($b = \overline{e}_u$) and the permit allocation is adjusted down to account for the supply of non-additional offsets. The trade ratio and the limit are not utilized to achieve the first best.

Next we simulate the model under four second-best settings that are characterized by an exogenous permit allocation set equal to the No Offsets optimum. First, we simulate the model when the baseline, trade ratio and limit are selected simultaneously by the policy maker. Importantly - and surprisingly - the policy maker finds it optimal to couple a trade ratio less than one with a low baseline. This finding is robust to different parameter assumptions, as confirmed in the sensitivity analysis below. From the first-order condition of the capped firm problem, a trade ratio less than one has the effect of increasing the offsets price. A higher offsets price encourages a larger supply of additional offsets and a larger quantity of under-credited emissions reductions. The policy maker simultaneously adjusts the baseline down to reduce the supply of non-additional offsets. This increases welfare through the non-additional offsets effect as greater emissions reductions are achieved. Adjusting the baseline down, however, reduces the welfare gains from the additional offsets baseline effect as fewer uncapped firms find it profitable to opt in. A trade ratio less than one counteracts this effect by boosting up the offsets price. This leads to a welfare gain that is represented by the additional offsets trade ratio effect.

In practice, however, it is unlikely for a policy to adopt a trade ratio less than one.[25] In addition to the

[25] We are not aware of an offsets program that uses a trade ratio less than one. A recent survey of environmental offsets programs finds that there do not exist programs assigning a trade ratio less than one (Hahn and Richards, 2010).

effects described above, a trade ratio less than one allows capped firms to turn one offset into more than one fungible pollution permit. If not coupled with another instrument that lowers emissions, this has the effect of raising aggregate emissions.[26] For this reason, we consider a setting that allows the policy maker to select the three instruments simultaneously with the constraint that the trade ratio cannot be below one. In this setting, only the baseline is utilized. The optimal baseline in this setting is equal to $-229$ $MMTCO_2e$, a value that is significantly higher than the one from the previous setting. This is because the policy maker can no longer encourage the production of additional offsets by selecting a trade ratio less than one. The optimal trade ratio of one implies that it is not used as a method of reducing emissions. A ratio larger than one can reduce emissions but it also reduces the incentive for uncapped firms to opt in and it distorts the decision for uncapped firms to reduce emissions. While adjusting the baseline down also discourages uncapped firms from opting in, it does not distort the decision for uncapped firms to reduce emissions as it does not directly reduce the offsets price. This difference is represented by the term in the additional offsets trade ratio effect that is absent from the additional offsets baseline effect.

To compare the efficacy of the trade ratio and the limit, we remove the baseline from the policy maker's choice set and assume that it is exogenously set to equal the expected value of uncapped firm BAU emissions. In this setting, the second-best trade ratio equals 1.78, requiring capped firms to buy 1.78 offsets to account for one unit of emissions. The limit remains non-binding in this case, demonstrating that on welfare grounds, the trade ratio is a superior instrument. This is because the trade ratio and limit both discourage under-credited emissions reductions and the supply of non-additional offsets through the same mechanism - through a reduced offsets price. But the trade ratio can reduce emissions while the limit cannot. In fact, there is no analog to the capped firm trade ratio effect in the limit welfare formula.

To determine whether the limit is binding under any circumstances, we restrict the baseline and the trade ratio to be fixed and allow the policy maker to select a limit that maximizes welfare. The limit does not bind in this case. This suggests that the limit cannot improve welfare in the presence of adverse selection.[27]

For ease of exposition in the remaining sections, we identify the case when all three instruments are available as the Unrestricted policy. The Baseline policy denotes the setting when $r \geq 1$. The Ratio policy denotes the setting where a positive trade ratio is chosen and the Limit policy denotes the setting when only the limit is optimized.

[26] For example, the policy maker could lower the permit allocation to capped firms or create under-credited emissions reductions with a lower baseline.

[27] The result that the optimal policy suggests a non-binding limit begs the question of why offset limits offsets exist at all. Some programs that have limits explicitly state in its design summary that offsets are suppose to be "supplemental" to emission reductions taking place among capped firms (Kollmuss et al., 2010). This preference for supplementary reductions may stem from two reasons: First, it may be that policy makers are worried that not all offsets are additional, so that a limit restricts the potential increase in emissions. Second, it may be an ethical concern. Constituents may feel that polluters should not be able to depend on other uncapped firms to reduce emissions for them.

*Composition of Offsets and Emissions*

Table 6 compares the quantity of additional and non-additional offsets and the sources of emissions reductions for each of the simulation settings. In the first-best outcome, the supply of non-additional offsets is significant. Out of the total offset supply of $1,414$ MMTCO$_2$e, 928 MMTCO$_2$e are non-additional. These offsets come from the first-best instrument choice of the baseline set high enough to encourage all uncapped firms to opt in. At this baseline choice, every uncapped firm earns some non-additional offsets since BAU emissions are below each firm's baseline.

