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On Marketable Air-Pollution Permits: The Case for a System of Pollution Offsets

ALAN J. KRUPNICK

Resources for the Future 1755 Massachusetts Avenue, N. W., Washington, D.C. 20036

WALLACE E. OATES

Department of Economics and Bureau of Business and Economic Research, University of Maryland, College Park, Maryland 20742

AND

ERIC VAN DE VERG

Department of Economic and Community Development, 2525 Riva Road, Maryland 21401

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After examining the properties of several alternative forms of marketable permit systems for the control of air pollution, this paper proposes a system of pollution offsets as the most promising approach. Under the pollution-offset scheme, sources of emissions are free to trade emissions permits subject to the constraint of no violations of the predetermined air-quality standard at any receptor point. The paper shows that the pollution-offset system has the capacity to achieve the predetermined standards of air quality at the minimum aggregate abatement cost, while making comparatively modest demands both on the sources and on the administering agency.

For most air and water pollutants, the extent and spatial pattern of the damages to the environment depend not only upon the level of emissions, but upon the locations and the dispersion characteristics of the sources. This implies that there is an inherently spatial problem in the design of a system to control these pollutants. A regulatory system that ignores the spatial problem can pass up cost savings that are potentially quite large in the achievement of our objectives for environmental quality.

The purpose of this paper is to explore alternative techniques for incorporating spatial elements into a system of marketable air-pollution permits. There exist several such alternatives, and they have fundamentally different implications for the structure and functioning of a permits market. We shall contend that, among the alternatives, a system of "pollution offsets" offers the most promising approach to the design of an effective market in pollution permits. Moreover, we find that the Environmental Protection Agency (EPA) through its Emissions Trading policy has provided a framework for the introduction of such a system.

The seminal paper on this issue is that of Montgomery [8]. The Montgomery paper analyzes two systems of marketable pollution permits: a system of "pollution licenses" that defines allowable emissions in terms of pollutant concentrations at a set of receptor points, and a system of "emission licenses" that confer directly the right to emit pollutants up to a specified rate. Montgomery demonstrates that the

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former system satisfies the important condition that a market equilibrium coincides with the least-cost solution for attaining any predetermined level of environmental quality and does so for *any* initial allocation of licenses among polluters.

However, as we shall discuss, the transactions costs for polluting firms associated with Montgomery's system of pollution licenses are likely to be quite high. His alternative system of emissions licenses promises considerable savings in transactions costs. Unfortunately, however, the Montgomery paper also demonstrates that an extremely restrictive (and sometimes unattainable) condition is required for an initial allocation of permits to ensure that the market equilibrium is the least-cost solution. This finding is particularly disturbing on two counts. First, the environmental authority may not be able to find an initial allocation of permits that ensures an efficient outcome. And, second, even should such an allocation exist, a substantial degree of flexibility in the choice of this initial allocation may be lost; such flexibility can be extremely important in designing a system that is politically feasible (as well as efficient).

We show in this paper that this shortcoming of Montgomery's system of emission licenses is the result of an unnecessarily restrictive condition that he imposes on the trading of the licenses. By suitable (and quite straightforward) modifications of this condition, we find that an efficiency property similar to the one that characterizes his system of pollution licenses also characterizes our modified scheme of "pollution offsets": a "trading equilibrium" exists that coincides with the least-cost pattern of emissions for *any* initial allocation of emissions permits. We show also that the pollution-offsets approach offers some important advantages over other techniques in terms of minimizing the total abatement and transactions costs.

In the early part of the paper, we shall go back over some familiar terrain to put the problem and Montgomery's analysis in its proper perspective.[1] We shall then proceed to an analysis and assessment of the alternative approaches to the design of a system of marketable pollution permits.

I. A FORMAL STATEMENT OF THE PROBLEM: A BENCHMARK CASE

It will clarify the analysis and allow us to establish a baseline case if we set forth, at this point, a more formal statement of the spatial problem.[2] Let us assume that we have a specific region, an air shed, in which there are m sources of pollution, each of which is fixed in location. Air quality in terms of a particular pollutant is defined by concentrations at n "receptor points" in the region; we thus describe air quality by a vector $Q = (q_1, \ldots, q_n)$ where q_j is the concentration of the pollutant at point (receptor) j.[3] The dispersion characteristics of the problem are described in terms of

[1]Such a restatement is needed in part to clear up some confusion in the literature. Tietenberg [10], for example, has misinterpreted the Montgomery proposal for "emission licenses" to refer to a system of zones within which permits trade on a one-for-one basis (pp. 405–406). Montgomery's system of emission licenses is, however, quite different from a system of permit zones.

[2]Here we follow Montgomery [8] closely. Although we have framed the discussion in terms of air pollution, the analysis has obvious relevance to the regulation of water pollution as well.

[3]By receptor points, we are not referring to the location of monitors. Consider a concentration gradient for an area that is constructed, for example, from monitoring data in conjunction with an air-diffusion model. The environmental agency would select points on that gradient (e.g., the locations of relatively high concentrations of the pollutant) to be receptor points. There need not be any actual monitors at these locations.

a diffusion model which we represent by an $m \times n$ matrix of unit diffusion or transfer coefficients

$$D = \begin{bmatrix} & \vdots & \\ \dots & d_{ij} & \dots \\ & \vdots & \end{bmatrix}$$

In this matrix, the element d_{ij} indicates the contribution that one unit of emissions from source i makes to the pollution concentration at point j.[4]

The environmental objective is to attain some predetermined level(s) of pollutant concentrations within the region; we denote these standards as $Q^* = (q_1^*, \dots, q_n^*)$. Note that the standard need not be the same at each point; the environmental authority could, for example, prescribe lower concentrations as the target in densely populated areas.

