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A METHODOLOGY FOR REGIONAL ECONOMIC ANALYSIS OF URBAN REFUSE AS AN ENERGY SOURCE FOR THE NORTHEAST

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A METHODOLOGY FOR REGIONAL ECONOMIC ANALYSIS OF URBAN REFUSE AS AN ENERGY SOURCE FOR THE NORTHEAST*

Peter M. Meier and Tien Le

I. INTRODUCTION

Although the natural regional scale of many energy planning problems is by now well recognized, a number of problems still beset the application of the methods of regional analysis to energy planning and the implementation of coherent regional policy. Even at the national level, energy policy analysis encompasses a unique blend of economic, technological and environmental considerations, for which analytical tools are still in their infancy; and the addition of the spatial dimension essential to the regional perspective poses even greater conceptual and computational problems. Moreover, although the development of regional institutions focussed on energy policy implementation is still in the formative stages, the recognition of the importance of coherent regional energy policy-making has, over the past few years, led to the emergence of several increasingly active bodies in this field such as the New England Regional Commission, the Association of Rocky Mountain States, and the Western Governors Regional Energy Policy Office [24].

A case of point is the question of the potential contribution of municipal refuse as an energy source, a question obviously closely related to the spatial distribution and characteristics of population, and the cost of alternative fuels. Equally obvious is the fact that simplistic calculations that assume all municipal refuse to be potentially available for energy conversion, ignoring economic realitites, is useful only as an indication of upper bound. Preferable would be a methodology that integrates population, interregional fuel price variations, and other engineering variables into a single model that can be subjected to sensitivity analysis helpful to the policy maker. The objective of this paper is to develop such a framework in the context of the Northeast States.[1]

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[1]New England, New York, New Jersey, Pennsylvania, Maryland, Delaware, and the District of Columbia.

A number of methodological issues emerged very early in our analysis. Whilst there is a wealth of material on the use of refuse as an energy source from the national perspective, [25,11,9] and any number of detailed engineering studies for particular metropolitan applications [27,29] many of the variables central to the analysis of policy trade-offs at the regional scale are not readily incorporated into traditional engineering methodologies. For example, even in the face of strong regulatory postures of federal energy agencies in matters of energy allocation and energy costs, one of the key issues concerns intra- and inter-regional fuel price differentials, an issue that can be captured only to the extent that the methodology itself has a spatial dimension. An appropriate approach seemed to be one based on the application of a generalized model of urban structure that captures the necessary compromise between detailed enginering feasibility studies on the one hand, and regional scale models on the other. Thus, in addition to a resolution of the energy policy issue itself, the purpose of this paper is to illustrate the extension of analytical and empirical models and methods developed in urban geography and regional science over the past decade to their prescriptive application to energy policy analysis.

2. SOME CONCEPTUAL AND PRACTICAL PROBLEMS OF PRACTICAL REGIONAL ANALYSIS

The two extremes of the specturm of analytical approaches are readily disposed of. At the one extreme, one might attempt to perform detailed engineering-economic analysis for every SMSA in the region, aggregating to an appropriate regional total. The difficulty here is primarily logistic, since the resources likely to be allocated to the type of policy question considered in these pages obviously precludes such an effort. Moreover, even given the circumstance that one might build on those studies that already exist, inspection of even a very small sample of detailed studies will likely show great divergence of analytical methods and standards of data collection, resulting in substantial difficulty, therefore, in cross-comparisons. At the other extreme stands the case study approach, in which one seeks to analyze in detail some "representative" sample of cases, followed by a suitable aggregation procedure. Unfortunately the spatial differentiaion of economic and demographic variables makes such an aggregation very difficult without explicit consideration and quantification of intra-regional spatial trends, and the expedient of simply working with average regional values, and regional totals, proved to yield little of any value for policy analysis (athough useful as an order of magnitude check).

One approach to the aggregation problem was developed by Isard et al. [12] in a comparitive analysis of nuclear energy centers with their dispersed sited counterparts: to avoid detailed analysis of the substantial number of dispersed sites, these were grouped into "surrogate" categories, based on common demographic-social and economic criteria. The results of multiplier analysis conducted for each of the surrogate categories were then readily aggregated to yield the desired comparisons. This line of attack, however, was not deemed appropriate to our problem, largely as a result of the difficulties of a surrogate classification of urban energy systems.

The approach finally selected was indeed to identify all SMSA's and non-SMSA urban areas in excess of 25,000 population in the Northeast, but than use a common model of urban population structure, and derive regional totals by sumation. Use of matrix algebra makes such an approach not unusally formidable from a computable viewpoint, and the issue of aggregation is inherently solved. There were, to be sure, some computational difficulties in model parameter estimation for the 78 subregions (SMSA's, urban areas) included (see Section 7, below), but the model, once operational, allowed examination of important policy issues associated with land use and intra-regional price differentials at low cost.

The problem of data, too, is especially difficult in the solid waste field, as there is no comprehensive national-regional data base of adequate detail and reliability for even the most basic variables in a study of this kind--the per capita generation of residential refuse as a function of socioeconomic characteristic. To be sure, numerous studies and estimates exist for individual towns and cities,[2] but quantitative comparisons are made difficult by the significant variations in reporting guidelines. For an estimate of solid waste generation to be acceptable, it must include specific information about the following items, among others: the extent of garbage grinding in homes; whether bulky wastes are collected separately and whether they are included in the total; what fraction of commercial refuse is included in the total; and whether, if garbage is collected separately, it is included

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[2]See, for example [5], a study relating refuse generation to socioeconomic variables in the Chicago area, or [9], focussed on Cincinnati. The problem from the perspective of a regional scale analysis, however, is the absence of a synthesis of these individual studies and the consequent lack of a consistent data base at the appropriate scale.

in the total (frequently it is not because its collection is privately contracted for delivery to piggeries, especially in the Northeast).[3] Yet such detail is all too often absent.

3. URBAN REFUSE AS AN ENERGY SOURCE

The energy accounting framework developed at Brookhaven for policy analysis and technology assessment is illustrated on Figure 1; termed a Reference Energy System, it portrays all of the elements of an energy system in terms of Btu flows.[1,3] Energy flows are indicated in 10^{12} Btu above each element, with conversion efficiencies indicated in parentheses. Energy from refuse might enter into the regional energy system in a number of ways--as a substitute for coal at coal-fired electric generation stations (typically as a fuel supplement to about 20% by weight as envisaged for a number of base load plants in the Northeast); as a source of synthetic natural gas (SNG), either by anaerobic digestion or by gas pyrolysis process such as the Union Carbide Purox Process (demonstrated at Charleston, W. Virginia); or as a source of industrial process steam by way of incineration in Waterwall boilers (exemplified by the Saugus Massachusetts Energy Recovery facility that provides process heat to a nearby General Electric Manufacturing Plant).[4]

The energy yield of a given quantity of refuse will depend not only on the conversion technology (since these vary quite substantially in efficiency), but also on the refuse composition. As an illustration of the type of computation necessary, consider the following computation of the heat value of refuse, the parameter of interest for direct combustion in utility

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[3]Recognizing the inadequacies of the existing solid waste data base, the U.S. Environmental Protection Agency (EPA) commenced in 1973 a systematic scientific data collection effort for a stratified random sample of Standard Metropolitan Statistical Areas (SMSA), the intent being to create a national data resource on solid waste quantities, composition, collection, and disposal costs. Unfortunately, this program has had its funding difficulties, and the fruits of the data collection effort are not yet apparent. In any event, there are too few SMSA's in the Northeast in the EPA sample to provide the basis for a quantitative relationship focused on our study region.

