Emissions Trading without a Quantity Constraint

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Abstract

This paper examines the differences between standard “cap-and-trade” emissions trading plans and “credit” plans in which individual agents create credits by reducing emissions below a firm-specific baseline. The two are equivalent if the baseline is a fixed quantity, but not if the baseline is specified as a baseline emissions ratio times current output. In the latter case there is no exogenous constraint on aggregate emissions. It may be called the case of “(ratio-based) credit trading”. Examples include the Clean Development Mechanism (CDM) of the Kyoto Protocol and the Canadian Pilot Emissions Reduction Trading plan (PERT).

Unlike the case of cap-and-trade, the theoretical properties of ratio-based credit trading plans are not well known. In the absence of a binding quantity constraint, it is even difficult to understand how an ERC plan can generate a positive price. This paper studies the difference between ratio-based credit trading and conventional “cap-and-trade” plans in the context of a very simple model. It also considers how the two plans might interact if, for example, credits from a credit plan could be applied to commitments under a quantity-based cap-and-trade plan, and applies its findings to current plans for credit trading, including PERT and the clean development mechanism.

The paper demonstrates that ratio-based credit trading is more like a tax instrument than a quantity instrument. It shows that there is no incentive to trade in a ratio-based market in which all firms receive baselines computed using their “business as ususal” emission ratios. Combining ratio-based credit trading with “cap-and-trade” allowance markets effectively relaxes the quantity constraint in the cap-and-trade plan and reduces the price of traded allowances. In the long run, there will be no effective constraint on emissions.

The results have strong implications for current policy. In particular, they suggest that mixing quantity-based and ratio-based emission trading plans is inappropriate.

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In the standard "cap-and-trade" model of emissions trading a central authority defines a total allowable discharge of a specified contaminant for a specified period. This cap is divided into individual rights (transferable discharge permits) to discharge specific amounts of the pollutant. The permits are either auctioned by the central authority or "grandfathered" (i.e. distributed free of charge to polluting firms). After the initial distribution, firms may trade the permits freely. In this model the aggregate quantity of emissions is constrained to a known amount and the price of permits is determined by the intersection of the market demand curve for permits with the vertical market supply.

Many plans for emissions trading do not fit the textbook model of tradable discharge permits. For example, the clean development mechanism under the Kyoto Protocol envisages a plan where non-Annex B countries can earn emission reduction credits (ERCs) for reducing emissions beyond the level that would normally be expected. These ERCs could be sold to Annex B countries, who would use them to meet their emissions requirements under the protocol. Other examples include various "open market" emission reduction trading plans which have been advocated and partially implemented for trading nitrogen oxides (NO_x) in the North American utility generating system (PERT, 1999).

In these plans credits are created for reducing emissions below a certain baseline quantity which is specified as a baseline emissions ratio times current output. The baseline quantity of emissions is conceived as the quantity of emissions that would have been created if the actual rate of output had been produced using a baseline, standard or "business-as-usual" technology. Because the baseline quantity of emissions depends upon the current level of output there is no externally imposed quantity constraint on aggregate emissions of the pollutant.

Unlike the properties of cap-and-trade plans, the theoretical properties of open market ERC trading plans are not well known. In the absence of a binding quantity constraint, it is even difficult to understand how an ERC plan can generate a positive price. The purpose of this note is to lay out a very simple model of emissions reduction credit trading and to compare its outcome to that of a standard “cap-and-trade” plan. Our fundamental conclusion is very simple: an open market ERC plan is equivalent to a cap-and-trade plan in which the cap increases in proportion to the output of the participating firms. This has strong implications. Specifically, ERC trading is efficient in that it equates marginal abatement cost across firms conditional on their output levels. Secondly, marginal abatement cost remains approximately constant as industry output expands. Consequently, ERC trading is more like a tax than a quantity instrument. Thirdly, combining an ERC plan with a “cap-and-trade” plan effectively relaxes and eventually vitiates the quantity constraint in the latter. Finally, granting credits for all reductions below “business-as-usual” technology, as is effectively proposed under the clean development mechanism, will eventually lead to complete absence of constraints on emissions.

The remainder of this note lays out an extraordinarily simple model to support these claims.

A First Approximation

We begin by showing that ERC and TDP trading are equivalent when the output of participating firms is exogenously determined. That is, for any ERC plan we can define a cap-and-trade plan such that the two plans lead to the same emissions for each firm and that the price of credits under ERC trading equals the price of permits under the cap-and-trade plan.

Consider a collection of N cost-minimizing firms indexed by $i \in [1,N]$. Each firm produces emissions e_i and output x_i in the ratio $r_i = e_i / x_i$. As a first approximation, let x_i be exogenously determined. The cost function of each firm is homogeneous of degree one in emissions and output and can be written as

$$C_i = C^{i}(x_i, e_i) = x_i C^{i}(1, e_i / x_i) = x_i c^{i}(r_i) \qquad \textbf{(1)}$$

where unit cost of output, $c_i = c^{i}(r_i)$, depends on the emissions ratio. Given that output is fixed, marginal abatement cost, m_i, is the negative of the first derivative of the unit cost function since direct computation shows that

$$m_i = -\frac{\partial C_i}{\partial e_i} = -x_i c_1^i(r) \frac{dr_i}{de_i} = -c_1^i(r) \equiv m^i(r) \tag{2}$$

Marginal abatement cost is assumed to fall at a decreasing rate as the emissions ratio rises, hence

$$\begin{aligned} m^i(r) &= -c_1^i(r_i) > 0 \\ m_1^i(r_i) &= -c_{11}^i(r_i) < 0 \end{aligned} \tag{3}$$

Total emissions by the i-th firm are $e_i = r_i x_i$. For each firm let there be an exogenously prescribed emission ratio r_i^B. ERCs are earned by emitting at a lower emissions ratio than r_i^B ; conversely, a demand for ERCs , z_i, is created by operating at an emissions ratio higher than the prescribed ratio.

$$z_i = (r_i - r_i^B)x_i \tag{4}$$

The i-th firm minimizes the net cost of output, defined as production cost plus the cost of any ERCs it must purchase. Its problem may be written

$$\min_{\{r_i\}} \quad c^i(r_i)x_i + p_z z_i \tag{5}$$

where p_z is the price of ERCs. As would be expected, the first order condition

$$x_i c_1(r_i) + p_z x_i = 0 \tag{6}$$

implies that firm should adjust its emissions ratio to set marginal abatement cost equals to the price of ERCs (provided output is positive).

$$p_z = -c_1^i(r_i) = m^i(r_i) \tag{7}$$

Invert (6) to obtain firm i's optimal emissions ratio as a function of the price of ERCs,

$$r_i = r^i(p_z) \tag{8}$$

Substituting into (4) we can define the firm's net demand function for ERCs.

$$z_i = (r^i(p_z) - r_i^B)x_i \equiv z^i(p_z) \tag{9}$$

Negative values of z_i denote a supply of ERCs . Market demand for ERCs is the sum of firm demands. In the absence of banking, net demand for ERCs must be non-positive and may only be negative if the price of ERCs is zero.

$$\begin{gathered}\sum_{i=1}^{N} z_i = \sum_{i=1}^{N} (r^i(p_t^z) - r_i^B)x_i \leq 0 \\ p_t^z \sum_{i=1}^{N} z_i = p_z \sum_{i=1}^{N} (r^i(p_z) - r_i^B)x_i = 0\end{gathered} \tag{10}$$

Rearranging (10) in the case of positive prices we have simply

$$\sum_{i=1}^{N} \overline{r}_i x_i = \sum_{i=1}^{N} r^i(p_z)x_i \tag{11}$$

Equation (11) determines the equilibrium price of ERCs, p_z^*. Given that price, each firm's optimal emissions ratio is determined by (7). We can now establish

Proposition 1. When all output levels are fixed, emission reduction credit trading is exactly equivalent to a cap-and-trade emissions trading plan in which each firm is allocated permits equal to its prescribed emissions ratio times its output, and the aggregate cap is the sum of these allocations.