In the Unrestricted policy, non-additional offsets are close to zero. This is because the non-additional offsets effect dominates the additional offsets baseline effect at the second-best optimal policy. The efficient baseline choice is so low in this setting that very few non-additional offsets are awarded to uncapped firms. Surprisingly, total emissions are lower in the Unrestricted setting relative to setting when offsets are not allowed. This is because the quantity of under-credited emissions reductions equal to 120 MMTCO$_2$e has the effect of lowering aggregate emissions. This effect dominates the increase in emissions from the supply of non-additional offsets and from a trade ratio less than one.

Under the Baseline policy, additional and non-additional offset supply are both higher than they appear in the Unrestricted policy. The Baseline policy sets a higher baseline to uncapped firms to encourage the supply of additional offsets. This also raises the supply of non-additional offsets from 4 MMTCO$_2$e to 29 MMTCO$_2$e. under-credited emissions reductions fall to 81 MMTCO$_2$e because the price of offsets is not boosted by a trade ratio less than one.

The Ratio and Limit policies show a substantially larger supply of non-additional offsets of 233 MMTCO$_2$e. This is because neither of these instruments are capable of reducing the supply of non-additional offsets. As a consequence, we see a much larger supply of offsets and higher aggregate emissions.

*Second-Best Welfare*

We now consider the welfare impacts – emission reduction benefits less economic costs – of the different policies. Table 7 presents the welfare impacts of the four second-best policies relative to a program that does not include offsets. The Unrestricted policy achieves the greatest welfare gain that is 35 percent greater than the welfare impact of a program without offsets. We see that under this policy that emission reduction benefits are 7 percent greater than the no offsets policy. This is because under-credited emissions reductions exceed the supply of non-additional offsets and the extra emissions from a trade ratio less than one (Table 6).

The same effect holds true for the Baseline policy which achieves an increase in benefits of 6 percent. The Baseline policy increases welfare by 34 percent, a value that is slightly less than the Unrestricted policy. This small difference suggests that the combination of the capped firm trade ratio effect and the additional offsets trade ratio effect is small. The additional efficiency gains from encouraging greater participation of uncapped firms through a higher offsets price just barely exceeds the welfare losses from higher emissions.

The Ratio and Limit policies achieve an increase in welfare that is smaller than the efficiency gains from the Unrestricted and Baseline policies. This result is driven by the absence of the non-additional baseline effect in the trade ratio and limit formulas. Since neither instrument can discourage the supply of non-additional offsets, benefits dramatically fall under these settings by 5 percent and 23 percent, respectively. The Ratio policy achieve a higher welfare gain compared to the Limit policy because of the capped firm trade ratio effect. This effect increases benefits by effectively lowering emissions via requiring capped firms to hold more than one offset to cover one unit of emissions. Even though the trade ratio discourages the supply of additional offsets and achieves a smaller cost reduction of 36 percent, the capped firm trade ratio effect more than compensates for this as the welfare gain under the Ratio policy is 11 percentage points higher than the welfare gain under the Limit policy.

*Distributional Concerns*

We now examine the distributional consequences of the policies in Table 8. Moving from a program that does not include offsets to the first-best outcome, we see a large reduction in capped sector rents from $105,170$ million dollars to $69,815$ million dollars. Under most of the second-best settings, however, the reduction in rents is smaller.

To evaluate the distributional formula (7), we calculate two terms: First, we require the difference between first-best welfare and the welfare from the particular policy. We denote this value in Table 8 as Welfare Change. The welfare change is the largest when offsets are not included in the program ($6,075$ million dollars) since all of the cheaper reductions from uncapped firms are not realized. The Unrestricted and Baseline policies achieve the lowest welfare loss of $2,331$ and $2,421$ million dollars, respectively. This is because these policies are able to encourage uncapped firms to opt in and reduce emissions. Second, we compute the avoided transfer of rents, which is defined as the quantity of capped sector rents in a particular policy minus the capped sector rents under the first-best solution. The avoided transfer is the largest under the no offsets setting ($35,335$ million dollars). The avoided transfers are lower under the second-best settings because the permit price is depressed from the existence of offsets.

The Baseline policy achieves a welfare cost per unit of avoided transfer of 0.16. This value is lower than the marginal excess burden of a labor tax of 0.40 dollars (Gruber, 2010). If the regulator had to choose among the policy options of sacrificing 0.16 dollars in welfare to avoid one dollar of transfers or allowing the rent transfer to take place but compensate capped firms through revenues generated from a labor tax, they should choose the former as it is less costly per dollar of transfers.

The welfare cost per unit of avoided transfer is substantially lower than the marginal excess burden. This follows from the fact that the rent transfer is significantly larger than the welfare gain stemming from the first-best mechanism. This result can be explained by illustrating the first-best mechanism using Figure 1. The first-best requires moving the baseline $b$ up to $b = \overline{e}$ so that all projects opt in. There are two sources of rent transfer from this action. First, projects that would have opted in without the first-best implemented now are awarded a significantly larger quantity of non-additional offsets that they sell to the capped sector. These projects are represented by areas $A_3$, $A_4$ and $A_5$. Second, projects that would not have opted in without the first-best mechanism now opt in and sell non-additional offsets. These projects are represented by areas $A_1$ and $A_2$. Therefore every eligible project sells a significant quantity of non-additional offsets under the first-best outcome. The rent transfer occurs to counter-act the emissions consequences of these offsets as the policy maker reduces the allocation of permits by an amount that is equal to the new quantity of non-additional offsets.