[4]There are a number of other possibilities, such a Brayton Cycle Power Generation (in which the exhaust gases from refuse combustion are used directly to power a gas turbine), various hydrogeneration processes, and a variety of exotic bioconversion processes including acid hydrolysis to ethyl alcohol, enzymatic conversion to glucose, or conversion to yeast. None of these technologies, however, were considered to be sufficiently well developed to make a measurable contribution to energy supplies over the next 10-15 years.

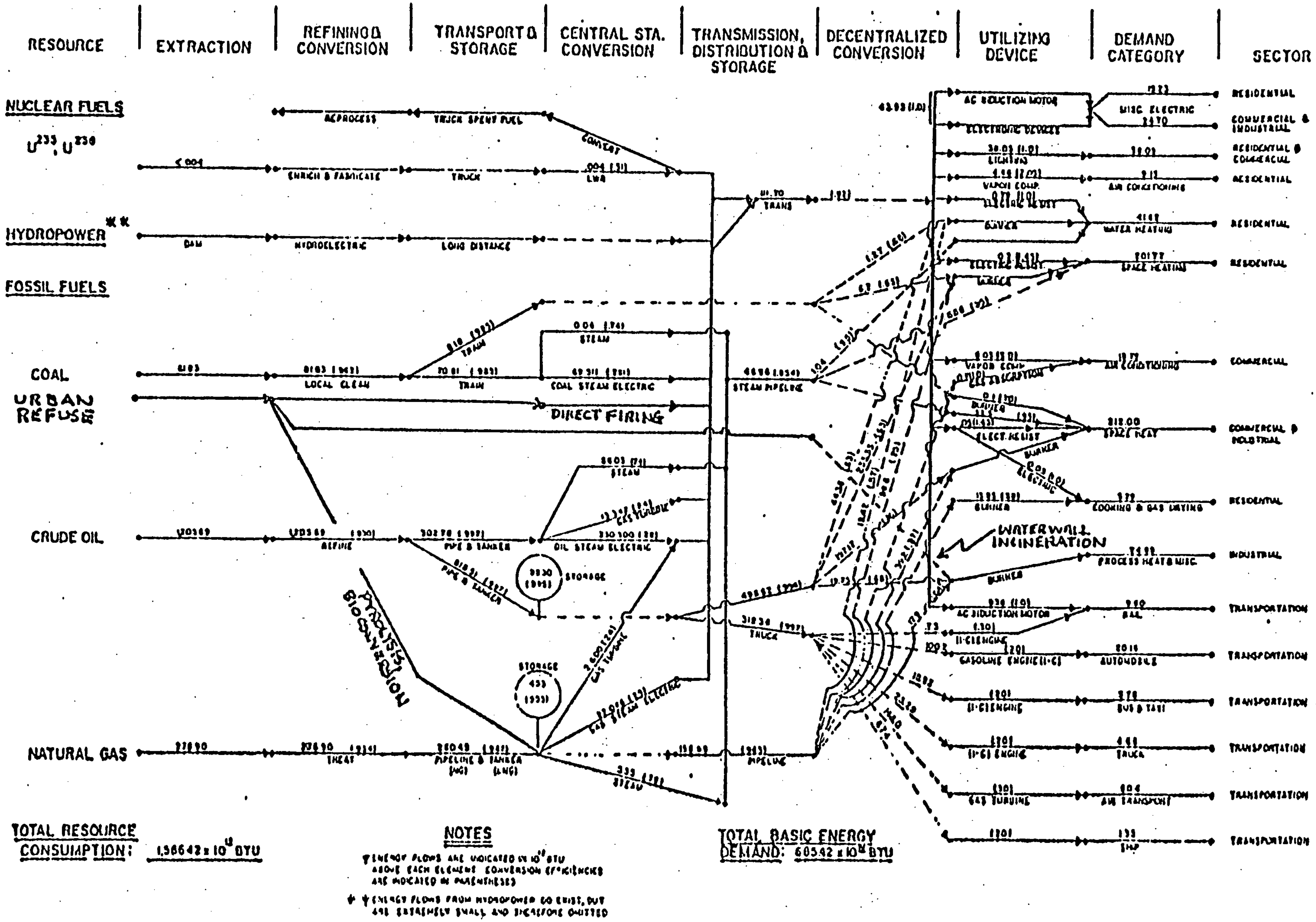

Figure 1: Reference Energy System for New York City, 1970 with refuse energy pathways superimposed.

boilers and waterwell incineration. Suppose C is an m x 1 vector representing the fractional composition of m refuse categories, and let W be a 1 x n vector whose elements represent the total quantity of refuse generated in each of n subregions.[5] Also, let T be an (m x k) matrix corresponding to the transforamtion from m refuse categores to k ultimate analysis categories. Then the matrix product

$$(1)\qquad \underset{(k\times m)}{T'} \times \underset{(m\times 1)}{C} \times \underset{(1\times n)}{W} = \underset{(k\times n)}{U}$$

represents the tons of k ultimate analysis categories generated in each of the n subregions per year. Table 1 shows the transforamtion matrix T and the base case refuse composition vector as used in our analysis. Then, armed with the ultimate analysis, one may apply an equation derived by Wilson [33] to obtain the heat value: using basic thermo-chemical principles and assuming complete combustion, the heat content, in Btu/lb, is given by

$$(2)\qquad 14096\ C + 64678\ H - 5950\ O + 1040\ N + 3982\ S$$

where C, H, O, N and S are the fractions of total carbon, oxygen, hydrogen, nitrogen and sulfur, respectively. However, due to the moisture in the refuse (in fact, one of the key parameters), this heat value will be reduced somewhat; if h_r is the heat vaporization of moisture, and H_2O the moisture content, then one must subtract $h_r H_2O$ from eq. (2). In matrix terms, the annual energy yield in each of n subregions, B_T, in 10^{12} Btu/yr, is given by

$$(3)\qquad \underset{(1\times n)}{B} = \frac{2000}{10^{12}} \underset{(1\times k)}{\gamma} \underset{(k\times m)}{T} \underset{(m\times 1)}{C} \underset{(1\times n)}{W}$$

where γ is the vector notation for Equation (2).