The problem thus becomes one of attaining a set of predetermined levels of pollutant concentrations at the minimum aggregate abatement cost. Or, in other words, we are looking for a vector of emissions from our m sources, $E = (e_1, \dots, e_m)$, that will minimize abatement costs subject to the constraint that the prescribed standards are met at each of the n locations in the region. The abatement costs of the ith source are a function of its level of emissions: $c_i(e_i)$. So our problem, in formal terms, is to

$$\begin{aligned} \text{Minimize} \quad & \sum_i c_i(e_i) \\ \text{s.t.} \quad & ED \leqslant Q^* \\ & E \geqslant 0. \end{aligned}$$

Montgomery [8] has shown that such a vector of emissions exists and, moreover, that, if the sources of pollution are cost-minimizing agents, the emission vector and shadow prices that emerge from the minimization problem satisfy the same set of conditions as do the vectors of emissions and permit prices for a competitive equilibrium in an air-permits market. In short, if the environmental authority were simply to issue q_j^* permits (defined in terms of pollutant concentrations) for each of the n receptor points, competitive bidding for these permits would generate an equilibrium solution that satisfies the conditions for the minimization of total abatement costs.

These results establish a benchmark case for a control system that minimizes abatement costs. Two properties of this outcome are noteworthy. First is the utter simplicity of the system from the perspective of the environmental agency. In particular, officials need have no information whatsoever regarding abatement costs; they simply issue the prescribed number of permits at each receptor point, and competitive bidding takes care of matters from there. Alternatively, the environmental authority could make an initial allocation of these permits to existing polluters. Subsequent transactions in a competitive setting would then establish the cost-mini-

[4] We should note that the d_{ij} are, in fact, dependent on stack height and diameter, gas temperature, and exit velocities, as well as on a host of meteorological conditions; we will consider some of these complications later.

mizing solution. As Montgomery [8] proves formally, the least-cost outcome is independent of the initial allocation of the permits. Second, in contrast to the modest burden it places on administrators, this system can be extremely cumbersome for polluters. Note that a firm emitting wastes must assemble a "portfolio" of permits from *each* of the receptor points that is affected by its emissions: a source at point i will have to acquire permits at each receptor j in the amount $(d_{ij}e_i)$. There will, therefore, exist n different markets for permits, one for each receptor point, and each polluter will participate in the subset of these markets corresponding to the receptor points affected by his emissions. It would appear that the transactions costs for polluters are likely to be substantial under our benchmark system, although this expense may be justified, under certain circumstances, by the savings in abatement costs.

II. THE DESIGN OF A MARKETABLE PERMIT SYSTEM: AN ALTERNATIVE APPROACH

The scheme examined in the preceding section is a prototype for an *ambient-based* system (APS) of pollution permits: the permits are defined in terms of pollutant concentrations at the receptor points. An alternative approach in the literature is an *emission-based* system (EPS) under which the permits are defined in terms of levels of emissions rather than in terms of the effects of these emissions on ambient air quality.[5] This latter approach often makes use of a set of emission zones within which emissions of a particular pollutant are treated as equivalent. The environmental authority determines an allocation of permits to each zone, and polluters within a zone trade permits on a one-to-one basis. There are no trades across zones: each zone is a self-contained market with its own price for permits determined by the polluters' demand for permits and the supply as determined by the authority.[6]

From this perspective, we can envision at one extreme for EPS (following Tietenberg [10]) a system in which the entire region is a single market. The environmental authority issues a fixed number of permits for the region as a whole, and the subsequent bids and offers of participants generate a single market-clearing price. As we move away from this special case, we encounter continually more finely divided systems of zones designed to take into account the spatial character of the air shed. However, regardless of the total number of zones, each pollution source will lie only in a single zone and will consequently operate in only one permit market for a given pollutant.

It is this last feature of EPS that constitutes its basic appeal. Recall that under APS the polluter must operate in a number of markets for each pollutant (in the benchmark case, one for each receptor site that his emissions affect) and is subject to a different "weighting parameter" (i.e., diffusion coefficient) in each market. The assembling of the requisite portfolio of permits could become quite complicated for

[5]For reasons that will become clear, our choice of terminology to describe alternative systems of marketable permits differs from that of Montgomery. Our ambient-based approach (APS) is in the spirit of his system of "pollution licenses." However, we shall distinguish among several types of emission-based systems that are quite different from Montgomery's system of emission licenses.

[6]Under a variant of this approach, trading may take place across zones at "exchange rates" set by the administering agency to reflect the damage attributable to emissions from the various zones. More will be said on this later.

firms; they might even find themselves, in some instances, buying in one market while selling in another (Russell [9]). It is not altogether clear just how large these "transactions costs" are likely to be (more on this shortly); some well-organized brokerage operations could conceivably facilitate greatly the transfer of permits. But it would appear, nonetheless, that, from the perspective of the polluter, EPS offers a major attraction by requiring polluters to buy and sell permits within a single market and with no system of source-specific weights attached to individual firms.