Proof: We show that the cap-and-trade plan described in the proposition also gives rise to equation (11) and hence the results are identical. Denote the firm's use of tradable emission permits (TEPs) by q_i , the initial distribution by $q_i^S = r_i^B x_i$, and the price of TEPs by p_q. The cap is $Q^S = \sum_{i=1}^{N} r_i^B x_i$. The firm's net demand for TEPs is $q_i^n = r_i x_i - r_i^B x_i = (r_i - r_i^B) x_i = z_i$, by (4). The firm minimizes the sum of production costs and net permit purchases, solving

$$\min_{\{r_i\}} \quad c^i(r_i) x_i + p_q q_i^n \tag{12}$$

But this is the same problem as (5), and consequently the solutions are identical.

Figure 1 illustrates the market equilibrium. The effective supply of TDPs, Q_X^S, is the quantity weighted sum of the prescribed emission ratios. The effective demand is the quantity-weighted sum of the individual unit demands, thus $Q_X^D = \sum_{i=1}^{N} r^i(p_z) x_i$. The equilibrium price, p^*, is determined by the intersection of the two curves and is identical for ERCs and TDPs.

The key difference between cap-and-trade plan and ERC trading is that under ERC trading the effective supply of permits increases as industry output increases. This prevents the price from rising. In fact we have

Proposition 2. When output is in fixed proportions, the equilibrium price of ERCs is independent of the output level.

Proof: Let the output of each industry be proportional to an output index X, that is $x_i = w_i X, \forall i$. Then for positive X, (11) implies that p_z^* solves

$$\sum_{i=1}^{N} r_i{}^B w_i = \sum_{i=1}^{N} r^i(p_z) w_i \tag{13}$$

which is independent of X.

This result is explained by Figure 1, which illustrates the effect of a shift in the output index. The initial position is represented by the intersection of Q_X^S and Q_Y^D. Let the industry output index increase from X to $Y = \lambda X,\ \lambda > 1$. The supply curve shifts from $Q_X^S = \sum_{i=1}^{N} r_i{}^B w_i X$ to $Q_Y^S = \sum_{i=1}^{N} r_i{}^B w_i Y = \sum_{i=1}^{N} r_i{}^B w_i \lambda X = \lambda Q_X^S$. The demand curve shifts from $Q_X^D = \sum_{i=1}^{N} r^i(p_z) x_i$ to $.\, Q_Y^D = \sum_{i=1}^{N} r^i(p_z) w_i Y = \sum_{i=1}^{N} r^i(p_z) w_i \lambda X = \lambda Q_X^D$. Note that the multiplicative shift of the demand curve effectively rotates the demand curve about the vertical axis. Since (13) holds, the shifts offset each other and the price remains constant.

The invariance of price allows us to draw an alternative representation of the market, based on unit demand curves. Figure 2 is drawn with emissions per unit of output on the horizontal axis. Figure 2(b) shows the unit emissions demand curve for an individual firm with prescribed emissions ratio r_i^B. These may be aggregated using output weights w_i to form the market demand for emissions per unit of output, $R^D(p_z)$, illustrated in Figure 2(a).

The supply side of the market is represented by weighted average baseline ratio,

$$R^{B} = \sum_{i=1}^{N} w_i r_i^{B} \qquad \textbf{(14)}$$

R^{B} and R^{D} are the left and right sides of (13), respectively. The equilibrium price, p_z^{*} is determined by their intersection, independently of the level of output.

Now let us consider the efficiency of ERC trading. Equation (7) implies that ERC trading leads to the equalization of marginal abatement cost across firms, thus ensuring that both open-market ERC trading and cap-and-trade permit trading are efficient in the sense that they minimize the cost of achieving an exogenously determined level of emissions. The efficiency gains can be illustrated in using the unit emissions demand curve of Figure 2(b) . The firm chooses an equilibrium emissions ratio $r_i^{*} = r^{i}(p_z^{*})$. Suppose the equilibrium ratio exceeds the prescribed emissions ratio. The firm will increase the emission ratio from r_i^{B} to r_i^{*}, paying an amount equal to area *a* but saving area *a* plus area *b* in abatement cost, thus earning additional profits equal to area *b* on each unit of output. Similar results hold for firms for which the equilibrium emissions ratio is less that the prescribed ratio. These firms sell credits and reduce emissions, earning profits equal to the difference between sales revenue and the incremental cost of abatement.

Emissions reduction credit trading and binding standards

Cap-and-trade TDP trading places a potentially binding constraint on total emissions. If it is binding, the market generates a positive price for permits. If the cap exceeds the aggregate emissions of uncontrolled firms, trading may occur but the equilibrium price of permits will be zero. In open-market ERC trading the prescribed emission ratios fulfil the same function. It is obvious from Figure 2 (b) that the price of credits will depend positively on the severity of the average performance standard, R^{B}. Proposition 3 establishes that the prescribed performance standards must be sufficiently strict for at least one firm to exceed its standard in equilibrium. Otherwise the price of credits will be zero.

Proposition 3. If the price under ERC trading is positive, at least one firm must be exceeding its prescribed emissions ratio.

Proof: If the price is strictly positive, Equation (8) and proposition (2) imply that $\sum_{i=1}^{N}(r^i(p_z)-\bar{r}_i)w_i=0$. Since the weights w_i are non-negative, either all unit demands are equal to the corresponding performance ratios, $r^i(p_z)=\bar{r}_i, \forall i$, and there is no trade, or there must be at least one firm for which $r^i(p_z)>\bar{r}_i$ and one for which $r^i(p_z)<\bar{r}_i$.

Many discussions of open market ERC trading plans state that credits will only be given for real and verifiable reductions which are surplus to regulatory requirements. This may give the impression that no firm is permitted to violate the regulatory requirement. Proposition 3 establishes that this is not possible in equilibrium. A stand-alone ERC trading plan can only generate trades if some firms are using credits to offset violations of the prescribed performance standard.

Is ERC trading a price instrument or a quantity instrument?

We are used to thinking of emissions trading as a quantity-based instrument for environmental regulation, but Figure 1 suggests that emissions reduction credit trading may act more like a tax than a quantity constraint. Under an emissions tax, firms equate marginal abatement cost to a tax which is independent of industry output. Under ERC trading, firms equate marginal abatement cost to a constant price for ERCs that is independent of output. In fact we have

Proposition 4. ERC trading is equivalent to an emissions tax $t=p_z$ with a free base equal to the prescribed emissions ratio times output.

Proof: This follows immediately from comparison of total cost under an emissions tax, , with total cost under ERCs, $c^i(r_i)x_i+p_z(r_ix_i-r_i^Bx_i)$.

This suggests that the outcome of ERC trading may differ from the outcome of emissions taxes because of demand-side effects. In discussing this, it is useful to compare the average costs of output under emissions taxes, under ERC trading, and under a hypothetical command-and-control performance standard equal to r_i^B for each firm. We have

Proposition 5. Let c_c be the average cost of output under command-and-control with performance standards equal to the prescribed emissions ratios. Let c_r be the average cost of output under emissions reduction credit trading with the same prescribed emissions ratios. Let c_t be the average cost of output under an emissions tax equal to the equilibrium price of credits. Then

(a) $c_r < c_t$.

(b) $c_r <= c_c$

Proof: The average cost of output under command-and-control regulation is $c^i(r_i^B)x_i$ The total cost of output under ERC trading is $c^i(r_i)x_i + p_z(r_i x_i - r_i^B x_i)$, hence $c_r = c^i(r_i^*) + p_z r_i^* - p_z r_i^B$. The average cost of output under an emissions tax of $t = p_z$ is $c^i(r_i^*) + t r_i^*$. Since $p_z r_i^B > 0$, the third expression exceeds the second, establishing 6(a).