The results of this procedure, extended to other conversion technolgies, and summed over all in subregions, are shown on Table 2, which shows the potential contribution that municipal refuse could make to particular elements of the Northeastern Energy System on the assumption that <u>all</u> the refuse in the region were so utilized. Thus, for example, we note that refuse could have contributed, in 1972, 6.1% of the region's natural gas supply, <u>or</u> replaced 18% of the coal used for electric generation.

However, although it is highly unlikely that all refuse would be so converted, and even though the maximum contribution to the region's energy

[5]Subregional identities need to be preserved for reasons elaborated in Section 5, below.

TABLE 1

ASSUMPTIONS

ULTIMATE ANALYSIS CATEGORIES

C	Carbon
H	Hydrogen
O	Oxygen
N	Nitrogen
S	Sulfur
INRT	Inerts
H_2O	Moisture

ULTIMATE ANALYSIS TRANSFORMATION MATRIX (T)

	PAPR	GARB	GARD	PLST	METL	GLSS	OTHR	HSO
C	.4400	.4400	.4800	.4700	.0450	.0050	0.0000	0.0000
H	.0610	.0570	.0590	.0300	.0063	.0007	0.0000	0.0000
O	.4160	.2760	.4240	.2400	.0420	.0036	0.0000	0.0000
N	.0043	.0279	.0029	.0190	.0085	.0003	0.0000	0.0000
S	.0012	.0025	.0011	.0055	.0091	0.0000	0.0000	0.0000
INRT	.0765	.2187	.0289	.1970	.9040	.9902	1.0000	0.0000
H_2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
TOTAL	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Omega Victor (ω)

C	14096.0
H	64678.0
O	-5940.0
N	1040.0
S	3982.0
INRT	0.0
H_2O	-1120.0

TABLE 2

POTENTIAL ENERGY CONTRIBUTION: TO THE NORTHEAST U.S.

BASE YEAR 1972

Process	Efficiency	Potential Btu Yield 10^{12} Btu/year	Resource Replaced	1972 Resource Use 10^{12} Btu/year[a]	Potential Percentage Replacement Resource
Gas Pyrolysis	.55	161	Natural gas	2635	6.1
Bioconversion	.493	144			5.4
Oil Pyrolysis	.487	143	Fuel oil for steam electric	1630	8.7
Direct Firing	.272	80	Electricity	1239	6.4
	.85	250	Coal for steam electric	1335	18.7
Steam Generation	.73	214	Non-electric industrial process heat	1686	12.7

[a]From Lee [14]

supply is small, the potential contribution is of the same order of magnitude as some of the estimates of the more controversial regional resources, especially offshore oil and gas. Thus, from the point-of-view of policy analysis, the range of zero to six percent contribution to gas supply (corresponding to no refuse conversion, and utilization of the entire resource, respectively) is entirely inadequate, since that range of uncertainty would aid little in an evaluation of the necessity for the more controversial alternatives. Thus the injection of economic variables, the focus of the remaining sections of this analysis, was justified on the basis of providing the overall study with more useful information on which to analyze policy alternatives.

4. THE BREAKEVEN REFUSE PRICE

The central concept of the economic analysis used in our model is that of the breakeven refuse price. This is the price of refuse that an electric utility or private enterpreneur is willing to pay for refuse delivered to his facility, and is defined as that price for which the discounted present worth of annual returns equals the original investment:

$$\sum_{t=1}^{n} \left\{ \left[\left(S' - P_R \right) q_R(t) - O(t) \right] \frac{1}{(1 + i)^t} \right\} = I \tag{4}$$

where i = oportunity cost of capital

n = recovery period

$q_R(t)$ = quantity of refuse purchased in period t, tons/year

$P_R(t)$ = breakeven price of refuse in period t, \$/ton.

$O(t)$ = other operating costs in period t, \$/ton.

S' = revenue for sale of recovered energy, \$/ton.

I = necessary investment, \$

Note that P_R can also have a negative sign, which implies that a municipality would pay the entrepreneur for disposing of refuse, payments frequently referred to as tipping fees. Indeed, current conditions make this the likely situation; but provided that the tipping fee to the entrepreneur is less than that incurred by alternative means, say by incineration or remote landfill, even negative values would provide the necessary market incentives for conversion.

The capital cost I is of course a function of the facility size; if one assumes that the usual exponential rule adequately captures the available scale economies, i.e.

$$(5) \qquad I = C\left(q_R\right) = C\left(q_o\right)\left(\frac{q_R}{q_o}\right)^b$$

where C(q) is the investment cost at annual capacity q, b is the scale coefficient, typically around 0.7 for complete process facilities, and q_0 plant size for which a good engineering cost estimate $C(q_0)$ is available, then, under the additional constraints of constant capacity, say q_R, and constant P_R, rearrangement of (4) leads to

$$(6) \qquad P_R = S' - 0' - CRF(i,n)I_o'\left(\frac{q_R}{q_o}\right)^b$$

where CRF (i,n) is the capital recovery factor at interest rate i and time horizon n, 0' is the per ton operating cost and I_o' the per ton capital cost at a facility of capacity q_o tons/year. But S' is equal to the product of the energy P_E (say as 10^6 Btu per ton of refuse) and the market price of energy, e, ($/$10^6$ Btu), and hence P_R solves to

$$(7) \qquad P_R = P_E e - 0 - CRF(i,n)I_o'\left(\frac{q_R}{q_o}\right)^{b-1}$$

Applying this to the 4 major conversion technologies noted earlier for 1000 ton per day facilities, and assuming i = 10%, n = 20 years, the results of Figure 2 emerge: the fuel costs used here are as given by March 1979 data for delivered fuel costs at electric power plants under long term contract (spot prices are generally much higher, and more volatile). Decreases in interest rate, and increases in plant size, result in upward, parallel shifts in the indicated curves.