However, while the EPS approach may simplify life for polluters, it is a potential nightmare for the administrators of the system. Recall that under APS the environmental authority need only establish the number of permits to be offered for sale at each receptor site (so as to meet the prescribed air-quality standard) and specify the diffusion or transfer coefficients for each source of pollution. Market forces take over from there and, under competitive conditions, generate the least-cost pattern of waste emissions.[7]

In contrast, EPS will not, in general, achieve the least-cost outcome, and it makes enormous demands on an administering agency that tries to approach the least-cost solution. To do so, the agency must have knowledge of the source-specific abatement costs in addition to the air-modeling data required for APS. Moreover, EPS requires continuing readjustments among zonal stocks of permits. The reason the least-cost solution is unlikely to be achieved is straightforward; since polluters with somewhat varying dispersion coefficients are aggregated into the same zone, one-for-one trades of pollution rights will not reflect the differences in the concentrations contributed by their respective emissions. The price of emissions to each polluter will not, in short, reflect accurately the shadow price of the binding pollution constraint. Further, the system of zones may prevent one source from making beneficial trades with another source which happens to be located in a different zone.

These objections to EPS need not be serious, if the dispersion characteristics for emissions within zones are not very different (Hahn and Noll [5]). This suggests that an increase in the number of zones can reduce the "excess abatement costs" associated with EPS. However, increasing the number of zones will tend to reduce the number of participants in each market with the undesirable repercussions from the decrease in competitiveness of markets for permits and increased uncertainty of permit prices.

A more troublesome issue is that, even were there no differences in the dispersion characteristics of emissions within each zone, the environmental authority must still determine an allocation of permits to each zone. And this determination requires *the complete solution* by the administrator of the cost-minimization problem. To reach this solution, the administering agency must have not only an air-quality model (to provide the d_{ij}) and a complete emissions inventory, but source-specific abatement cost functions and the capacity to solve the programming problem.[8] With less-than-

[7] This may be something of an oversimplification for the reason that changes in emission levels can be associated with changes in dispersion coefficients. A polluter may reduce his emissions by the installation of new equipment, of bag houses, precipitators or scrubbers, or by the addition of after burners to stacks in such ways as to alter the source's emission parameters. Trades involving such changes may thus require a recalculation of dispersion coefficients.

[8] Of course, with all this information, a market would hardly be necessary. After solving the cost-minimization problem, the environmental authority could simply distribute the optimal number of permits to each polluter.

perfect information, the agency's zonal allocation of permits may fail to attain the ambient air-quality targets. If pollution were excessive, the authority would have to reenter the market (in at least some of the zones, where again the pattern of zonal purchases would require a fairly sophisticated analysis) and purchase or confiscate permits. Such an iterative procedure is not only cumbersome for the administrator of the system, but may create considerable uncertainty for firms as to the future course of permit prices.

We stress, moreover, that this procedure involves more than just groping once and for all toward an unchanging equilibrium. Altered patterns of emissions resulting from the growth (or contraction) of existing firms, the entry of new firms, and changing abatement technology will generate a continually shifting least-cost pattern of emissions across zones. Under EPS, the environmental authority faces a dynamic problem that will require periodic adjustments to the supplies of permits in each zone. We conclude that the zone approach suffers both from its inability to realize the least-cost pattern of emissions and from the formidable burden it places on the administering agency.

III. A HYBRID APPROACH: A MARKET FOR POLLUTION OFFSETS

From Sections I and II, we find that both the ambient-based and emission-based systems for pollution control have some troublesome properties. There is an alternative, however, that combines certain characteristics of both the APS and EPS approaches and possesses some quite attractive properties. The basic idea is to define permits in terms of emissions and to allow their sale among polluters, but not on a one-to-one basis. More specifically, transfers of emission permits are subject to the restriction that the transfer does not result in a violation of the air-quality standard at any receptor point. The source of new emissions (or of expanded emissions) must purchase a sufficient number of emission permits from existing sources to "offset" the effects of the new emissions on pollutant concentrations in such a way that the pollution constraint is everywhere satisfied. For this reason, we prefer to call this general approach to a system of marketable permits one of "pollution offsets."

The hybrid character of the offset approach is apparent. Like EPS, it involves the purchase and sale of emission permits; the permits are not associated explicitly with a particular receptor market as under APS. At the same time, however, it captures the spirit of the ambient-based system in that the ratio at which permits exchange for one another depends on the relative effects of the associated emissions on ambient air quality at the receptor points.

The Montgomery system of "emission licenses" is, in fact, a special case of the offset approach. Montgomery places as a constraint on the transfer of emission permits a "nondegradation condition": he effectively requires that any transactions among polluters result in no increase in pollutant concentrations at any receptor point. As we shall see shortly, this condition is unnecessarily restrictive. Moreover, it generates an outcome that, for many initial allocations of permits, will not coincide with the least-cost solution.