The welfare gain from the first-best mechanism comes from encouraging projects that can cheaply reduce emissions that otherwise would not have opted in. These projects appear in area $A_1$. The welfare gain from the first-best mechanism will be a function of the cost-effectiveness of these projects relative to the most expensive abatement occurring in the capped sector. This welfare gain is likely to be substantially less than the rent transfer associated with implementing the first best because of two reasons. First, most projects that have cheap mitigation costs would already opt in without the first-best implemented (areas $A_3$ and the left of $A_4$). Second, the size of $A_1$ is most likely a small fraction of the universe of eligible projects (areas $A_1 - A_5$). Since this result may depend on policy design parameters that we use in our central case, in the next section we investigate various alternative assumptions to test its sensitivity.

# 4 Further Analysis

*4.1 Alternative Baselines*

Thus far we have focused on a setting where a policy maker has access to all three offsets instruments. In some emissions trading programs, however, it may be the case that baselines are set independently from the choice of the trade ratio or the limit. This feature motivated our consideration of treating the baseline as exogenous to the policy maker under the Ratio and Limit policies. Under these policies, however, we considered a baseline set to equal the expected value of BAU emissions. Some baseline protocols could, in practice, call for higher or lower baselines, depending on the stringency of the offset standard. To consider how different baselines influence outcomes for welfare and rent transfers, we simulate the model assuming alternative baselines. In particular we set the baseline equal to 50 percent and 200 percent of the expected value of BAU emissions. The results appear in Table 9. The Low Baseline and High Baseline settings are simulated with a baseline set to equal 50 percent and 200 percent of the expected value of BAU emissions, respectively. For the Low Baseline case, the optimal trade ratio is now only 1.45. The policy maker does not need to set a stringent trade ratio in this case because the baseline has already been set low. The same intuition applies to the high baseline case. Here we see a higher trade ratio of 2.69 to account for a large supply of non-additional offsets.

In contrast to our results above, we find that it is optimal to place a limit of zero in the High baseline case. For a high baseline, the efficiency losses from higher emissions dominate the efficiency gains from including offsets in the program. Therefore the optimal limit of zero is equivalent to not allowing offsets into the program. We conclude that this is the only possible mechanism for the limit to bind.[28]

*4.2 Transaction Costs*

Several studies have documented that transaction costs associated with the production of carbon offsets can be non-trivial. We evaluate the impact of transaction costs on the efficacy of the instruments considered by adding a 5 dollar per ton of offsets produced.[29] We assign transaction costs to offset projects in line with an analysis of Waxman-Markey by the Congressional Budget Office (Kile, 2009). This value lies within a range of transaction costs estimated in previous work.[30]

We simulate the model with a 5 dollar per ton transaction cost and calculate the optimal set of instruments. Our results appear in Table 10. We see two results emerge from the simulations. First, transaction costs do not play a role in determining the relative efficacy of the three instruments. This result is illustrated by comparing Table 5 to the top panel of Table 10. For example, under the baseline policy, it is always optimal to set a stringent baseline but keep the trade ratio equal to one. Second, the existence of transaction costs dramatically reduces the welfare cost per unit of avoided transfer across all of the policies, which is reported in the last row of Table 10. For the unrestricted and baseline second-best policies, the cost is less than five cents per dollar of avoided transfer. The reason that these values are significantly smaller than those we find in a model without transaction costs stems from the fact that a transaction cost essentially shifts the price curve in Figure 1 to the left, which reduces the area $A_1$. This is the mass of uncapped firms

[28]Our model does not include other market failures besides the emissions externality and the information asymmetry. When additional failures exist, such as the adoption of new technology, binding limits my be optimal as shown in Cain and Tavoni (2012).

[29]Denoting the per unit transaction cost by $t$, the profit function of an uncapped firm becomes

$$\pi^i = \max_{\alpha \leq e \leq e^i} \left\{ (p_f - t)(b - e) - c^i(e^i - e) \right\}. \tag{15}$$

[30]For example, Antinori and Sathaye compute transaction costs for 26 carbon offset projects around the world Antinori and Sathaye (2007). Their survey includes a variety of offset project types, including forestry, energy efficiency, fuel switching, fuel capture, and renewables. These projects operated between 1991 and 2005 and were verified and monitored through different offset protocols, including the CDM, the Chicago Climate Exchange and Climate Trust. The authors find that transaction costs per ton of $CO_2$ for the surveyed projects fall within the range of 0.03 per ton of $CO_2$ and 4.05 per ton of $CO_2$ with an average of 0.36 per ton of $CO_2$. Galik et al. estimate transaction costs for US-based forest carbon offset projects Galik et al. (2012). The authors used a detailed spreadsheet model that includes dis-aggregated forest types and 10 different regions. For all project types, transaction costs are estimated to be less than 25 percent of median implementation costs, which the authors define as the sum of production costs and transaction costs. We follow the CBOs approach by assigning a 5 dollar per ton of $CO_2$ to all projects as this value represents a central value to those reported in existing studies.

that bring efficiency gains from the first-best mechanism. Since the efficiency gains will be less with higher transaction costs, the sacrifice in welfare when moving to the second-best policies will be lower.