It should be noted that these curves are likely to show significant shifts through time: Figure 3, for example, uses the same derivation but with 1975 estimates of capital and operating costs, and indicates 1975 fuel cost ranges. With OPEC induced oil price increases, and the beginning of gas deregulation, these ranges have shifted to the right with time (compare Figure

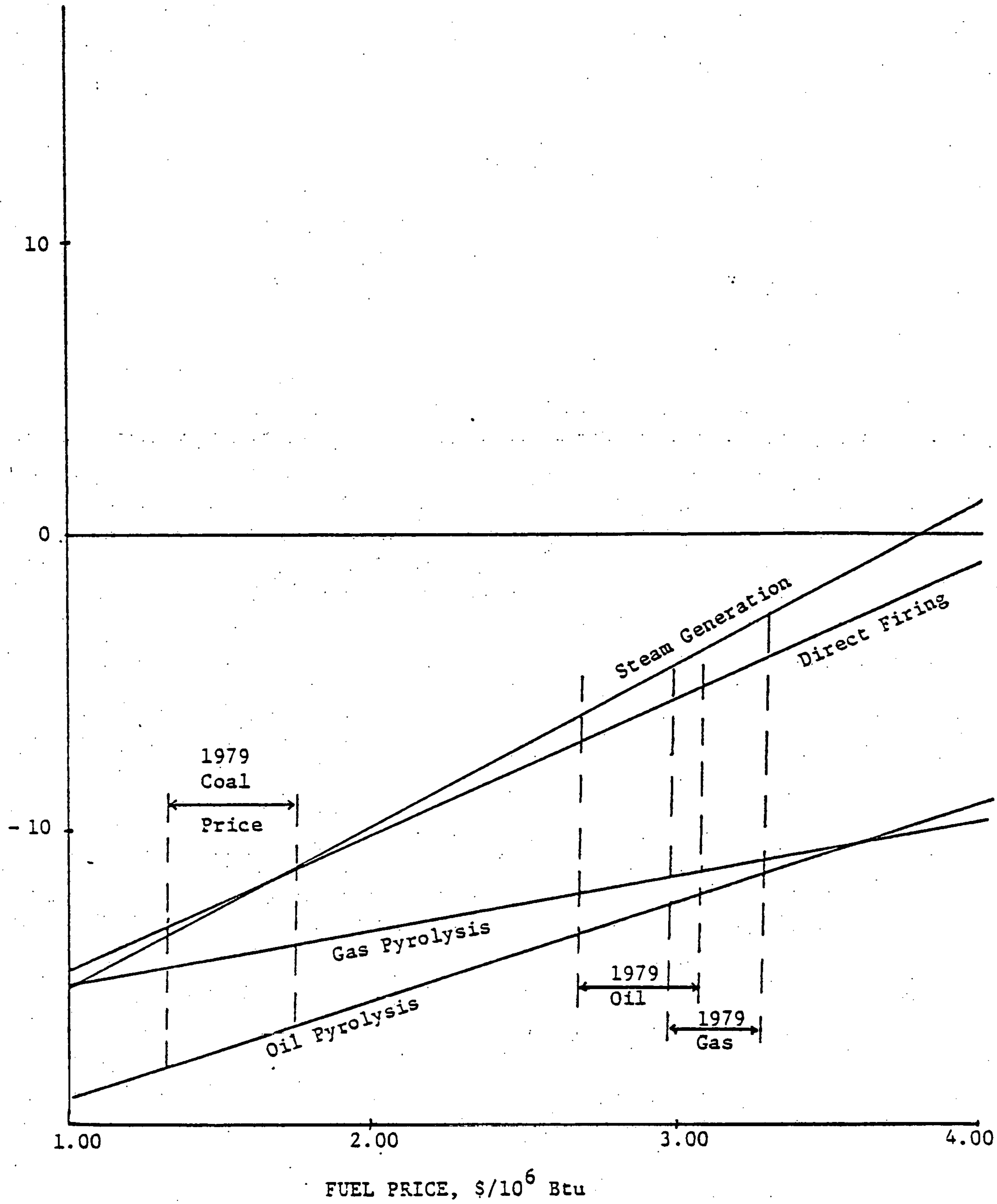

Figure 2: 1979 Breakeven Refuse Price Curve.

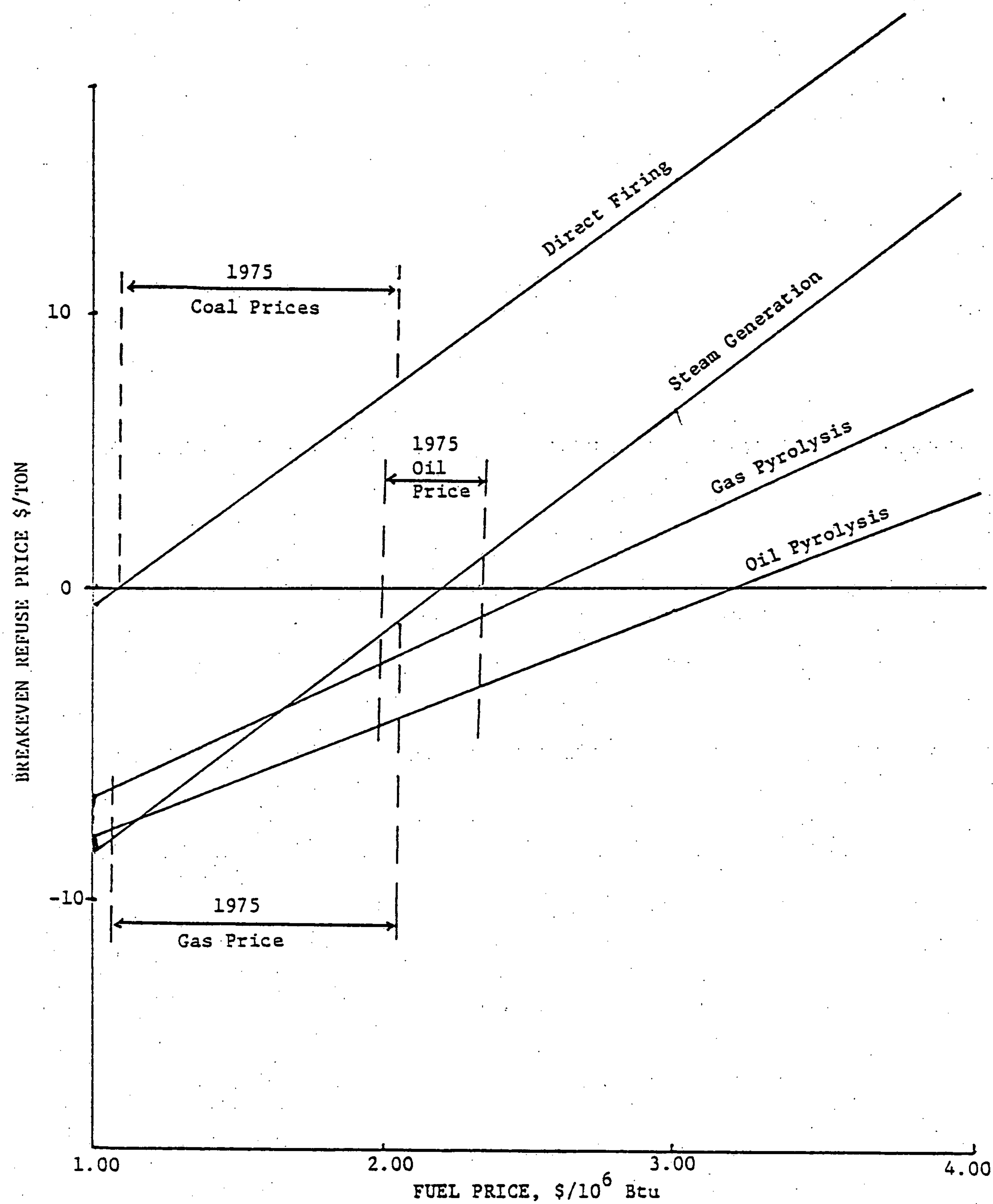

Figure 3: 1975 Breakeven Refuse Price Curves.