By relaxing Montgomery's overly stringent constraint on the trading of emissions permits, we can show that an equilibrium outcome under an appropriately designed system of pollution offsets coincides with the least-cost solution irrespective of the initial allocation of emission permits. We develop the argument in terms of Fig. 1 in

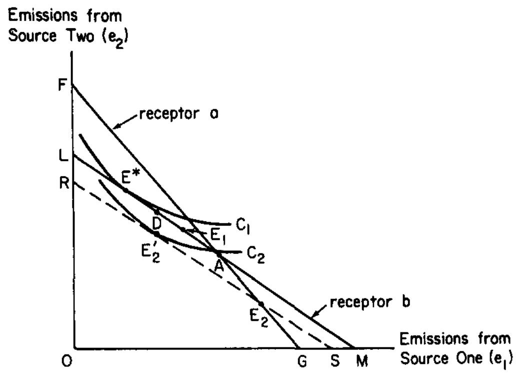

FIG. 1. Spatially differentiated permit systems.

which the horizontal and vertical axes measure, respectively, the levels of emissions of firms 1 and 2 (i.e., e_1 and e_2).[9] The curves C_1 and C_2 are isocost curves for pollution abatement costs.[10] Note that higher curves correspond to lower total abatement costs ($C_1 < C_2$). The line FG indicates the pollution constraint associated with receptor a. Points on FG denote combinations of e_1 and e_2 for which $q_a = q_a^*$; the slope of the line equals the ratio of the transfer coefficients (i.e., the rate at which emissions from firm 2 can substitute for emissions from firm 1 with no change in pollution concentrations at receptor a). Similarly LM depicts the pollution constraint for receptor b. The combinations of emissions from firms 1 and 2 that satisfy the pollution constraint at both receptors are thus the set of points $OLAG$. We see immediately that the least-cost solution occurs at E^*, at which point the ratio of marginal abatement costs equals the ratio of the transfer coefficients.

E^* is therefore the optimum; our problem is to determine the circumstances under which E^* will also be the market equilibrium. Under Montgomery's system of "emission licenses", the environmental authority makes an initial allocation of permits to polluting firms, after which firms are free to buy and sell the permits subject to a "nondegradation" condition. More formally, each firm faces the constraints

$$d_{ij}e_i \leqslant \sum_k d_{kj}l_{ik} \qquad j = 1, \ldots, m$$

where l_{ik} is the emission permits that firm i purchases from firm k. This restriction implies that a transfer of emission permits from one polluter to another must take place in such a way that there is no increase in the level of pollution at *any* receptor point.

Returning to Fig. 1, suppose that the environmental authority established an initial allocation of emission permits indicated by E_1. Firm 2 would then find it profitable to purchase permits from firm 1.[11] The effective rate of exchange of

[9]This diagram is a modification of Fig. 2 in Montgomery [7, p. 30].

[10]A sufficient (but not necessary) condition for the isocost curves to have the desired curvature in Fig. 1 is that both firms face a schedule of rising marginal abatement costs.

[11]The potential gains-from-trade from sales of emission rights by firm 1 to firm 2 follow from the fact that the linear pollution constraint at E_1 is steeper than the isocost curve passing through that point. In the case, for example, where the slope of the constraint LM is minus one (indicating that emissions from

permits would be the slope of the line *LM*, since the constraint at receptor *b* is, in this instance, the binding constraint. The gains from trade would be exhausted at E^*. For the initial allocation of rights indicated by E_1, we thus find that the market equilibrium coincides with the optimum.

Suppose, however, that instead of E_1, the environmental authority had selected E_2 as the initial allocation of permits. Once again firm 2 would find it profitable to purchase permits from firm 1, but Montgomery's nondegradation constraint would now limit the feasible set of outcomes to ORE_2G. Trading would now take place along the dotted line *RS* (which is parallel to *LM* since the ratio of the sources' diffusion coefficients is unchanged). The market equilibrium would, in this instance, be E_2', which does not coincide with the optimal outcome. The solution at E_2' entails an excessive level of expenditure on abatement resulting in a sense from an "excessive" level of environmental quality. The nondegradation constraint prevents a movement from E_2' to E^*. We thus find that attainment of the least-cost solution is not independent of the initial allocation of emission permits.

The problem confronting the environmental authority in our example is that it must know which segment of the frontier contains E^* before it can determine an initial allocation of permits that makes the market solution coincident with E^*. There is one qualification: if the initial allocation is that represented by point *A*, market transactions will move the outcome to E^* irrespective of whether E^* happens to lie on line segment *LA* or segment *AG*. This is Montgomery's restriction on the initial allocation of permits: the initial allocation must be such that the pollution constraint is binding at all receptor points to ensure that the market equilibrium coincides with the least-cost solution.[12]

While this condition seems reasonable enough in terms of our example in Fig. 1 with only two receptor points, the severity of the problem becomes clear when we introduce additional receptors. A third line in Fig. 1 indicating the pollution constraint for yet another receptor point would pass through point *A* only by coincidence. This implies that, for the two-source case, with three or more receptor points there will not, in general, exist a vector of emissions for which all the pollution constraints are binding! In such instances, the environmental authority typically will not be able to find an initial allocation of permits that will ensure the least-cost outcome without a complete solution of the programming problem. In these cases, Montgomery's system requires the agency to determine E^* (which requires knowledge of firms' abatement cost functions as well as the transfer coefficients) before it can specify an initial allocation of permits that will ensure that E^* is the market equilibrium. Even if this can be done, it removes most of the

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firms 1 and 2 have equivalent effects on pollutant concentrations at receptor *b*), firm 2 has a higher marginal abatement cost at E_1 than does firm 1 so that transfers of permits from 1 to 2 can be mutually profitable.