Proposition 5(b) follows from profit maximization, since under ERC trading firms retain the option of withdrawing from the market and producing at the command-and-control emissions ratio. Thus $c^i(r_i^*) + p_z r_i^* - p_z r_i^B \leq c^i(r_i^B)$.

Proposition 5 implies that once demand side effects are admitted, ERC trading and emissions taxes will no longer be equivalent. The model developed so far cannot accommodate a formal comparison, but the general situation for a competitive industry comprised of firms like firm *i* is illustrated by Figure 3. The horizontal axis now represents industry output. Under ERC trading the long run industry supply curve will be horizontal at S_2.. Under an equivalent tax, the industry supply curve would shift upwards to S_1 and industry output would be lower than under ERC trading.. Emissions ratios would be the same in the two cases, so total emissions will be higher under ERC trading. Under command-and-control regulation the long-run supply curve of the industry output would also be higher than in the case of ERC trading. Suppose it is at S_3. Note that the relative positions of S_2 and S_3 cannot be determined.. Industry output would be higher under ERC trading than under command-and-control. The emissions ratio under ERC trading will be higher than under command-and-control if the industry is a net purchaser of permits and lower than under command-and-control if the industry is a net seller of permits. Therefore total emissions will be higher under ERC trading than under command and control if the industry is a net purchaser, and total emissions may be higher, lower, or the same as in command-and-control beecause total output and emissions ratio are moving in opposite directions.

The comparison with cap-and-trade TDP trading is more complex. Under TDP trading the cap is fixed and the price of permits rises as industry output expands. If the industry is a net purchaser of credits, the long run industry supply curve, S_4, becomes positively sloped. In the initial equilibrium ERC trading and emissions trading are equivalent, but if demand shifts to the right industry price will rise and industry output will expand less rapidly under cap-and-trade emissions trading. Interestingly, the reverse seems to be true for an industry that is a net *supplier* of permits. For emissions trading in such an industry the long run supply price will *decline* as output increases, because the increased demand for permits will drive up their price, leading to greater average revenue from sales of permits. The long run industry supply curve is negatively sloped. Under emissions trading, the rise in permit prices due to an increase in industry demand for output will cause the industry's emission ratio to fall, rendering the effect on industry emissions ambiguous. Of course, aggregate emissions across all industries will remain constant under emissions trading.

Combining ERCs and Emissions Trading

Many proposals for emissions trading imply combining a “cap-and-trade” system with an open-market system. One example is Ontario Hydro’s plan to use emission reduction credits generated under the Pilot Emissions Reduction Trading Program (PERT) to meet its voluntary cap of 38,000 tonnes of NOx emissions in the year 2000 (Ontario Hydro, 1998, p.95) and proposals for combining certified emission reduction credits generated under the Clean Development Mechanism with Emissions Trading under Article 17 of the Kyoto Protocol. In the short run, such combined plans can generate trades at positive prices. In the long run, the price of ERCs in the open market will dominate.

To illustrate this, suppose there are two groups of firms, A and B, operating in separate emissions trading and ERC trading markets, respectively. Return to the case in which output is exogenously fixed.. We adopt a standard diagram from the literature. Figure 4 (a) illustrates the situation when a cap-and-trade system and an ERC trading system operate independently. The cap in the quantity controlled group of firms is Q_A, and the corresponding price of permits is p_A. The effective supply of ERCs , given the output of the credit-trading group, is Q_B. The market clearing price is p_B. We assume $p_B < p_A$.

Figure 4 (b) illustrates the effect of integrating the markets. The effective supply of permits and credits is $Q_T = Q_A + Q_B$. The demand of Group A is plotted from the origin in the normal manner. The demand of Group B is plotted in a leftwards direction from Q_T. The equilibrium price is p_T, with E_A permits and credits in the hands of Group A and the remainder, $Q_B = E_T - Q_A$ in the hands of Group B. On the assumptions of the example, the equilibrium price in the combined market lies between the prices in the two markets operating separately and the quantity-controlled Group A is a net purchaser of credits from Group B.

Notice that in this scenario it is possible for all Group B firms to be net suppliers of credits. Thus Proposition 4 does not hold in the case of integrated cap-and-trade and ERC credit trading markets and it becomes credible to speak of ERCs being generated by reductions in excess of regulatory requirements without simultaneously permitting other firms to fall short of theirs.

These results are not surprising. What does bear emphasis, however, is that as the output of the Group B firms increases, the price in the integrated market will asymptotically approach the price in the ERC market, that is, p_T will become arbitrarily close to p_B. This is shown in Figure 4(b) by an increase in Group B's output from Q_B to $Q_B^{/}$. As described earlier, this causes the effective demand for emission to rotate counter-clockwise about the vertical intercept. When this new curve is plotted on panel (b) it is seen that the price of permits declines.

Under these circumstances the cap-and-trade plan is essentially vitiated. Firms in Group A face an effective tax of p_B on emissions, with a free base equal to their original permit distributions. They are disadvantaged relative to the firms in Group B in that their free base does not increase as output increases. There is no long-run constraint on aggregate emissions.

Conclusions

We have examined the differences between traditional cap-and-trade permit trading and open-market emissions reduction credit trading. The two methods lead to identical results when output is fixed. Short run cost efficience is guaranteed because firms equate their marginal abatement costs to the price of permits or credits. When output increases, however, the effective supply of emissions remains constant under permit trading but increases under ERC trading. Thus the price of ERCs will tend to remain constant over time. Like an emissions tax, ERC trading achieves an efficient allocation of abatement responsibilities without a quantitative limit on aggregate emissions. In fact we have shown that open-market ERC trading is equivalent to an emissions tax with a free base equal to the prescribed emissions ratio times current output. This in turn implies that long run average cost is lower and industry output higher under ERC trading than under a comparable tax.

We have shown that a pure ERC trading plan will not generate trades if firms are given prescribed emissions ratios equal to current, unregulated practice. When integrated with a cap-and-trade system, however, an ERC system may be expected to expand the effective supply of emissions and to lower their price. As the ERC sector grows, the cap in the conventional ERC system becomes increasingly ineffective and the price of permits approaches the price of credits in a stand-alone ERC plan.

The choice between ERC and permit trading is thus similar to the choice between price and quantity instruments. In a world of certainty and exogenously determined output levels, the instruments have equivalent results, so the choice should probably be made so as to minimize administrative, monitoring and enforcement costs. When output is endogenous, it should be recognized that over time an ERC plan will lead to higher emissions and lower marginal abatement costs than would a cap-and-trade plan. In choosing between instruments policy makers should consider which pattern of marginal abatement cost changes are most likely to track changes in marginal damages. In a world of uncertainty, there may be still more to be said. When there is uncertainty about abatement costs, Weizman (1974) has shown that price instruments are to be preferred when the marginal damage function is flat relative to the abatement cost function. It seems reasonable to propose that ERC trading is particularly well suited to similar markets.

The effectiveness of ERC trading depends on imposing an average performance standard sufficiently strong to equate the price of credits to the marginal damage caused by emissions. This will not happen if participants are given “business-as-usual” performance standards. Such generous standards will progressively undermine any social value in emissions trading. This may be a major problem in the context of the “clean development mechanism” in the Kyoto Agreement. The CDM is designed to generate emission reduction credits which can be applied to the quantitative limits undertaken by the Annex B countries. There is a strong tendency for proponents of the CDM to advocate rapid deployment of projects with generous baselines for creation of credits. In sufficient quantity, such projects have the potential for driving the price of permits to zero and vitiating the Kyoto protocol entirely. A similar danger appears in the PERT and GERT pilot emissions reductions credit trading plans. Trades undertaken under these programs seem to imply a “business-as-usual” performance standard. Unless stronger standards are imposed these programs cannot hope to create the appropriate price signals for controlling pollution.