2 & 3)[6]. We note also a significant change in the y-intercept: the curves are lower in 1979 than 1975, reflecitng less optimistic estimates of capital costs now that several resource recovery facilities have actually been built: Figure 4, for example, compares the shift in the process cost curves for steam generation. These curves are readily interpreted for a given situation. Suppose, for example, that the cost of landfill disposal faced by a municipality were $5.00/ton, and suppose one were to consider the use of RDF fuel as a substitute for oil for steam generation: at the current range of oil prices, we see a breakeven refuse cost of between minus $4 to minus $6,implying a tipping fee of from 4 to 6$. It follows that if no additional transportation cost to the municipality to bring the refuse to the RDF facility is incurred, the tipping fee is about equal to the cost of alternative disposal, and the option would be economic. A haul cost of, say $5/ton, however, would in effect lower the RDF curve by that amount, bringing the curve below the alternative disposal cost, thus making the RDF alternative uneconomic (see Figure 4).[7]

5. REFUSE AS A SPATIALLY VARYING RESOURCE

The essence of the decision problem is the balance between breakeven refuse cost, haul cost to the energy conversion facility, and the alternative disposal cost to the municipality. Ceteribus Paribus, the greater the amount of refuse converted to energy at a single facility, the lower is the unit cost of processing. But, assuming a centrally located conversion facility, the greater the quanitity of refuse converted, the further from the center must one travel to obtain the necessary refuse, and thus the greater the transportation cost. Moreover, for every infinitesimal element of the urban continuum, breakeven refuse price minus haul cost must be less then the alternative disposal cost, given rational economic behavior. Thus, in a realistic

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[6]It is interesting to see that the range of gas prices encountered in the Northeast in 1979 is much narrower than the wide range of 1975.

[7]Much of the reasoning behind this approach to the problem was stimulated by correspondence in Science that dates back to 1974 and 1975, and particularly Roger Bolton's response to the article by J. Albert et al., Science 183, 1052. Albert el al. use the term "dump price" rather than tipping fee, or breakeven refuse price. It might be noted that the assumption of constant refuse quantities over time implied by the equations used here is not as unreasonable as may first appear, because agreements between entrepreneur and municipality typically span 15 to 25 years, guaranteeing supply arrangements and delivery price schedules over that interval.

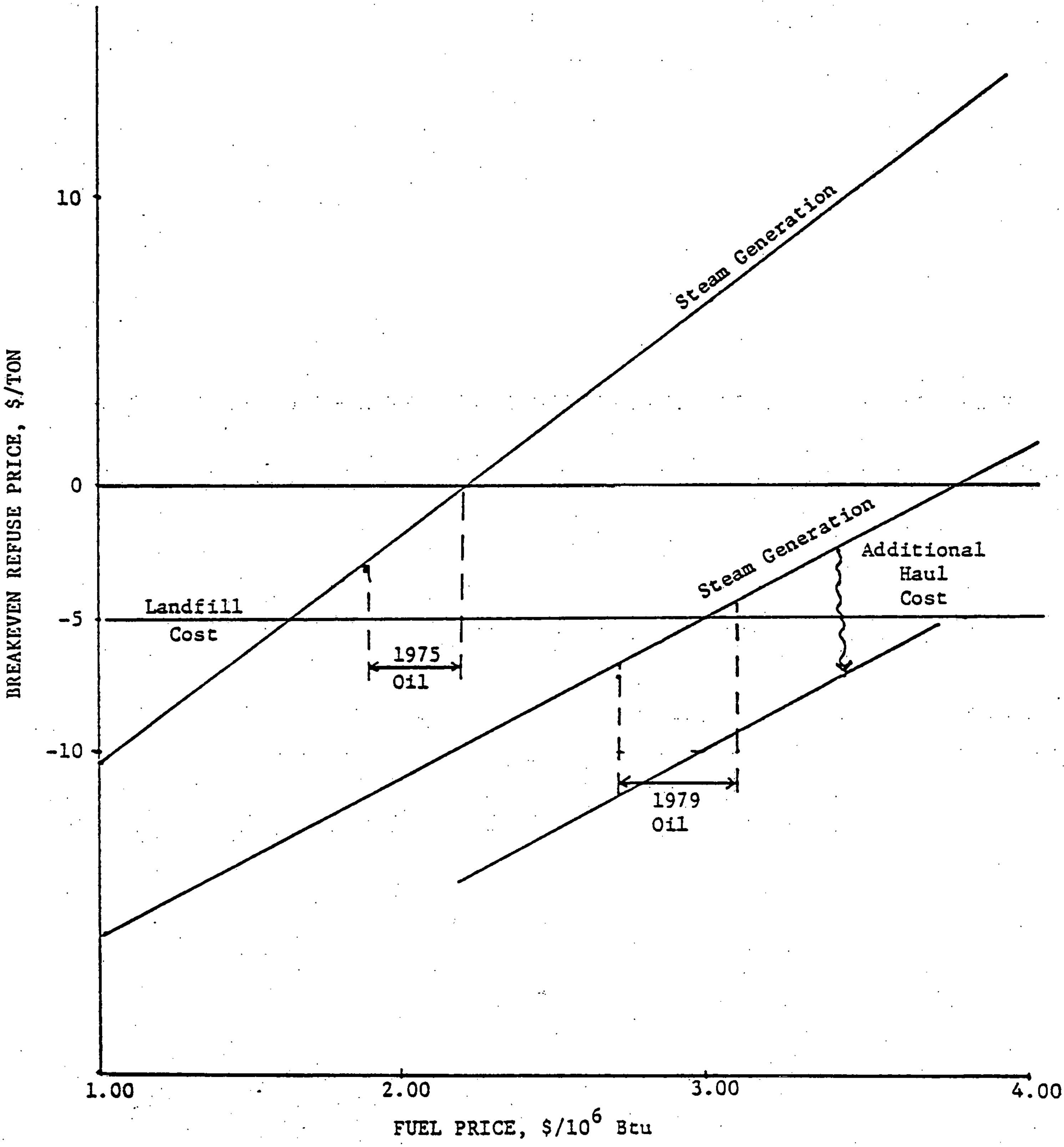

Figure 4: 1975 & 1979 Comparison for Steam Generation.

assessment of the extent of likely future refuse-to-energy conversion, the spatial distribution of refuse within each SMSA becomes as important as variations of refuse generation between SMSAs.