[12]The intuitive explanation of this condition is clear in terms of our discussion of the initial allocation of permits, E_2, in Fig. 1. More generally, suppose that the least-cost solution entails a binding constraint at some particular receptor point *j* (i.e., the least-cost solution implies that $q_j = q_j^*$). Assume, however, that the initial allocation of emission rights selected by the environmental authority results in pollutant concentrations at receptor *j* that are less than the allowable level so that the constraint at *j* is not binding. Under Montgomery's nondegradation restriction on subsequent trades of permits, it is clear that these trades cannot generate the least-cost outcome, because the restriction implies that ambient air quality at *j* cannot be less than that under the initial allocation. Thus, the constraint at *j* can never become binding. One way to circumvent this problem is to establish an initial allocation of permits such that $q_j = q_j^*$ for all *j*. However, as we note in the text, such an allocation may not even exist.

flexibility in setting the initial permit allocation, a flexibility that may be extremely important for rendering such a system politically feasible.[13]

However, as the analysis suggests, Montgomery's constraint on the market behavior of polluters is unnecessarily restrictive. Returning to our case in Fig. 1 where the initial allocation of permits was E_2, we saw that trades took place along the dotted line RS instead of the actual constraint LM implied by our predetermined standards of air quality. Montgomery's restriction on market trades of permits is sufficient to ensure that $q \leqslant q^*$ for all receptors, but it is not necessary. By relaxing this restriction, we can describe a modification of Montgomery's system for which the only point representing an equilibrium is the least-cost outcome.

Suppose that we supplement Montgomery's nondegradation condition on trades of permits with the following provision: *firms can always obtain from the environmental authority additional permits so long as the air-quality standard is not violated at any receptor point.* We note immediately in Fig. 1 that this disqualifies E_2' as a point of market equilibrium; since the pollution constraint is not binding at either receptor point, firms will obtain additional permits from the environmental agency.[14] Suppose, for example, that firm 2 obtained LR of additional permits thereby moving the vector of emissions from E_2' to point D. At D, there exists the potential for mutually profitable sales of emission permits by firm 1 to firm 2 until E^* is attained. In short, E^* would be a "trading equilibrium" (and the only such equilibrium).[15]

More generally, we can see that our amendment to Montgomery's condition on the issue and trading of permits gives the modified system two important properties:

(1) No point inside the frontier of feasible points established by the air-quality standards can be an equilibrium (since polluters will seek and obtain additional permits);

(2) No point on this frontier other than the least-cost solution can be an equilibrium (since at any other point mutually profitable transfers of permits exist).

Our amended version of the pollution-offset system is, however, a bit artificial or contrived. It may be useful, for expository purposes, to envision firms making trades along the line representing Montgomery's nondegradation constraint and then obtaining additional permits where there are no resulting pollutant concentrations in excess of the predetermined standards. However, there is a much more direct and less cumbersome method that can attain the same outcome. We can dispense altogether with the nondegradation condition and simply require the source of new emissions to induce existing polluters to reduce their emissions by amounts sufficient to prevent violations at any receptor point. Suppose, for example, that in Fig. 2 our

[13] More generally, in the case where the number of receptors exceeds the number of sources (where $m < n$), the system will typically be overdetermined so that there will not exist a vector of emissions such that the air-quality constraint binds at every receptor. If $m \geqslant n$, vectors (typically more than one) will exist that can be determined without knowledge of abatement costs and that allow the attainment of the least-cost solution under Montgomery's system of emission licenses. The vectors represent points where all *binding* receptor constraints intersect.

[14] This requires that, over the relevant range, the marginal product of waste emissions for polluting firms is strictly positive.

[15] We refer to our equilibrium under the offset approach as a "trading" equilibrium rather than a "market" equilibrium, since we have not shown formally that there exists a specific set of prices that will sustain an equilibrium among buyers and sellers corresponding to the efficient allocation of permits among polluters. We show instead that the only allocation of permits for which there exists no potential gains from trade (our definition of a "trading equilibrium") is the efficient one.

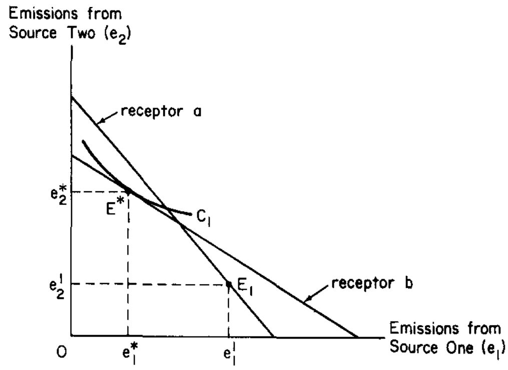

FIG. 2. An alternative pollution-offset system.

initial point were E_1, where $E_1 = (e_1^1, e_2^1)$ and $E^* = (e_1^*, e_2^*)$ are the emissions vectors corresponding to E_1 and E^*, respectively. Firm 2 would pay firm 1 to reduce its emissions from e_1^1 to e_1^*, which would enable firm 2 to increase its emissions from e_2^1 to e_2^*. This transaction would, at the same time, move the system directly from E_1 to E^* and exhaust the potential gains from trade. When we refer to our basic case of the pollution-offset system throughout the rest of this paper, it is this last case that we have in mind: firms are free to buy and sell emission permits subject only to the constraint that there result no violations of the standards for air quality at any receptor point.