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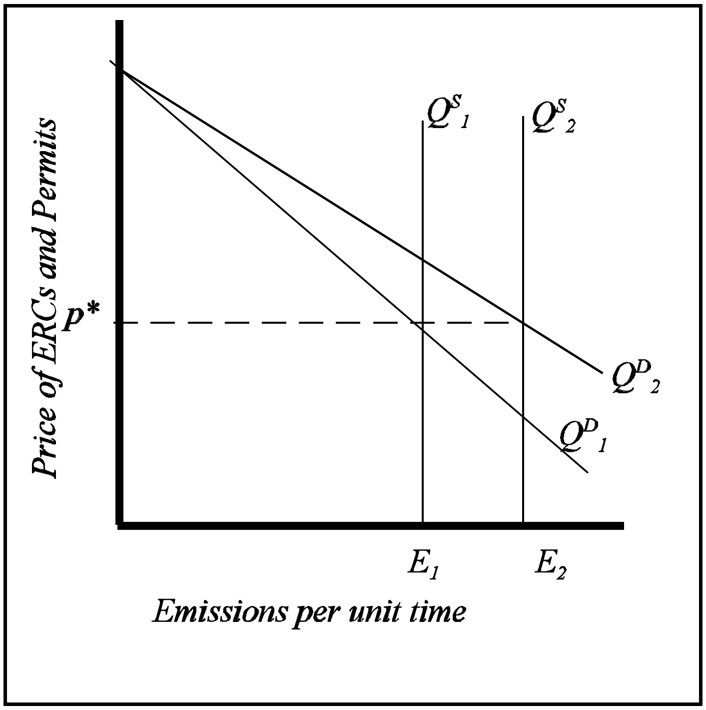


Figure 1. **Determination of the market price of ERCs.** The supply of credits is the output-weighted sum of individual performance standards. The demand is the output-weighted sum of unit demands for emissions. Proportionate growth in output shifts supply and rotates demand to the right, leaving the equilibrium price constant.

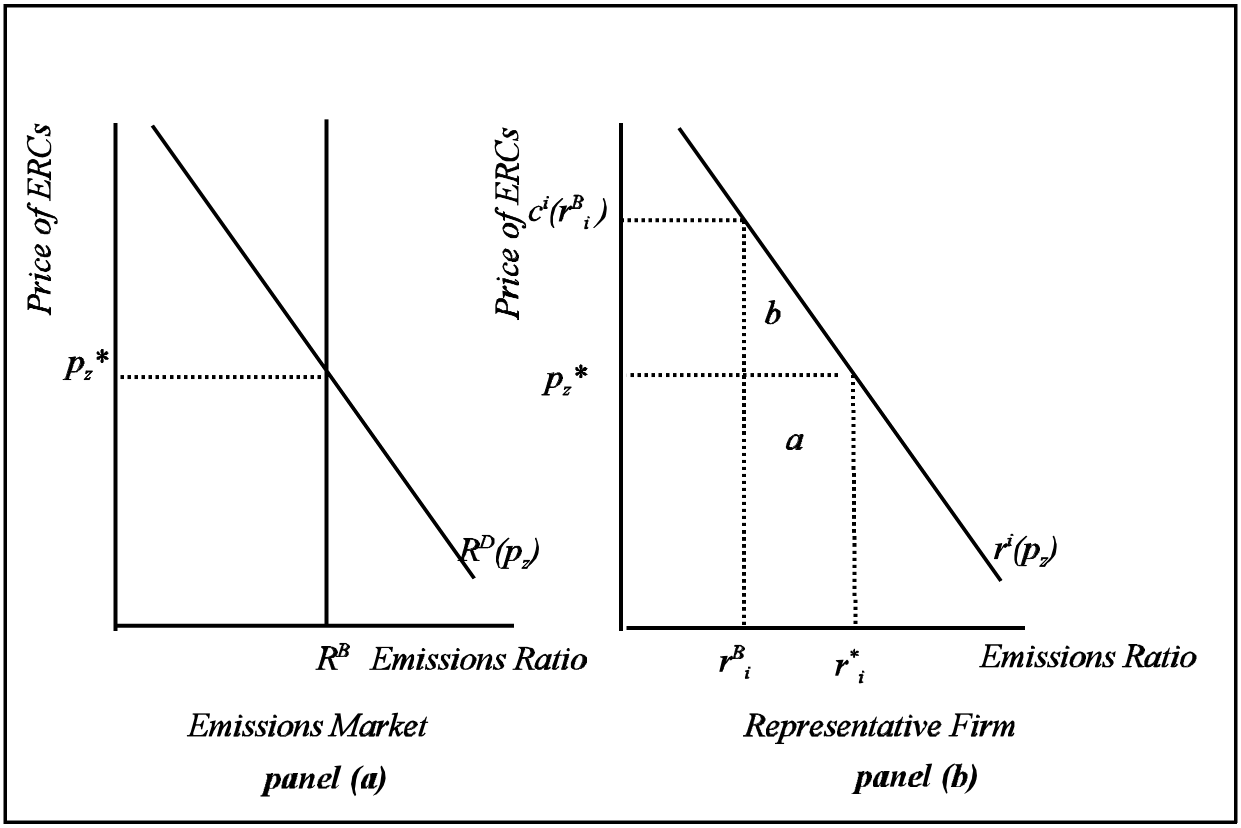


Figure 2. **Emissions Ratios and Efficiency.** The firm's demand for emissions per unit of output, $\mathbf{r}^i(p_z)$, is the inverse of the unit marginal abatement cost curve. These are weighted by industry output shares to obtain the market demand for emissions per unit of output, $R^D(p_z)=\sum_i^N w_i r^i(p_z)$. The equilibrium price is determined in panel (a) by the intersection of the market demand for emissions per unit of output with the output-weighted prescribed emission ratio, $R^B=\sum_i^N w_i r_i^B$. The representative firm in panel (b) chooses an emissions ratio r_i^* such that the marginal abatement cost equals the price of ERCs. The firm purchases $r_j^*-r_j^B$ credits per unit of output, saving area $a+b$ in abatement costs per unit of output and earning a profit equal to area b per unit of output.

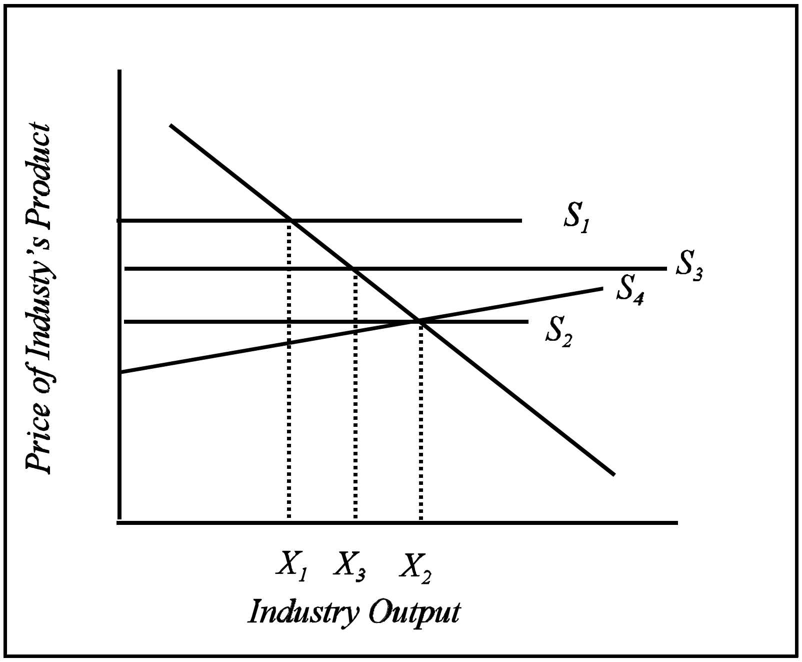


Figure 3. **Long Run Supply Curves**. Differing regulatory regimes generate different long run supply curves. The supply curve under an emissions tax, S_1, is horizontal at $c_i + tr_i$. The supply curve under emissions reductions trading, S_2, is horizontal at a lower price, $c_i + t(r_i - \bar{r}_i)$. The supply curve under command and control perfomance standards, $S_{3,}$ is horizontal at c_i. S_3 lies above S_2 . The supply curve under cap-and-trade emissions trading, S_4, is sloped because the price of permits rises as industry output increases. S_4 is positively sloped for net purchasers of permits, negatively sloped for net sellers of permits.