If one assumes constant per capita generation rate, then refuse generation per unit area will show the same spatial variation as population density. But population density in an urban area shows strong spatial variation, for which a widely used characterization is the classic formulation of Clark

$$d(r) = d_0\, e^{-\alpha r} \tag{8}$$

where d(r) is the population density at distance r from the city center, is the density gradient, and d_0 the extrapolated value of central density. It follows directly that if q is the per capita refuse generation rate, in pounds capita/day, the tons of refuse generated per unit area at distance r from the city center is

$$\frac{365}{1000}\, q d(r) = .1825 q d_0\, e^{-\alpha r} = a\, e^{-\alpha r} \tag{9}$$

It follows further that the quantity of refuse generated out to the distance R in the city of sector angle θ, Q(R), is given by

$$\begin{aligned} Q(R) &= \int^{R}\!\!\int^{\theta} a\, e^{-\alpha r} r\, dr\, d\theta = a\theta \int^{R} e^{-\alpha r} r\, dr \\ &= \frac{a\theta}{\alpha^2}\left[1 - (1 + \alpha R)\, e^{-\alpha R}\right] \end{aligned} \tag{10}$$

As a useful aside, what advantage is there to such a model formulation, as opposed to the use of an SMSA-wide average population density? If σ is the haul cost per ton per mile and R the SMSA radius then the assumption of constant density results in an average haul cost of $\frac{2}{3} R\sigma$ \$/ton for a conversion located at the city center. Elsewhere [19] we have shown that the assumption of the population density distribution (8) results in an average haul cost of

$$\sigma \frac{1}{\alpha}\; \frac{2 - \left(2\alpha R + \alpha^2 R^2\right) e^{-\alpha R}}{1 - (1 + \alpha R)\, e^{-\alpha R}} \tag{11}$$

For a typical SMSA of about 20 miles radius, with a typical α value of 0.3, use of (11) yields an average haul cost of 6.4 σ, as opposed to 14.4 σ yielded by the comparable constant average density assumption. Use of the constant average density assumption may thus typically introduce as much as a 50% error into the haul cost computation, and yields results biased against resource recovery, from which the additional complexity of the exponential model can indeed be seen to be worthwhile.

6. HAUL COSTS AND OPTIMAL RESOURCE UTILIZATION

Consider first the case of house-to-house refuse collection vehicles being driven directly to the energy conversion facility. Transportation costs of such vehicles are generally given in terms of $/hour to operate a truck of given capacity. If γ_h = cost, in $/hour, r = haul distance in miles, s = average truck speed, in miles/hour, and u = unloading time, in hours, then the haul cost per trip is

$$\gamma_h \left(\frac{2r}{s} + u\right) \tag{12}$$

and hence the cost per ton, as a function of haul distance, is

$$\frac{\gamma_h}{t} \left(\frac{2r}{s} + u\right) \tag{13}$$

where t is the truck capacity in tons.

With Eq. (9) used to obtain the refuse generation rate at distance r from the center, then the haul cost at that radius, c(r), is given by

$$\begin{aligned} c(r) &= \frac{\gamma_h}{t}\left(\frac{2r}{s} + u\right) q(r) \\ &= \frac{2\alpha\gamma_h}{ts}\, r\, e^{-\alpha r} + \frac{au\gamma_h}{t}\, e^{-\alpha r} \end{aligned} \tag{14}$$

Further, on the assumptions of a circular city of sector angle θ, and a conversion facility located at (or near) the city center, the total haul cost per year for the area within radius R, c(r), is given by[8]

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[8] θ describes the angle subtended by the city topology at its center: Chicago for example, has a θ value of about 180° (i.e., π radians), whereas the coastline of Boston Bay would prescribe an θ value of about 270°. In all of the above derivations, θ is of course in radians.

(15) $C(R) = \int^{\theta} \int^{R} c(r) r \, d\theta \, dr$

by further algebra omitted here, this integral can be shown to yield

$$C(R) = \frac{2a\theta\gamma_h}{ts\alpha^3}\left[2 - \left(2 + 2\alpha R + \alpha^2 R^2\right) e^{-\alpha R}\right] \quad (16)$$
$$+ \frac{au\theta\gamma_h}{t\alpha^2}\left[1 - (1 + \alpha R)\, e^{-\alpha R}\right]$$

Now consider the decision problem as to the service area of the conversion facility, expressed in terms of the distance from the central location to which haul and conversion still remains economic. Obviously, as the haul distance becomes greater, a point will be reached at which haul costs plus conversion costs minus alternative disposal costs exceed revenues from the sale of energy.

The total annual cost of refuse management y(R), if refuse is delivered within a radius R to a central conversion facility, is given by[9]

(17) $y(r) = - Q(R)P_R + \left[Q_T - Q(R)\right]P_D + C(R)$

where the first term represents revenue from energy conversion, the second the cost of disposing of the residual refuse (not delivered to the conversion facility) and the third the haul cost to the energy facility; and

$Q(R)$ = refuse converted to energy, tons/year
Q_T = total refuse in the region, tons/year
P_R = breakeven refuse price, \$/ton
P_D = alternative refuse disposal cost, \$/ton
$C(R)$ = cost of refuse delivery to conversion facility, \$/yr.

Since minimization of y is the objective, differentiating Eq. (17) with respect to R, setting and result to zero, and solving for R will yield the optimum distance (and hence, the amount of refuse optimally converted), i.e.,

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[9]This assumes that there is no haul cost for refuse beyond the radius R, an assumption that is justified on the basis of computational experience that shows R*, the optimum radius, to lie beyond the bounds of the central city, somewhere in the suburbs. In these areas, disposal is generally by individuals or private contractors to landfills there on an ad hoc basis; and since each suburb in the typically politically fragmented Northeast tends to have its own disposal site, such haul costs tend to be low.

$$\frac{dy(R)}{dR} = - P_R \frac{dQ(R)}{dR} + Q(R) \frac{dP_R}{dR} - P_D \frac{dQ(R)}{dR} + \frac{dC(R)}{dR} = 0$$

hence

(18) $$\left(P_R + P_D\right) \frac{dQ(R)}{dR} = Q(R) \frac{dP_R}{dR} + \frac{dC(R)}{dR}$$

but from (10)

(19) $$\frac{dQ(R)}{dR} = a\theta R\ e^{-\alpha R}$$

from (14)

(20) $$\frac{dC(R)}{dR} = a\theta R\ e^{-\alpha R} \left\{ \frac{u\gamma_h}{t} + \frac{2R\gamma_h}{ts} \right\}$$

and from (7)

(21) $$\frac{dP_R}{dR} = \frac{- CRF(i,n)I'_o}{q_o^{\beta-1}} (\beta - 1)Q(R)^{\beta-1} a\theta R\ e^{\alpha R}$$

Substituting these expressions into (18), and solving for the optimum radius R*, albeit omitting some algebra, yields

(22) $$R^* = \frac{ts}{2\gamma_h} \left\{ P_E \epsilon - 0' + \frac{CRF(i,n)I'_o}{q_o^{\beta-1}} \left[(\beta - 1)Q(R^*)^{\beta} - Q(R^*)^{\beta-1} \right] - \frac{u\gamma_h}{t} \right\}$$

which must be solved simultaneously with (10) to obtain the solution for the two variables of interest, R* and Q(R*). Since neither can be obtained explicitly, we must resort to numerical techniques; in this case, the Newton-Raphson algorithm proves to be the appropriate procedure. Simply by substituting (10) into (22), one obtains the desired value of R* by determination of the root of the resulting function.