We conclude that the trading equilibrium under our offset system coincides with the least-cost solution irrespective of the initial allocation of emission permits; like APS, a suitably designed offset system can achieve the predetermined standards for air quality at the least cost for any initial allocation of emission permits.

Moreover, as we discuss in detail in the next section, the offset system should typically require fewer transactions than APS. Instead of purchasing ambient permits in each of the receptor markets affected by its emissions, a polluting firm need only purchase emission permits from other firms sufficient to prevent any violations of the air-quality standards.[16]

IV. THE CHOICE AMONG ALTERNATIVE SYSTEMS: SOME FURTHER THOUGHTS

Our search is for the system that promises to minimize the sum of abatement and transactions costs for the attainment of predetermined levels of ambient air quality.[17] As we noted earlier, the object of our quest depends in fundamental ways on the characteristics of the particular pollutant and the geographical setting. Consider, for

[16] This determination, incidentally, would involve a fairly straightforward procedure making use of an air-quality model. One would simply enter a new emissions vector (incorporating the proposed addition to emissions and deleting the offsetting reductions) and examine through a simulation exercise the projected effects on pollutant concentrations at each of the receptor points. The proposed transaction would be approved so long as there were no violation of standards at any receptor point.

[17] We define transactions costs broadly to include both the costs to polluters and the costs to the environmental authority of managing the system.

example, a polar case of perfect mixing where a unit of emissions from a point within the air shed has the same effect on concentrations at all points in the area. For this special case, all three of our systems essentially degenerate into one. Since there is a need only for a single receptor point and the dispersion coefficients of all sources are identical, the APS system will involve only a single market in which permits trade on a one-for-one basis. This is obviously identical to an EPS system with a single zone encompassing the entire air shed or to an offset system in which sources will find that, to increase emissions by one unit, they must induce another source (any source in the air shed) to reduce its emissions by one unit.

The simplicity of this special case is a great attraction; it implies substantial savings in transactions costs for both polluters and administrators. Under APS, for example, polluting firms need operate in only a single permit market. Under EPS, the single, large zone means more potential buyers and sellers along with a much simplified planning problem for the environmental agency. Likewise, under the offset approach, the increased scope for trades at a single "rate of exchange" should facilitate the functioning of the permit market.

An interesting case of (at least virtually) perfect mixing involves the emission of chlorofluorocarbons (CFCs) which are thought to affect adversely the stratospheric ozone layer. The location of emissions is, as we understand it, irrelevant; CFCs and the ozone problem seem to involve a truly global public good so that there is no need to differentiate the incentives for abatement by the location of the source. For cases like CFCs, the permit market can take on a very simple structure, and, other things equal, should work quite well. The EPA is, in fact, considering a national permit market for CFC emissions.

The potential savings in transactions costs suggest that, even for cases that deviate somewhat from perfect mixing, it may, on balance, be beneficial to maintain the fiction of our polar case. Existing EPA procedures for modeling the effects of hydrocarbon emissions are an important example; these procedures allow one-for-one trades over a wide area. In such circumstances, the savings in transactions costs may exceed the "excess" abatement costs from the failure to make finer spatial distinctions. In an intriguing study of water pollution involving BOD emissions into the Willamette River, Eheart [3] has found that only a very small increase in total abatement costs results from simply allowing all sources to trade permits on a one-for-one basis. Hahn and Noll [5] suggest a similar result for sulfate pollution of the atmosphere in Southern California. For such cases (and even where the abatement cost differential is somewhat larger), the optimal system is likely to be our polar case.

The more general point is that the attempt to introduce finer spatial differentiation, while reducing total abatement cost, results in increased transactions costs for both polluters and administrators. There is, in short, a tradeoff between the savings in abatement costs and the higher transactions costs associated with finer spatial distinctions. As we move farther away from our case of perfect mixing, the excess abatement costs from ignoring spatial differences tend to grow. For air pollutants like particulate matter and nitrogen dioxide, for example, the spatial pattern of emissions is typically quite important.[18] For such cases, our problem becomes that of

[18] See, for example, the Atkinson and Lewis study [2] of particulate emissions in the St. Louis AQCR and the studies of nitrous oxide emissions by Anderson *et al.* [1] and EPA [11] in the Chicago AQCR and by Krupnick [6] for the Baltimore AQCR. All these studies produce large estimates of the potential cost-savings from a spatially sensitive policy.

choosing among our three general approaches to the design of a system of marketable permits.

Our treatment establishes a strong presumption in favor of our modified system of pollution offsets, especially where the number of receptor points is large. The APS approach has the attractive property of minimization of aggregate abatement costs. But, as we have shown, so does the offset approach. Moreover, the offset system should entail large savings in transactions costs relative to APS, since under the latter a polluter will typically have to operate in a multiplicity of different permit markets.[19]

While promising some savings in transactions costs for sources, the EPS approach with a system of emission zones cannot, in general, attain the least-cost pattern of emissions. And, as we discussed earlier, the planning problem for the environmental agency wishing to approach the least-cost solution is a very formidable one for which the solution is continually changing over time. In addition, the assumption under EPS that a unit of emissions from one source in a zone is precisely equivalent in its effects on air quality to a unit of emissions from any other source in the zone *may*, under certain circumstances, do serious violence to reality. The ambient effects of emissions do not depend solely on the geographical location of the source; they depend in important ways on such things as stack height and diameter, and on gas temperature and exit velocity. Variations in these parameters across polluters can be accommodated under the offset system through their effects on the source's vector of transfer coefficients. In contrast, EPS cannot readily incorporate such elements without losing the basic simplicity of one-for-one transfers of emission rights. EPS has some problems that are potentially quite troublesome and that do not plague the pollution-offset scheme.