*4.3 Further Sensitivity Analysis*

Table 11 summarizes the sensitivity of the numerical results to a range of values for relevant parameters. We vary the social cost of carbon, the upper bound of the marginal cost of emissions reductions distributions for the capped and uncapped sectors and the benchmark percentage of offsets that are non-additional. Table 11 displays for different parameter values the efficient instrument choices and the welfare cost per unit of avoided transfer ($\Delta W/\Delta V$).

Changing the social cost of carbon has a significant impact on the Ratio policy but leaves the central results unchanged for the other policies. The Unrestricted and Baseline policies show a welfare cost per unit of avoided transfer that is substantially less than 0.40. For a low social cost of carbon, however, the Ratio policy has a welfare cost per unit of avoided transfer above 0.40. This result stems from two features of our model. First, the share of offsets that are non-additional is larger when the social cost of carbon is low.[31] Second, the trade ratio cannot eliminate the supply of non-additional offsets. Together these features lead to the Ratio policy incurring a significant welfare cost relative to the first best outcome.

When the social cost of carbon is higher, the welfare cost per unit of avoided transfer lies below 0.40 for all of the policies with the exception of the limit policy.[32] The cap is more stringent in this setting, leading to high equilibrium permit and offset prices. As a consequence, the share of offsets that are non-additional is lower since more projects find it profitable to opt in and reduce emissions. Therefore the welfare cost of the second best policies is not large relative to the rent transfer.

The results appear to be insensitive to adjusting the upper bound of the marginal cost of emissions reductions distribution for the capped and uncapped sectors. Optimal instrument choices move in intuitive directions as we adjust the bounds of the uncapped sector marginal cost distribution. A higher upper bound for the uncapped sector marginal cost distribution encourages the policy maker to relax the stringency of the offsets instruments in the second-best settings. A higher upper bound for the capped sector marginal cost distribution suggests that the policy maker sets more stringent instrument choices. This occurs as a response to a less stringent exogenous permit allocation.

Our simulation results are sensitive on our assumption for the benchmark level of non-additional offsets. This level is related to the heterogeneity in uncapped project BAU emissions, where a greater amount of heterogeneity implies a larger fraction of non-additional offsets. In this section we vary the parameter values

[31]The exogenous allocation of permits is higher when there is a low social cost of carbon. As a result, the equilibrium permit and offset price is lower.

[32]Recent estimates suggest that the social cost of carbon will rise to 45 dollars in the year 2050 under a three percent discount rate EPA (2010).

that set the level of heterogeneity to determine how the share of offsets that are non-additional influence our results. In the fourth panel of Table 11 we vary the benchmark share of non-additional offsets between two extreme cases: 20 percent and 60 percent. The 20 percent case represents a program that sets stringent additionality standards while the 60 percent case more closely resembles a program that includes international offsets.[33]

Changing the benchmark percentage of offsets that are non-additional has a significant impact on the welfare cost per unit of avoided transfer. When the benchmark percentage is low, the cost is high because capped firm rents in the first-best setting are not much lower than they are in the second-best settings. This occurs because the baseline does not need to be adjusted up very much to encourage all uncapped firms to opt in, requiring a smaller reduction in permits to capped firms to account for the supply of non-additional offsets. Under either benchmark percentage, however, the cost per unit of avoided transfer remains below the marginal excess burden of 0.40.

# 5 Conclusion

In this paper we analyze the efficiency of several instruments in carbon offsets programs that are plagued by adverse selection. This issue has been the most controversial aspect of including offsets in climate change mitigation programs because adverse selection can destroy the integrity of emissions trading programs and in many cases some policy prescriptions involve large distributional transfers. Our analysis of three instruments – baselines, trade ratios and limits – accounts for both of these features in evaluating which combination of methods is best for dealing with adverse selection.

The paper provides several key insights. We find that the first best can be achieved by adjusting two instruments: The allocation of permits to capped firms and the uncapped firms baseline. The first-best solution, however, has significant distributional implications. It requires transferring substantial rents from capped firms to uncapped firms, a feature that may be politically difficult to implement. For this reason, we consider optimal instrument choice in a second-best setting where the regulator cannot adjust the allocation of permits which define capped firm rents. We find that adjusting the baseline is the most preferable mechanism from an efficiency and a distributional standpoint. In particular, the baseline achieves higher welfare relative to the trade ratio the value of offsets or limiting the use of offsets. Finally, a binding offsets limit is never optimal from an efficiency viewpoint. The offsets limit only discourages the supply of additional offsets and under-credited emissions reductions and yields no emissions benefits.

[33] International offsets have been viewed as less likely to be additional. For this reason, domestic programs either ban the use of international offsets (as in the case of California's new cap-and-trade program) or discount them (as in the case of Waxman-Markey).