The assumption that the refuse energy conversion facility be at (or near) the city center, however, is rarely satisfied. Inspection of a number of SMSA's, and some experimentation as to sensitivity of the results to assumptions, showed that two further situations needed explicit consideration--the case of an arbitrary location for the conversion facility (even, possibly, beyond the limits of the SMSA), and the case of a transfer station mode of refuse management, in which collection vehicles would deliver not directly to the conversion facility, but to some transfer station located

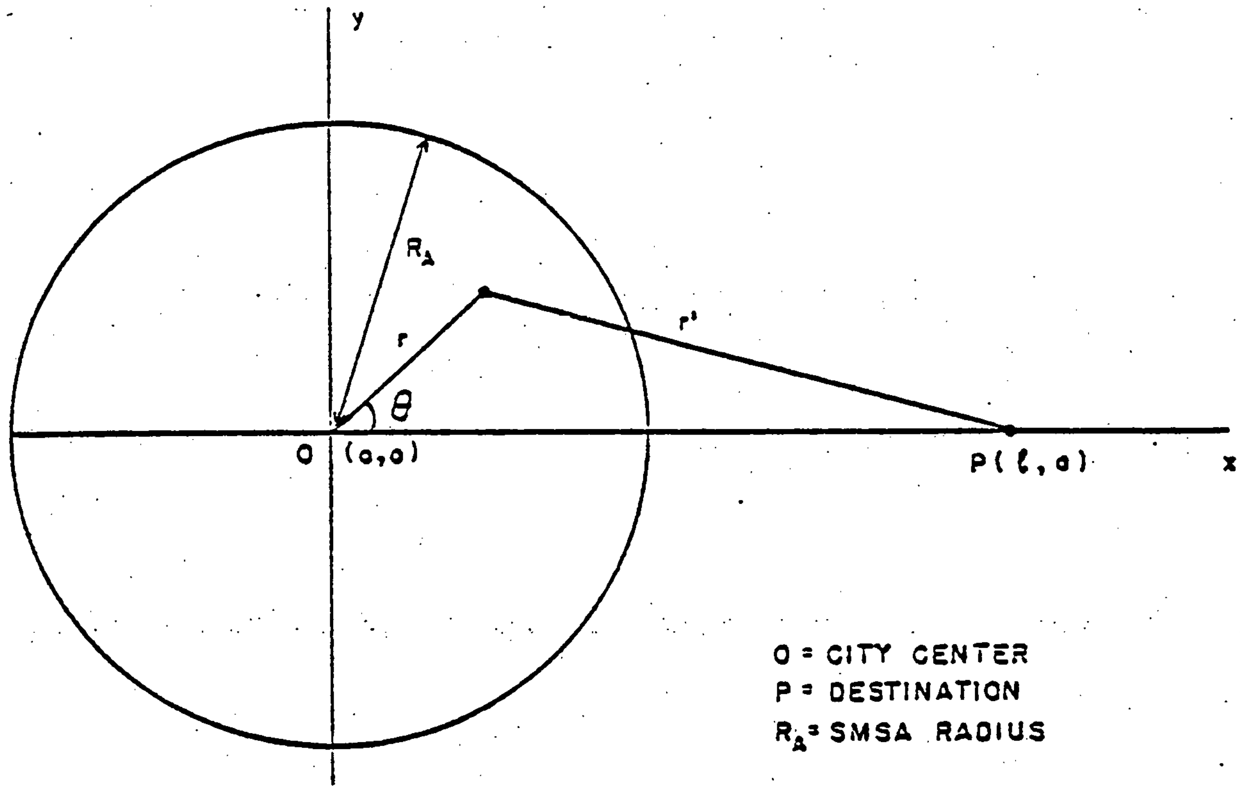

Figure 5: Definition Sketch: General Conversion Facility Location

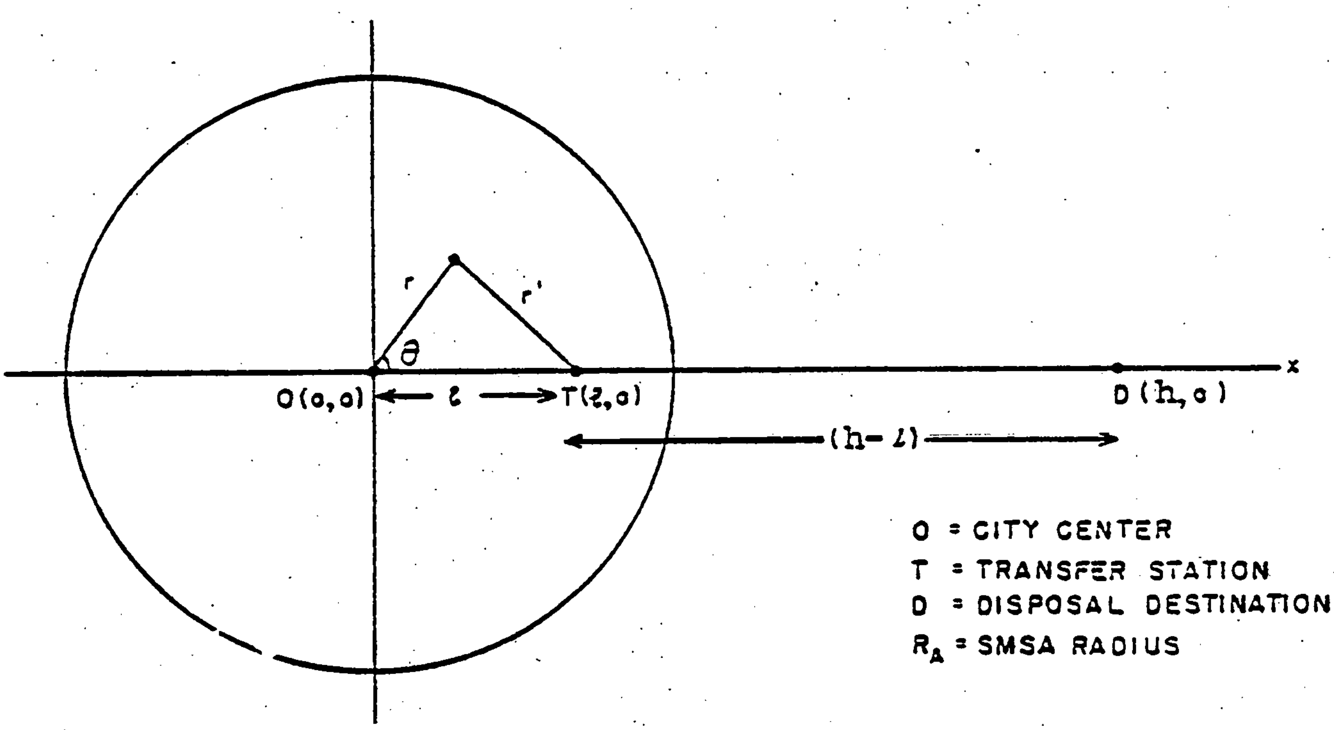

Figure 6: Definition Sketch: Transfer Station Case

within the SMSA, and subsequent haul from that transfer station by large tractor-trailers.[10]