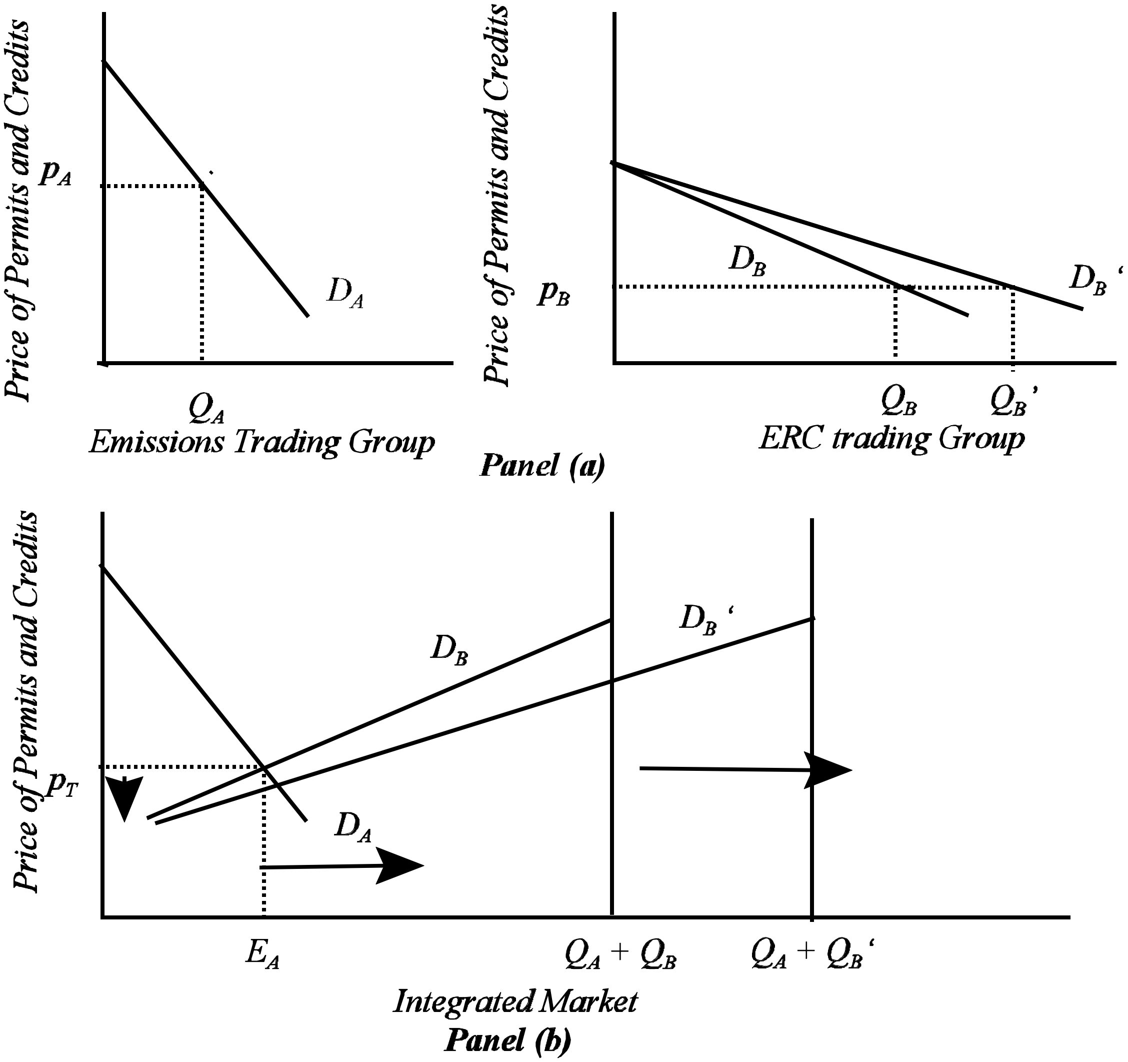


Figure 4. **Integrating cap-and-trade and ERC trading.** The top graphs represent independent cap-and-trade and ERC markets. Combining them leads to a price between the stand-alone prices and allows the emissions of one group to expand. Here, the emissions trading group purchases $E_A - Q_A$ credits from the ERC trading group. Over time, the output of the ERC trading group increases, rotating the effective supply of permits and credits counter-clockwise. Applying the new graph to panel (b) shows that the integrated price falls and approaches the price in the stand-alone ERC market.