When the allocation of permits cannot be adjusted because of distributional concerns, the second-best Baseline policy still achieves a increase in welfare relative to a policy that does not allow offsets. We quantify the distributional cost of leaving the permit allocation fixed by computing the the per unit cost of avoided transfer. We find that this value is relatively small: The regulator can avoid transferring one dollar of rents from the capped to the uncapped sector at a cost of 16 cents. This value is relatively low relative to the marginal excess burden of a labor tax of 40 cents (Gruber, 2010). We find that this result is insensitive to altering parameters of our model for two reasons. The first reason is that the first-best mechanism does not achieve a significant welfare-improvement over the second-best outcomes because many of the low mitigation cost projects would opt in when baselines are stringent. The second reason is that the first-best mechanism requires awarding all eligible projects with a large quantity of non-additional offsets. These offsets represent the rents being transferred from the capped to the uncapped sector. Together these reasons imply that the welfare per dollar of transfers is likely to be low, regardless of the cap stringency or uncertainty in uncapped sector BAU emissions.

Some limitations of our study deserve attention.[34] First, we focus on the problem of adverse selection in markets for carbon offsets. For some types of offsets, including those from land use and land use change, carbon offseting form carbon sequestration includes the problem of permanence. An offset project is considered to generate a permanent offset if the carbon stored is not released at a later date due to natural or economic reasons. These types of projects require a monitoring protocol well after the project has ended to ensure that the offset remains permanent. Some have suggested that these types of projects should be discounted to account for this possibility (Kim et al., 2008). For other types of projects, carbon leakage may be severe. In most current offsets protocols including those in the CDM, offset payments are discounted to account for potential market leakage. Whether these leakage-based discount rates are optimal is uncertain and is a question we leave for future research. Second, our model is static. Our analysis various policy instruments may have significant differences with respect to how each encourages long run entry and exit in carbon offsets markets. These dynamic effects may have significant welfare consequences that are not captured by our analysis.

[34]Although our simulation focuses on a federal United States cap-and-trade program, our results can be extended to other regional programs within the U.S. and other international schemes. For example, California has just launched its own cap-and-trade program that includes a significant offset provision. This program has placed limits on the use of offsets, a policy prescription that we suggest may actually increase the relative share of non-additional offsets supplied to capped firms. Furthermore, the flexibility mechanisms in the Kyoto Protocol permit countries to purchases offsets from developing countries to comply with the program targets. A program following the Kyoto Protocol will most likely include an offsets provision that will require setting a set of instruments aimed at balancing efficiency and distributional concerns that are illustrated in our analysis.

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## Table 1: Marginal Effects of the Offsets Instruments

| Instrument[a] | Non-Additional Offsets | Additional Offsets | Under-Credited Emissions Reductions | Total Emissions[b] |
|---|---|---|---|---|
| Baseline | Decreases | Decreases | Ambiguous | Decreases |
| Trade ratio | No effect | Decreases | Decreases | Ambiguous |
| Limit | No effect | Decreases | Decreases | Increases |

[a] The marginal effects represent more stringent instrument choices. We consider the marginal effect of reducing the baseline, increasing the trade ratio and reducing the limit.

[b] For the Baseline and Limit, the marginal change in emissions is equal to the marginal change in non-additional offset supply plus the marginal change in under-credited emissions reductions. For the Trade Ratio, the marginal change in emissions equals the marginal change in non-additional offset supply, the marginal change in under-credited emissions reductions and the marginal change in capped firm emissions.

## Table 2: Benchmark Data

| Description | Value | Source |
|---|---|---|
| Capped sector BAU emissions[a] | 5,071 | EPA Data Annex (2009) |
| Uncapped sector BAU emissions | 365 | EPA MAC Curves (2009) |
| Capped sector emissions reductions | 864 | EPA Data Annex (2010) |
| Uncapped sector emissions reductions | 486 | EPA MAC Curves (2009) |
| Uncapped sector sequestration potential | 1,027 | EPA MAC Curves (2009) |
| Percent of offsets that are non-additional[b] | 40 | Schneider (2007) |
| Social cost of carbon[c] | 25 | EPA Technical Support Document (2010) |

[a] Emissions are reported in million metric tons of $CO_2$ equivalent.
[b] Equal to the quantity of non-additional offsets divided by total offset supply at a baseline equal to the expected value of uncapped firm BAU emissions.
[c] Represents an estimate for the year 2016 and is reported in (year 2000) dollars per ton of $CO_2$ equivalent.

## Table 3: Implied Parameter Values

| Parameter description | Parameter | Value |
|---|---|---|
| Capped sector lower bound of marginal costs[a] | $\underline{c}_r$ | 0 |
| Uncapped sector lower bound of marginal costs | $\underline{c}_u$ | 0 |
| Capped sector upper bound of marginal costs | $\overline{c}_r$ | 147 |
| Uncapped sector upper bound of marginal costs | $\overline{c}_u$ | 72 |
| Capped sector average BAU emissions[b] | $e_{0r}$ | $5,071$ |
| Uncapped sector average BAU emissions | $e_{0u}$ | 365 |
| Capped sector lower bound of BAU emissions | $\underline{e}_r$ | $5,071$ |
| Uncapped sector lower bound of BAU emissions | $\underline{e}_u$ | $-563$ |
| Capped firms upper bound of BAU emissions | $\overline{e}_r$ | $5,071$ |
| Uncapped sector upper bound of BAU emissions | $\overline{e}_u$ | $1,293$ |

[a] Marginal costs are reported as (year 2000) dollars per ton of $CO_2$ equivalent.