Finally, there is an extremely important issue that goes beyond the confines of the formal problem as set out at the beginning of the paper. The analysis has run in terms of a given and fixed set of receptor points at which predetermined levels of air quality must be attained. However, the Clean Air Act requires that the National Ambient Air Quality Standards (NAAQS) be met at *all* locations. But for pollutants with more localized effects (and this includes most of the criteria air pollutants), it is possible for changing locational patterns of emissions to generate "hot spots" that do not coincide with designated receptor points. To prevent the occurrence of localized hot spots for such pollutants, a relatively fine mesh of receptor points will be needed implying comparatively high transactions costs under an APS system or small zones (and thin markets) under EPS.

Further, since under the APS system each receptor is associated with an individual permit market, receptor points would tend to become "institutionalized." Moving a receptor point to account for new pollution patterns would create dislocations: it would alter the structure of permit markets and would probably give rise to difficult administrative and legal problems. Moreover, it would not preclude the need for future readjustments. This problem, however, is easily resolved under the offset system, since there is no need to institutionalize the receptor points.

Under the offset approach, the environmental agency can adopt air-modeling procedures that effectively identify the location of the worst air quality, no matter

[19]Based on a given set of dispersion coefficients, the APS approach also encounters problems where (as noted earlier) trades entail changes in dispersion coefficients. The offset approach accommodates such changes more routinely by incorporating them into the calculations of the net effects on air quality of a proposed trade.

where it is, for each individual transaction. The agency would maintain a current record of the emissions and emission characteristics of each source and the currently applicable air model for the pollutant being traded. Proposed emissions trades would be "modeled" to ensure that the resulting pattern of pollutant concentrations meets the air-quality standard everywhere in the air shed. This procedure would, in principle, produce the same abatement costs and pattern of emissions as an APS system with a receptor at every location (i.e., an infinite number of receptors). Unlike APS, however, the transactions costs under the offset system would be essentially unchanged as the number of receptor points under consideration increases to infinity.

In comparing the APS and the offset systems, it is important to recognize that since the market (or trading) equilibrium under both systems coincides with the least-cost solution, the two schemes imply the same transfer of emissions entitlements among sources from any initial allocation of permits to the equilibrium. The number of sources that must take part in trading to achieve the least-cost pattern of emissions is consequently the same under both systems. The difference is in the number of individual transactions that are needed to reach the equilibrium solution. Under APS, one source can find itself purchasing (and, conceivably, at the same time selling) ambient permits from (to) another source such that the number of separate transactions between the two sources can be as many as the number of different receptor points for which their transfer coefficients are both nonzero. Note that each transaction will involve the transfer of ambient permits designated in terms of a particular receptor and will have its own price per permit. In contrast, under the pollution-offset system, all these separate transactions can, in principle, be effected through a single transfer of emissions permits between the two sources.[20]

The pollution-offset system thus offers compelling advantages both to sources and to the administering agency for regulating air quality where the spatial element is important. In particular, the offset system meets practical criteria that enable an environmental agency to use it in all circumstances including those in which the APS system becomes unworkable because it requires the environmental agency to monitor sources' impacts on pollution at a specific set of locations and either to ignore pollution levels at other locations or to institutionalize a very large number of receptors. In contrast, the offset system allows the environmental agency the flexibility to consider pollution levels at any and all locations when evaluating an emissions trade. At the same time, it promises significant savings in transactions costs for sources.

[20] More specifically, consider a proposed increase in emissions from one source in the air shed. Suppose that relative to the initial emissions vector, the new equilibrium (least-cost) outcome entails changes in emissions levels for m_k sources (where m_k is a subset of the m sources in the air shed). Then under the pollution-offset system, the maximum number of transactions (two-party trades) required to attain the new equilibrium is $\binom{m_k}{2} = (m_k(m_k - 1))/2$. Under APS, the required number of transactions could be as many as n times this quantity: $n\binom{m_k}{2}$, where n is the number of receptor markets where trades are necessary.

In a dynamic framework with imperfect knowledge, things can admittedly become more complicated. Initial trades among some parties may generate opportunities for further profitable trades among others. There would result some kind of iterative process until the potential gains-from-trade were exhausted. This, incidentally, would be the case both for the APS and pollution-offset systems.