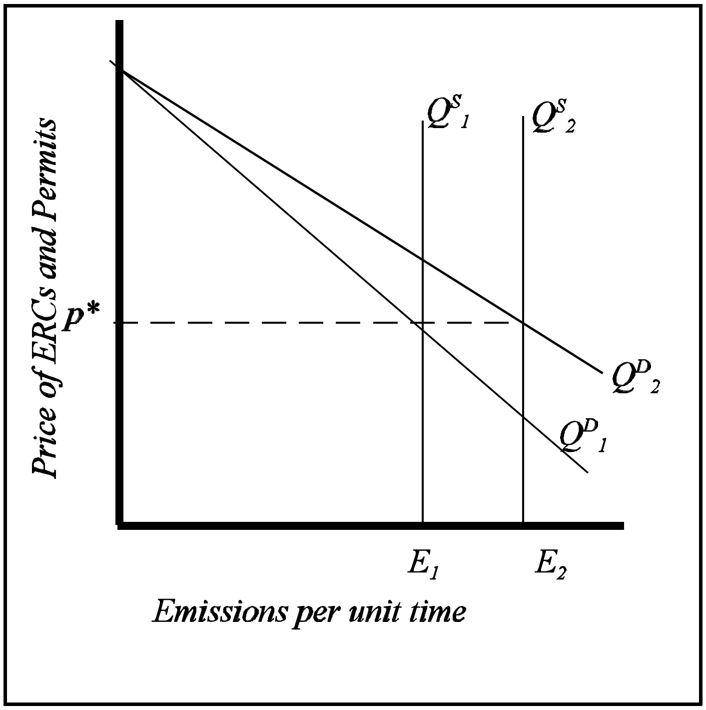
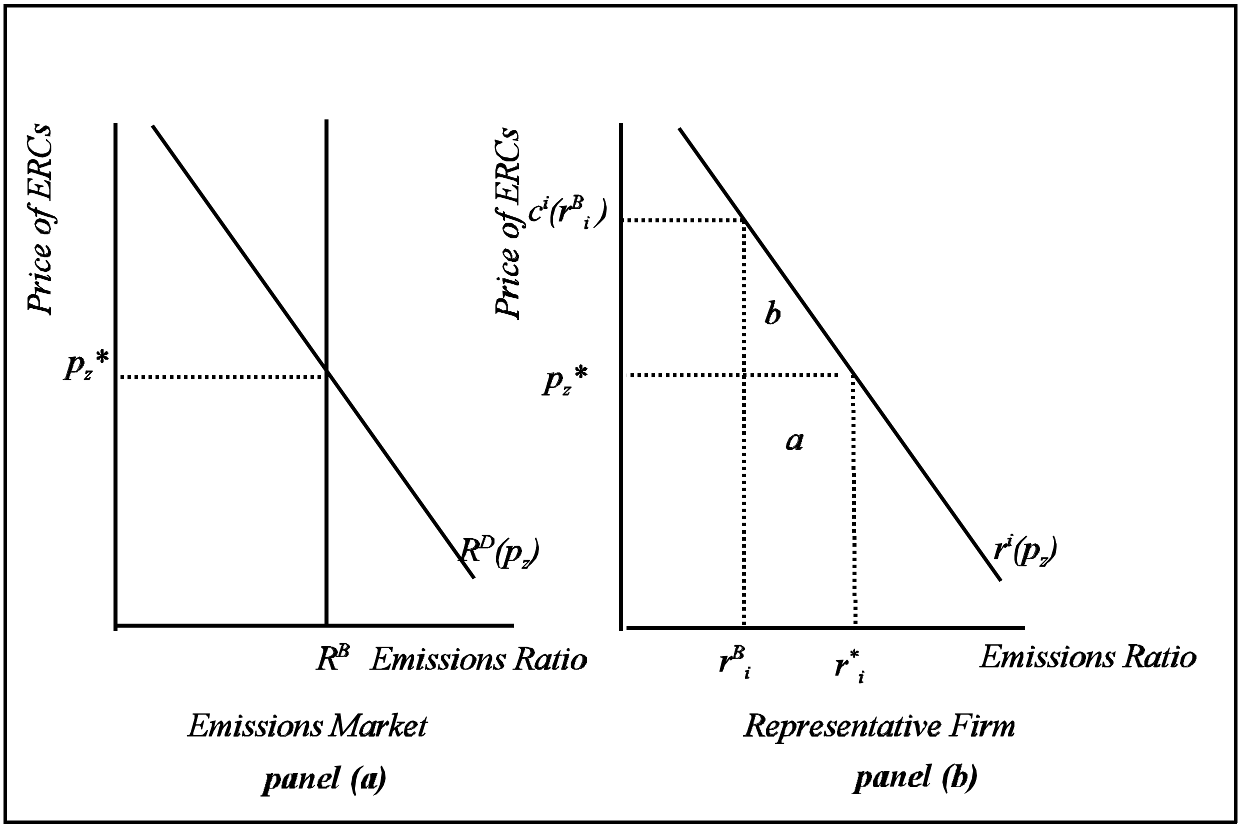


Figure 5. **Determination of the market price of ERCs.** The supply of credits is the output-weighted sum of individual performance standards. The demand is the output-weighted sum of unit demands for emissions. Proportionate growth in output shifts supply and rotates demand to the right, leaving the equilibrium price constant.



Emissions Market
panel (a)

Representative Firm
panel (b)

Figure 6. **Emissions Ratios and Efficiency.** The firm's demand for emissions per unit of output, $\mathbf{r}^i(p_z)$, is the inverse of the unit marginal abatement cost curve. These are weighted by industry output shares to obtain the market demand for emissions per unit of output, $R^D(p_z)=\sum_i^N w_i r^i(p_z)$. The equilibrium price is determined in panel (a) by the intersection of the market demand for emissions per unit of output with the output-weighted prescribed emission ratio, $R^B=\sum_i^N w_i r_i^B$. The representative firm in panel (b) chooses an emissions ratio r_i^* such that the marginal abatement cost equals the price of ERCs. The firm purchases $r_j^*-r_j^B$ credits per unit of output, saving area $a+b$ in abatement costs per unit of output and earning a profit equal to area b per unit of output.

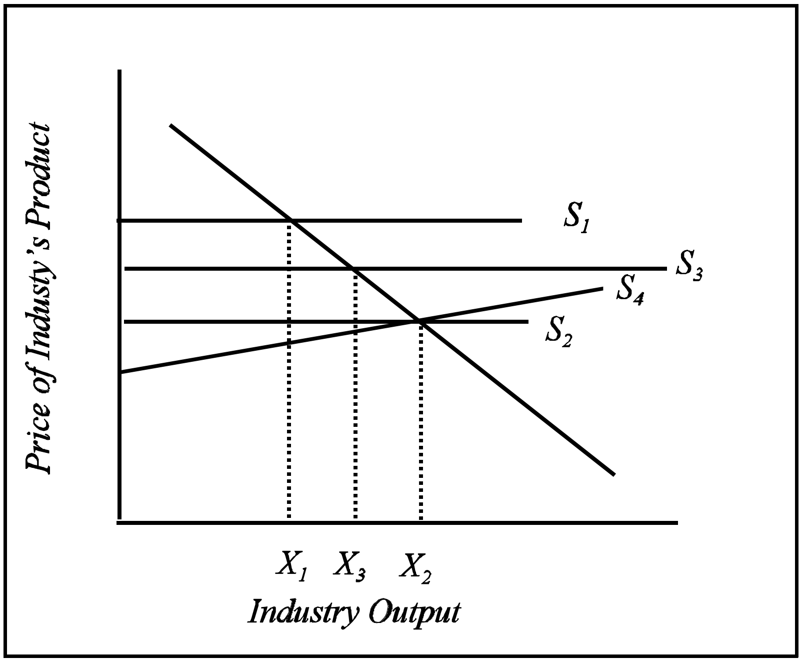


Figure 7. **Long Run Supply Curves**. Differing regulatory regimes generate different long run supply curves. The supply curve under an emissions tax, S_1, is horizontal at c_i+tr_i. The supply curve under emissions reductions trading, S_2, is horizontal at a lower price, $c_i+t(r_i-\bar{r}_i)$. The supply curve under command and control perfomance standards, $S_{3,}$ is horizontal at c_i. S_3 lies above S_2 . The supply curve under cap-and-trade emissions trading, S_4, is sloped because the price of permits rises as industry output increases. S_4 is positively sloped for net purchasers of permits, negatively sloped for net sellers of permits.