[b] Emissions are reported as million metric tons of $CO_2$ equivalent.

## Table 4: Welfare and Rents Under Benchmark Settings

| | No Offsets | Full Information[a] | | Imperfect Information[b] | |
|---|---|---|---|---|---|
| *Permits* | *Optimal* | *No Offsets setting* | *Optimal* | *No Offsets setting* | *Optimal* |
| *Baselines* | – | *Firm-specific* | *Firm-specific* | *Mean* | *Optimal* |
| Welfare[c] | 10,800 | +36 % | +56 % | +15 % | +56 % |
| Costs | 10,800 | -36 % | +56 % | -62 % | +56 % |
| Benefits | 21,600 | 0 % | +56 % | -23 % | +56 % |
| Cost per ton of emissions reductions[d] | 12.5 | 8.0 | 12.5 | 6.2 | 12.5 |
| Capped Sector Rents[e] | 105,170 | 67,310 | 93,024 | 54,827 | 69,815 |

[a] Defined by the policy maker observing uncapped firm-specific BAU emissions. Under this setting, baselines are set equal to BAU emissions so that the supply of non-additional offsets and the quantity of under-credited emissions reductions equals zero.

[b] Defined by the policy maker observing the distribution of uncapped firm BAU emissions. Under this setting, a common baseline is set for all uncapped firms.

[c] Reported in millions of dollars in the No offsets setting. Values in the Full Information and Imperfect Information settings are reported relative to the No Offsets setting.

[d] Measured in dollars per ton of $CO_2$ equivalent.

[e] Reported in millions of dollars and defined as the product of the capped sector permit allocation and the equilibrium permit price.

## Table 5: Instrument Choice

| | No Offsets | First Best | Second Best[a] | | | |
|---|---|---|---|---|---|---|
| *Permits* | *Optimal* | *Optimal* | *No offsets setting* | *No offsets setting* | *No offsets setting* | *No offsets setting* |
| Value[b] | 4,207 | 2,793 | 4,207 | 4,207 | 4,207 | 4,207 |
| *Baseline* | – | *Optimal* | *Optimal* | *Optimal* | *Mean* | *Mean* |
| Value[b] | – | 1,293 | -447 | -229 | 365 | 365 |
| *Ratio* | – | *Optimal* | *Optimal* | *Restricted Optimal*[c] | *Optimal* | *1:1 ratio* |
| Value | – | 1 | 0.67 | 1 | 1.78 | 1 |
| *Limit* | – | *Optimal* | *Optimal* | *Optimal* | *Optimal* | *Optimal* |
| Value | – | Non-binding | Non-binding | Non-binding | Non-binding | Non-binding |

[a] Defined as fixing the permit allocation equal to 4,207 MMT$CO_2$e.

[b] Measured in million metric tons of $CO_2$ equivalent.

[c] The restricted optimal setting is defined by the policy maker selecting the baseline, trade ratio and limit subject to the constraint $r \geq 1$.

## Table 6: Composition of Offsets and Emissions

| | No Offsets | First Best | Second Best Unrestricted | Second Best Baseline | Second Best Ratio | Second Best Limit |
|---|---|---|---|---|---|---|
| Capped sector emissions reductions[a] | 864 | 864 | 684 | 699 | 650 | 450 |
| Uncapped sector emissions reductions | 0 | 486 | 237 | 217 | 171 | 211 |
| Under-credited emissions reductions | 0 | 0 | 120 | 81 | 24 | 30 |
| Additional offsets | 0 | 486 | 117 | 136 | 162 | 181 |
| Non-additional offsets | 0 | 928 | 4 | 29 | 233 | 233 |
| Offset supply | 0 | 1,414 | 121 | 165 | 395 | 414 |
| Capped sector emissions | 4,207 | 4,207 | 4,388 | 4,372 | 4,421 | 4,621 |
| Uncapped sector emissions | 365 | -121 | 128 | 148 | 193 | 154 |
| Total emissions[b] | 4,572 | 4,086 | 4,515 | 4,520 | 4,614 | 4,775 |

[a] Emission reductions, offsets and emissions quantities are measured in million metric tons of $CO_2$ equivalent.
[b] Equal to the sum of capped and uncapped sector emissions.

## Table 7: Second-Best Welfare

| | No Offsets | Unrestricted | Second Best Baseline | Ratio | Limit |
|---|---|---|---|---|---|
| Welfare[a] | 10,800 | +35 % | +34 % | +26 % | +15 % |
| Costs | 10,800 | -21 % | -22 % | -36 % | -62 % |
| Benefits | 21,600 | +7 % | +6 % | -5 % | -23 % |

[a] Reported in millions of dollars in the No offsets setting. Values in the Second Best settings are reported relative to the No Offsets setting.