V. TOWARD IMPLEMENTATION

We have described in a fairly general way a model of a pollution-offset system under which polluting firms trade emission permits subject to the constraint of no violations of the ambient air-quality standards at any receptor point. And we have demonstrated the efficiency properties of this system: we found that potential gains-from-trade exist for any vector of emissions other than the least-cost one.[21]

We have not, however, been very specific about the market structure or institutions under which such trading of permits would take place. In fact, over the past several years the Environmental Protection Agency (EPA) has been in the process of introducing regulatory reforms that bear a close resemblance to our pollution-offset scheme [12]. Under the rubric of Emissions Trading, the EPA has assembled a set of provisions to facilitate the trading of emission permits: the "Bubble, Offset, and Banking" provisions. With the Bubble, existing firms were initially permitted to make intraplant "swaps" of emissions of a particular pollutant to effect savings in abatement costs; the Bubble provision has subsequently been extended to encompass emission swaps across existing plants and even across existing firms so long as air pollution is not made worse. In a similar spirit, the EPA Offset provision requires that new sources of emissions in nonattainment areas obtain offsets from existing sources for their "net" emissions (i.e., those remaining after the installation of required technologies). In addition, under Banking, firms can accumulate credit for emissions reductions beyond those required in the State Implementation Plan.

We emphasize, however, that while the framework created under the Emissions Trading policy establishes the potential for creating systems that could realize much of the cost savings, each state must specify the exact form of its Emissions Trading system. Emissions Trading defines only a legal framework, not a fully specified system.[22] And it is on the details of the design and implementation of these systems by the states that the success of the program will largely depend. In addition, certain statutory provisions under the Clean Air Act and additional regulatory requirements prevent the realization of all the potential cost savings, even if the states were to resolve fully any problems of implementation. For example, the New Source Performance Standards that require new sources to adopt specific abatement technologies, or the regulatory stipulation that "reasonable further progress" be measured by reductions in emissions rather than in pollutant concentrations, are serious impediments to the efforts to achieve our environmental standards at lower costs.

Although formidable obstacles remain to the ultimate introduction of efficient systems of marketable permits, it is reassuring to find that EPA has adopted, in principle, what we see as the most promising approach to the design of such systems. To cite one specific case, a proposed system of this type is currently under consideration in the State of Maryland. Under the Maryland version of Emissions Trading, a polluting firm would propose a package of emissions reductions by

[21]Allan Gruchy [4] has recently proposed yet another conceptual alternative to Montgomery's system of "emission licenses." Gruchy's scheme effectively makes the initial allocation of rights endogenous; each polluter, in a sense, defines his own rights in the course of determining his level of emissions. Gruchy shows that his version of the emission-license system, in contrast to Montgomery's, generates the least-cost solution. While the Gruchy system is thus of considerable interest at a conceptual level, we have been unable to translate it into a workable proposal for a system of marketable pollution rights.

[22]Van De Verg and Frucht [13] examine some of the pitfalls which states may encounter as they prepare Emission Trading regulations.

existing polluters (for which it presumably makes payment to the latter) and an increase in its own emissions subject to the restriction that the resulting pattern of pollutant concentrations does not violate the air-quality standards at any receptor point. Such a system promises to encourage an efficient pattern of emissions consistent with the attainment of air quality standards and to do so with relatively modest transactions costs.

VI. CONCLUDING REMARKS

The preceding sections have explored a wide range of issues concerning the design and administration of systems of tradeable emission permits. From this discussion, we emerge with a proposed design for a system of pollution offsets for which we have been able to demonstrate its capacity for realizing the least-cost pattern of abatement activity; at the same time, the system promises to make relatively modest transaction demands on both sources and the administering agency. We have found, moreover, that the EPA has established the framework for introducing such systems under its Emission Trading strategy for the control of air pollution. However, as we have noted, a number of changes need to be made in the Clean Air Act and in existing regulatory procedures before the potential cost savings from a market-oriented approach to the management of air quality can be fully realized.

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REFERENCES

1. R. Anderson *et al.*, "An Analysis of Alternative Policies for Attaining and Maintaining a Short-Term NO_2 Standard," Math–Tech, Inc., Princeton, N.J. (Sept. 17, 1979).
2. S. Atkinson and D. Lewis, A cost-effectiveness analysis of alternative air quality control strategies, *J. Environ. Econ. Manag.* **1**, 237–250 (1974).
3. J. W. Eheart, Cost-effectiveness of transferable discharge permits for the control of BOD discharges, unpublished paper (1980).
4. A. Gruchy, Market systems for pollution control—Another view, unpublished paper (1980).
5. R. Hahn and R. Noll, Designing a market for tradable emissions permits, unpublished paper (April 1981).
6. A. Krupnick, "Simulating Alternative Policies for Controlling NO_x Emissions," draft report for the Department of Economic and Community Development, State of Maryland (July 1981).
7. W. D. Montgomery, Artificial markets and the theory of games, *Public Choice* **18**, 25–40 (1974).
8. W. D. Montgomery, Markets in licenses and efficient pollution control programs, *J. Econ. Theory* **5**, 395–418 (1972).
9. C. Russell, The Delaware model in the Sloan project: Alternative instruments and model structure, unpublished paper (March 1980).
10. T. Tietenberg, Transferable discharge permits and the control of stationary source air pollution: A survey and synthesis, *Land Econ.* **56**, 391–416 (1980).
11. U.S. Environmental Protection Agency, An analysis of market incentives to control stationary source NO_x emissions, unpublished paper (October 1980).
12. U.S. Environmental Protection Agency, Emission trading policy statement, *Fed. Regis.* **47** (67), 15076–15086 (April 7, 1982).
13. E. Van De Verg and P. Frucht, On trying to be first: Maryland's efforts to implement EPA's "Controlled Trading" policy, unpublished paper (June 1981).