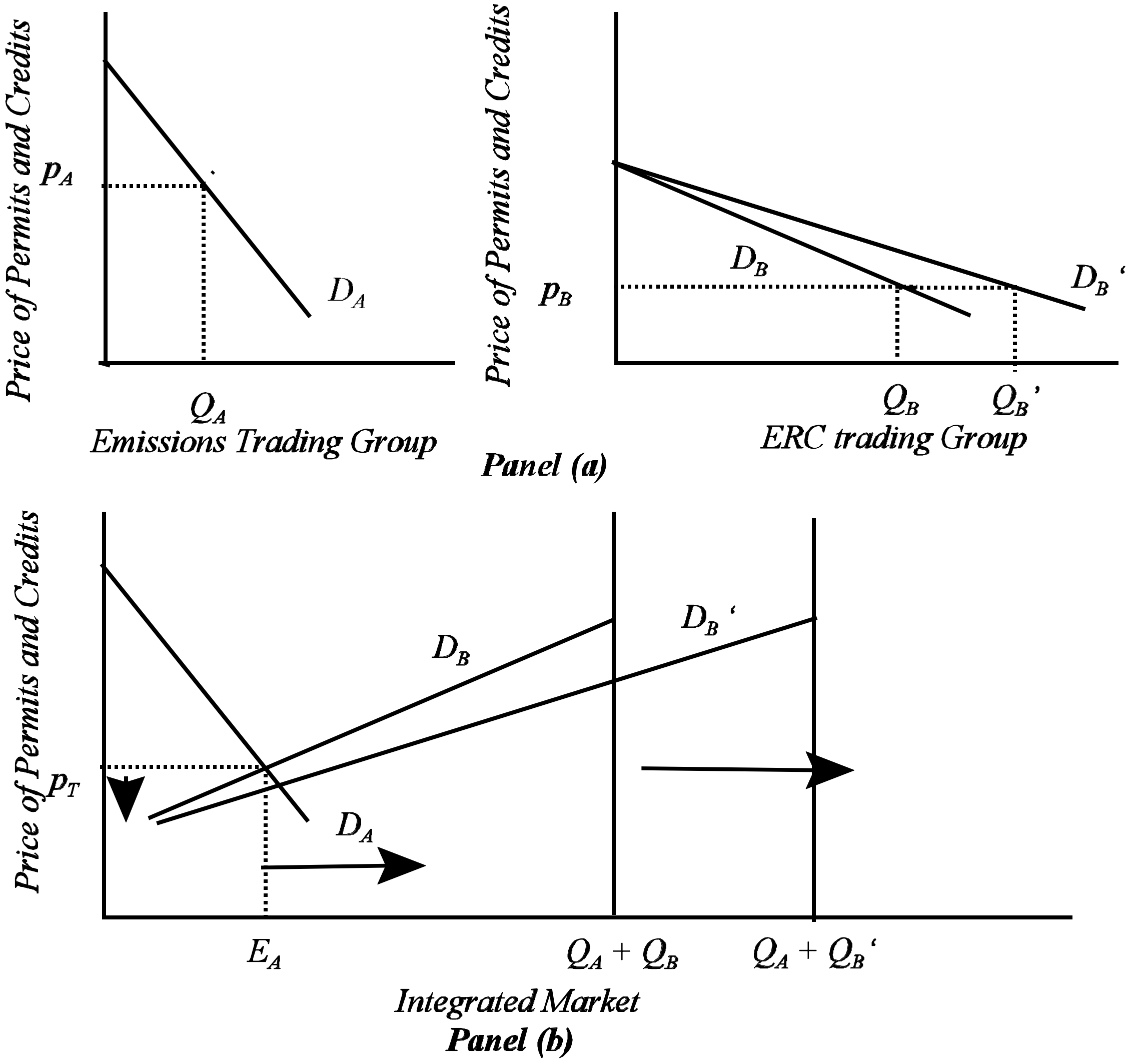


Figure 8. **Integrating cap-and-trade and ERC trading.** The top graphs represent independent cap-and-trade and ERC markets. Combining them leads to a price between the stand-alone prices and allows the emissions of one group to expand. Here, the emissions trading group purchases $E_A - Q_A$ credits from the ERC trading group. Over time, the output of the ERC trading group increases, rotating the effective supply of permits and credits counter-clockwise. Applying the new graph to panel (b) shows that the integrated price falls and approaches the price in the stand-alone ERC market.

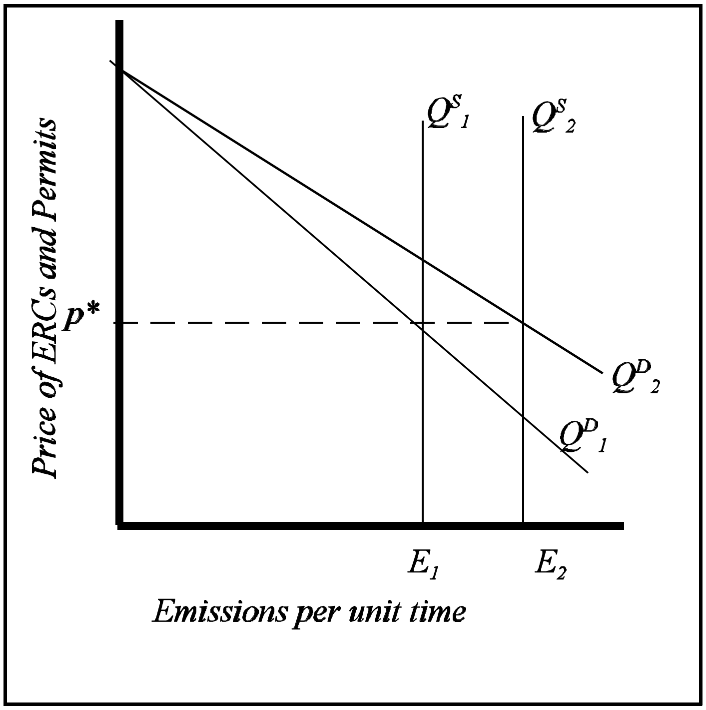


Figure 9. **Determination of the market price of ERCs.** The supply of credits is the output-weighted sum of individual performance standards. The demand is the output-weighted sum of unit demands for emissions. Proportionate growth in output shifts supply and rotates demand to the right, leaving the equilibrium price constant.

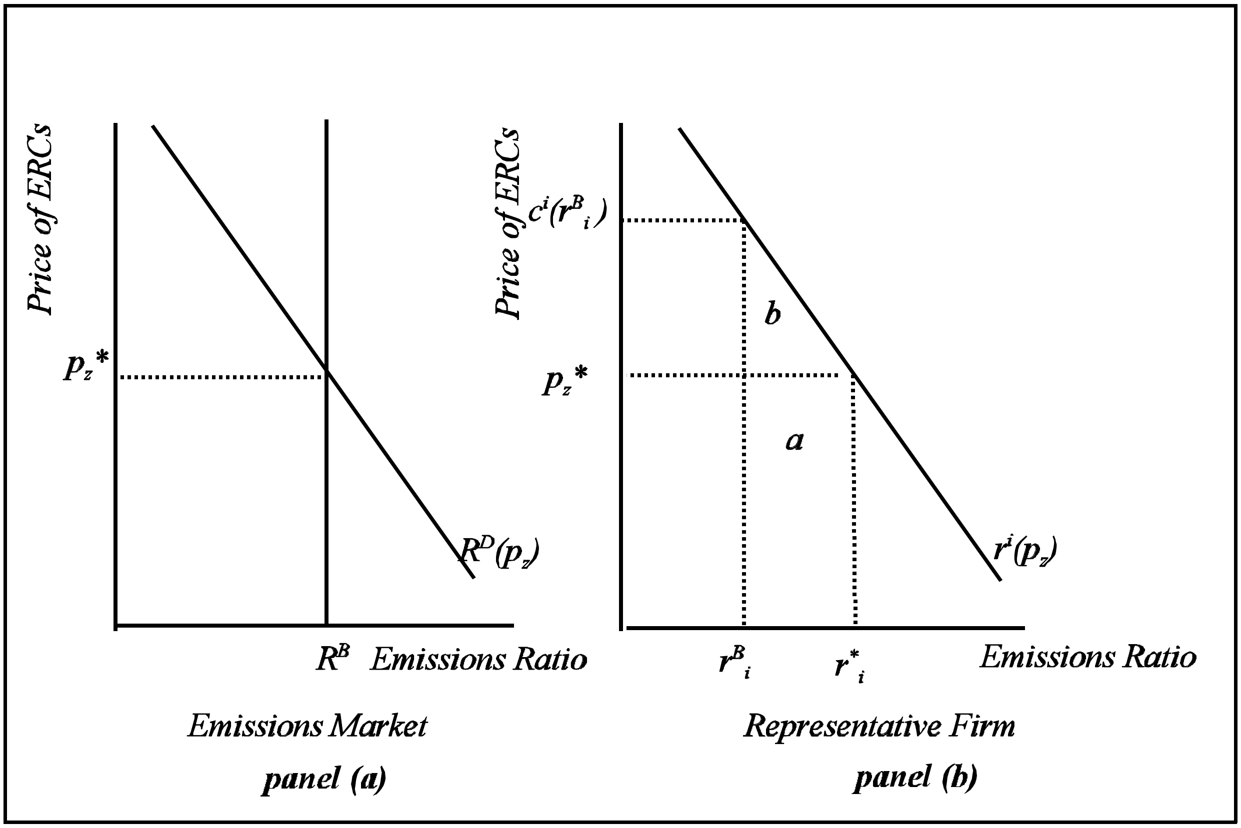


Figure 10. **Emissions Ratios and Efficiency.** The firm's demand for emissions per unit of output, $\mathbf{r}^i(p_z)$, is the inverse of the unit marginal abatement cost curve. These are weighted by industry output shares to obtain the market demand for emissions per unit of output, $R^D(p_z)=\sum_i^N w_i r^i(p_z)$. The equilibrium price is determined in panel (a) by the intersection of the market demand for emissions per unit of output with the output-weighted prescribed emission ratio, $R^B=\sum_i^N w_i r_i^B$. The representative firm in panel (b) chooses an emissions ratio r_i^* such that the marginal abatement cost equals the price of ERCs. The firm purchases $r_j^* - r_j^B$ credits per unit of output, saving area $a+b$ in abatement costs per unit of output and earning a profit equal to area b per unit of output.