## Table 8: Distributional Effects

| | No Offsets | First Best | Unrestricted | Second Best Baseline | Ratio | Limit |
|---|---|---|---|---|---|---|
| Capped sector rents[a] | 105,170 | 69,815 | 83,334 | 85,046 | 79,183 | 54,827 |
| Permit price[b] | 25.00 | 25.00 | 19.81 | 20.22 | 18.82 | 13.03 |
| Welfare change[c] | 6,075 | – | 2,331 | 2,421 | 3,227 | 4,455 |
| Avoided transfer[d] | 35,335 | – | 13,519 | 15,231 | 9,368 | -14,988 |
| Welfare cost per unit of avoided transfer[e] | 0.17 | – | 0.17 | 0.16 | 0.34 | -0.30 |

[a] Reported in millions of dollars.
[b] Reported in dollars.
[c] Defined by subtracting the welfare in the current setting from the First-Best welfare. Reported in millions of dollars.
[d] Defined by subtracting the capped sector rents in the First-Best setting from the current setting. Reported in millions of dollars.
[e] Defined as the ratio of the welfare change and the avoided transfer.

## Table 9: Alternative Baselines

| | Low Baseline ($b = 0.5e_{0u}$) | | High Baseline ($b = 2e_{0u}$) | |
|---|---|---|---|---|
| Ratio | *Optimal* | *1:1 ratio* | *Optimal* | *1:1 ratio* |
| Value | 1.45 | 1 | 2.69 | 1 |
| Limit | *Optimal* | *Optimal* | *Optimal* | *Optimal* |
| Value | Non-binding | Non-binding | Non-binding | 0 |
| Offset supply[a] | 304 | 331 | 571 | 0 |
| Additional offsets | 155 | 182 | 121 | 0 |
| Non-Additional offsets | 149 | 149 | 450 | 0 |
| Under-credited emissions reductions | 38 | 45 | 7 | 0 |
| Welfare[b] | 13,980 | 13,491 | 12,920 | 10,800 |
| Costs | 7,209 | 5,494 | 6,565 | 10,800 |
| Benefits | 21,189 | 18,985 | 19,485 | 21,600 |
| Capped sector rents | 79,705 | 64,721 | 79,307 | 105,170 |

[a] Offset supplies and emission reductions are reported in million metric tons of $CO_2$ equivalent.

[b] Welfare, costs, benefits and rents are reported in millions of dollars.

## Table 10: Transaction Costs[a]

| | First Best | Second Best | | | |
|---|---|---|---|---|---|
| | | Unrestricted | Baseline | Ratio | Limit |
| Baseline | *Optimal* | *Optimal* | *Optimal* | *Mean* | *Mean* |
| Value | 1,293 | -563 | -351 | 365 | 365 |
| Ratio | *Optimal* | *Optimal* | *Restricted Optimal* | *Optimal* | *1:1 ratio* |
| Value | 1 | 0.50 | 1 | 1.68 | 1 |
| Limit | *Optimal* | *Optimal* | *Optimal* | *Optimal* | *Optimal* |
| Value | Non-binding | Non-binding | Non-binding | Non-binding | Non-binding |
| Offset supply[b] | 1,352 | 91 | 100 | 323 | 365 |
| Additional offsets | 424 | 91 | 88 | 90 | 132 |
| Non-Additional offsets | 928 | 0 | 12 | 233 | 233 |
| Under-credited emissions reductions | 0 | 135 | 7 | 15 | 22 |
| Transaction costs[c] | 6,761 | 453 | 501 | 1,617 | 1,820 |
| Welfare | 14,179 | 13,926 | 13,364 | 12,621 | 12,094 |
| Costs[d] | 14,848 | 8,461 | 9,693 | 6,829 | 4,242 |
| Benefits | 30,241 | 22,827 | 23,058 | 19,449 | 16,336 |
| Capped sector rents | 69,815 | 84,540 | 92,969 | 81,780 | 60,870 |
| $\Delta W/\Delta V$ | – | 0.02 | 0.04 | 0.13 | -0.23 |

[a] The simulations presented in this table include a per ton of $CO_2$ offset transaction cost of 5 dollars.
[b] Offset supplies and emission reductions are reported in million metric tons of $CO_2$ equivalent.
[c] Transaction costs, welfare, costs, benefits and rents are reported in millions of dollars.
[d] Costs are equal to mitigation costs plus transaction costs.