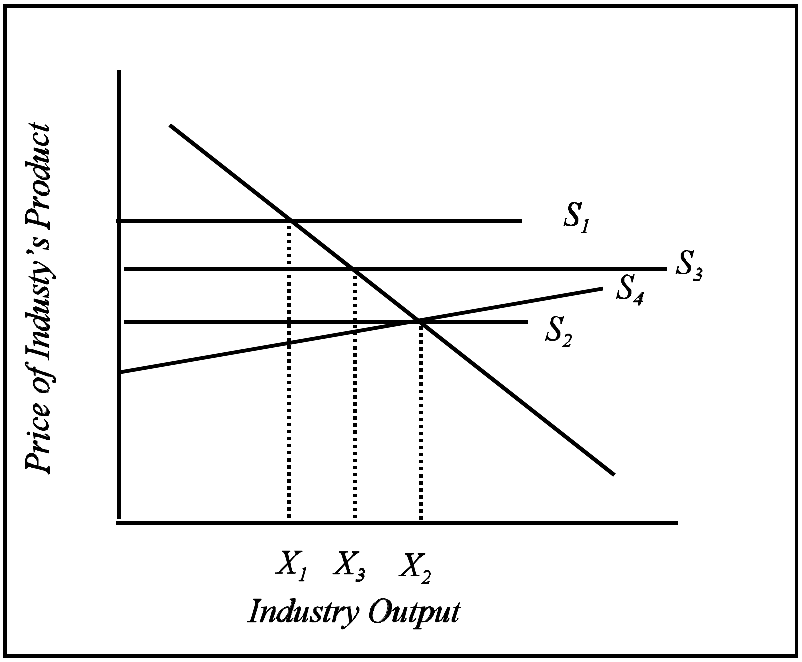


Figure 11. **Long Run Supply Curves**. Differing regulatory regimes generate different long run supply curves. The supply curve under an emissions tax, S_1, is horizontal at c_i+tr_i. The supply curve under emissions reductions trading, S_2, is horizontal at a lower price, $c_i+t(r_i-\bar{r}_i)$. The supply curve under command and control perfomance standards, $S_{3,}$ is horizontal at c_i. S_3 lies above S_2 . The supply curve under cap-and-trade emissions trading, S_4, is sloped because the price of permits rises as industry output increases. S_4 is positively sloped for net purchasers of permits, negatively sloped for net sellers of permits.

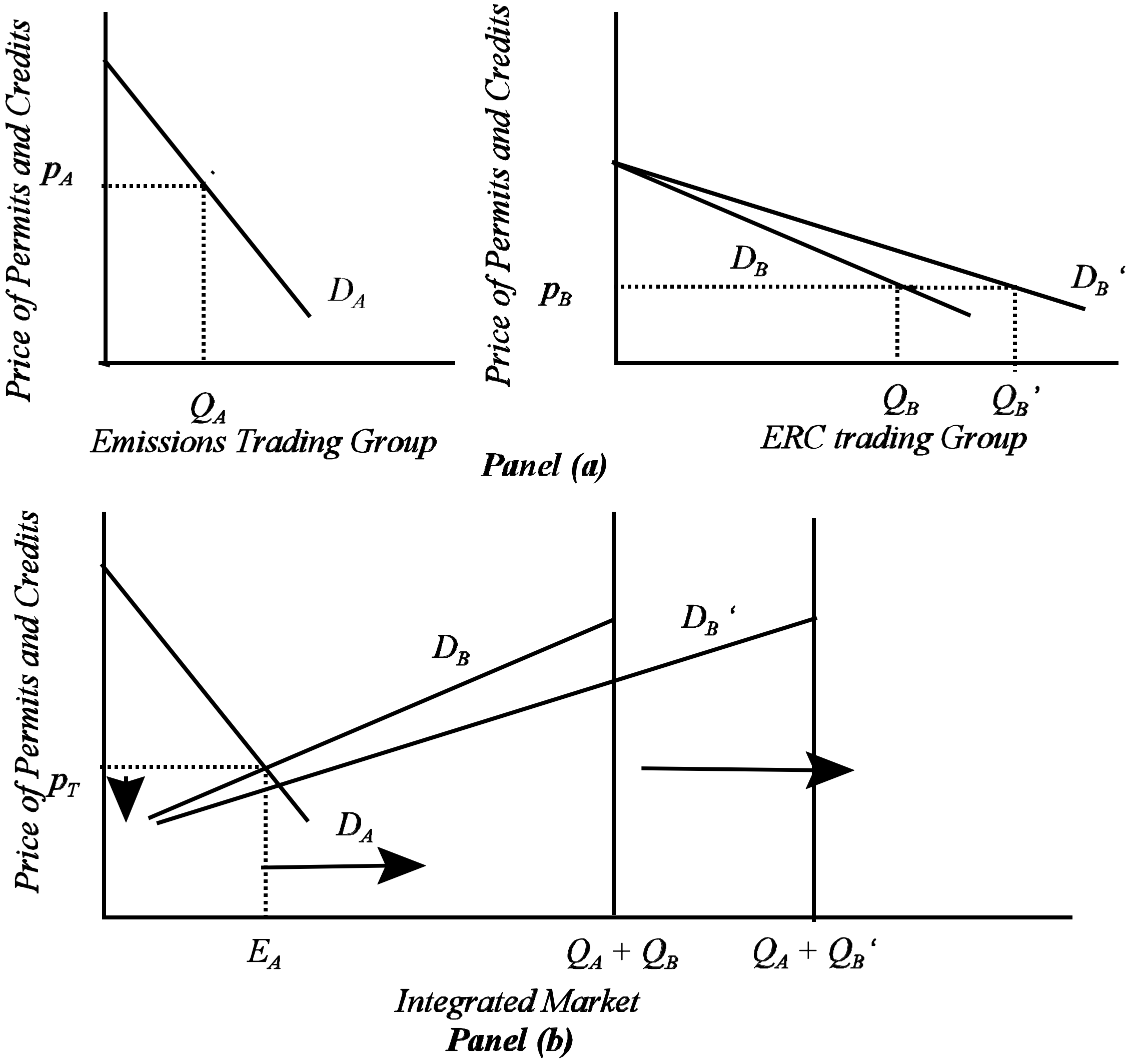


Figure 12. **Integrating cap-and-trade and ERC trading.** The top graphs represent independent cap-and-trade and ERC markets. Combining them leads to a price between the stand-alone prices and allows the emissions of one group to expand. Here, the emissions trading group purchases $E_A - Q_A$ credits from the ERC trading group. Over time, the output of the ERC trading group increases, rotating the effective supply of permits and credits counter-clockwise. Applying the new graph to panel (b) shows that the integrated price falls and approaches the price in the stand-alone ERC market.

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