## Table 11: Further Sensitivity Analysis

| | | | No Offsets | First Best | Second Best | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Unrestricted | Baseline | Ratio | Limit |
| Social Cost of Carbon | 40 | Permits[a] | 3,689 | 1,984 | 3,689 | 3,689 | 3,689 | 3,689 |
| | | Baseline | – | 1,293 | -295 | -162 | 365 | 365 |
| | | Trade Ratio | – | 1 | 0.82 | 1 | 1.52 | 1 |
| | | $\Delta W/\Delta V$ | 0.23 | – | 0.16 | 0.16 | 0.22 | 1.07 |
| | 10 | Permits | 4,725 | 3,362 | 4,725 | 4,725 | 4,725 | 4,725 |
| | | Baseline | – | 1,293 | -563 | -345 | 365 | 365 |
| | | Trade Ratio | – | 1 | 0.54 | 1 | 3.28 | 1 |
| | | $\Delta W/\Delta V$ | 0.09 | – | 0.23 | 0.12 | 0.55 | -0.07 |
| Capped Sector Upper Bound of Marginal Costs | 172 | Permits | 4,334 | 2,920 | 4,334 | 4,334 | 4,334 | 4,334 |
| | | Baseline | – | 1,293 | -484 | -263 | 365 | 365 |
| | | Trade Ratio | – | 1 | 0.65 | 1 | 1.92 | 1 |
| | | $\Delta W/\Delta V$ | 0.17 | – | 0.22 | 0.19 | 0.47 | -0.22 |
| | 122 | Permits | 4,032 | 2,695 | 4,032 | 4,032 | 4,032 | 4,032 |
| | | Baseline | – | 1,293 | -403 | -190 | 365 | 365 |
| | | Trade Ratio | – | 1 | 0.69 | 1 | 1.64 | 1 |
| | | $\Delta W/\Delta V$ | 0.18 | – | 0.16 | 0.15 | 0.30 | -0.45 |
| Uncapped Sector Upper Bound of Marginal Costs | 97 | Permits | 4,207 | 3,112 | 4,207 | 4,207 | 4,207 | 4,207 |
| | | Baseline | – | 1,101 | -371 | -152 | 365 | 365 |
| | | Trade Ratio | – | 1 | 0.68 | 1 | 1.63 | 1 |
| | | $\Delta W/\Delta V$ | 0.16 | – | 0.17 | 0.14 | 0.54 | -0.19 |
| | 47 | Permits | 4,207 | 2,222 | 4,207 | 4,207 | 4,207 | 4,207 |
| | | Baseline | – | 1,620 | -465 | -327 | 365 | 365 |
| | | Trade Ratio | – | 1 | 0.77 | 1 | 2.01 | 1 |
| | | $\Delta W/\Delta V$ | 0.19 | – | 0.21 | 0.19 | 0.28 | -0.67 |
| Benchmark Percentage of Non-Additional Offsets | 60 % | Permits | 4,207 | 2,123 | 4,207 | 4,207 | 4,207 | 4,207 |
| | | Baseline | – | 1,959 | -583 | -386 | 365 | 365 |
| | | Trade Ratio | – | 1 | 0.65 | 1 | 2.35 | 1 |
| | | $\Delta W/\Delta V$ | 0.12 | – | 0.12 | 0.12 | 0.16 | -0.69 |
| | 20 % | Permits | 4,207 | 3,302 | 4,207 | 4,207 | 4,207 | 4,207 |
| | | Baseline | – | 784 | -294 | -154 | 365 | 365 |
| | | Trade Ratio | – | 1 | 0.8 | 1 | 1.63 | 1 |
| | | $\Delta W/\Delta V$ | 0.21 | – | 0.33 | 0.26 | 0.66 | -0.21 |

[a] Permits and baselines are reported in million metric tons of $CO_2$ equivalent.

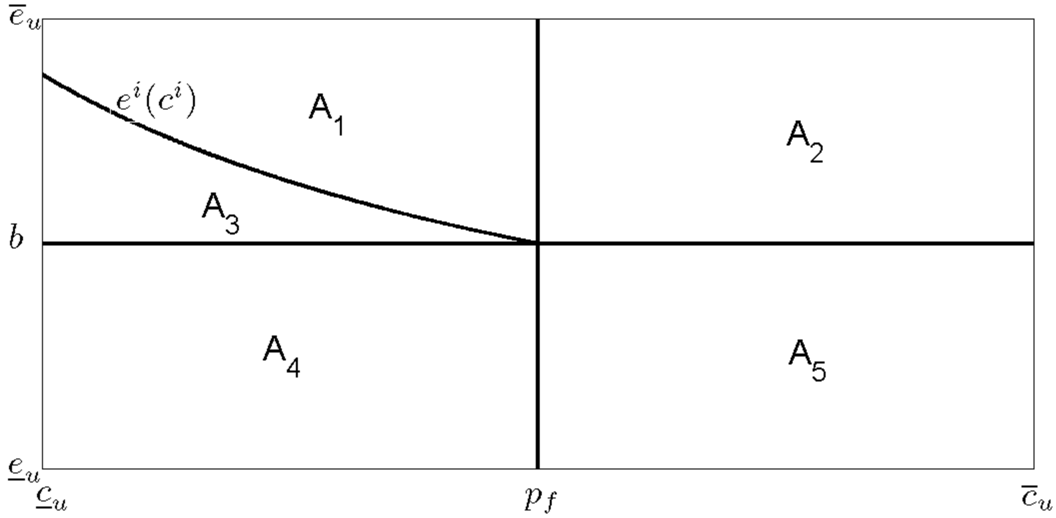


Figure 1: Decisions of Uncapped Firms