Consider first a conversion facility located a distance from the city center (Figure 5). In this case the distance between the infinitesimal element and its destination is given by

$$(24) \qquad r'^2 = r^2 + \ell^2 - 2r\ell \cos\theta$$

and hence substituting into (13) gives the haul cost per unit area at (r,θ) as

$$(25) \qquad c(r,\theta) = \frac{\gamma_h}{t}\left[\frac{2}{s}\left(r^2 + \ell^2 - 2r\ell \cos\theta\right)^{1/2} + u\right] q(r)$$

The total average system haul cost is given by

$$(26) \qquad C_A(R) = \frac{\int_{r=0}^{R} \int_{\theta=0}^{2} c(r,\theta) r \, dr \, d\theta}{\int_{r=0}^{R} \int_{\theta=0}^{2} q(r) r \, dr \, d\theta}$$

which yields

$$(27) \qquad = \frac{2\gamma_h}{ts} \frac{\int_{r=0}^{R} \int_{\theta=0}^{2} \left(r^2 + \ell^2 - 2r\ell \cos\theta\right)^{1/2} q(r) r \, dr \, d\theta}{\int_{r=0}^{R} \int_{\theta=0}^{2} q(r) r \, dr \, d\theta} + \frac{\gamma_h}{t} u$$

After considerable but tedious algebra, again omitted here, we obtain, finally,

$$(28) \qquad = \frac{4\gamma_h \alpha^2}{\pi ts} \frac{\int_0^R r(r + \ell) \, e^{-\alpha r} E\left(\frac{2\sqrt{r\ell}}{r + \ell}\right) dr}{1 - (1 + \alpha R) \, e^{-\alpha R}} + \frac{\gamma_h}{t} u$$

where $E(x)$ is a complete alliptical integral of the second kind.[11] Note that for the special case $\ell = 0$, this reduces to Eq. (16), and that Eq. (28) is

---

[10]Haul by rail or by barge from transfer station to conversion facility was not considered on ground of it being applicable only in very special situations.

[11]An Elliptical integral of the second kind is defined as the general form

$$E(X) = \int_0^{\phi_0} \left(1 - x^2 \sin^2\phi\right)^{1/2} d\phi$$

if $\phi_0 = \pi/2$, $E(X)$ is called a complete elliptical integral (of the second kind).

valid for any ℓ, within or outside R_A.

As the distance from population center to haul destination increases, the cost of transporting refuse in the vehicle used for house-to-house collection increases. At some break-even distance, it becomes cheaper to build a transfer facility near the population center and to haul refuse from there to the disposal (or energy recovery) site in large tractor-trailers.

Such a system is diagrammed in Figure 6. Haul cost to the transfer station in collection vehicles is given by Eq. (28). To this must be added the haul cost from transfer station to disposal site, given by

$$(29) \qquad \frac{\gamma^*}{t^*}\left[\frac{2(h - \ell)}{s^*}\right] + u^*$$

where γ^* = cost, \$/hour
t^* = truck capacity, tons
s^* = speed, miles/hour
u^* = loading and unloading time, hours

This is analogous to Eq. (13), with the asterisk indicating reference to a transfer vehicle rather than a collection vehicle (note that u^* includes both loading and unloading time whereas u included only unloading time).

The capital cost of the transfer facility must also be considered. The cost of processing a ton of refuse at a transfer station, C_T, has been expressed as [15].

$$(30) \qquad C_T = b/T^m$$

where b and m are constants characteristic of the station design and construction costs, and T is the transfer station capacity in tons/day. If T is in the range 100 to 1500, then from [15], b = 33.4 and m = 0.55, and hence the average cost per ton for a transfer station serving a city of radius R is

$$(31) \qquad C_T = \frac{33.4}{[Q(R)/260]^{0.55}}$$

where Q(R), in tons/year, is given by Eq. (10) and 260 represents the number of working days per year. The total cost for delivering refuse to the transfer station, transferring it, and hauling it to the destination point is thus given by

$$(32) \qquad C_T(R) = \frac{4\gamma_h \alpha^2}{\pi t s} \cdot \frac{\int_0^R r(r + \ell)\, e^{-} \, r_E \left(\frac{2\sqrt{r\ell}}{r + \ell}\right) dr}{1 - (1 + \alpha R)\, e^{-\alpha R}} + \frac{\gamma_h}{t} u$$

$$+ \frac{\gamma^*}{t^*}\left[\frac{2(h - \ell)}{s^*}\right] + \frac{33.4}{\left\{\frac{a\theta}{260\alpha^2} \cdot \left[1 - (1 + \alpha R)\, e^{-\alpha R}\right]\right\}^{0.55}}$$

We are now in a position to determine the optimum radius R*, and hence the optimum quantity of municipal refuse converted to energy, for each SMSA and for each alternative conversion technology. For each SMSA we solve (17) for that R that yields the minimum total annual cost. Only in the special case of collection vehicle haul to a centrally located facility can one use the rather simple solution of the two simultaneous equations (10) and (22); where C(R) in Eq. (17) is given by (32), one has the additional search dimension for ℓ, and the additional suboptimization problem of whether or not to utilize transfer stations. This may, however, all be readily computed, and computation times for a run of 78 SMSA's required some 3 seconds of CDC 7600 CPU time, thus allowing extensive sensitivity analyses at not unreasonable cost.

7. COMPUTATIONAL ASPECTS OF THE EXPONENTIAL DENSITY MODEL

Before proceeding to a discussion of results, mention should be made of model parameter estimation problems. The traditional method of determination of the α and d_0 parameters of (8) from historical data rests on a linear regression estimation of the corresponding logarithmic version of (8), an approach exemplified by Treadway [30], Winsborough [34], Muth [23], Martin [16] and Guest [10]. Unfortunately, there are a number of statistical and computational difficulties inherent in this approach, difficulties that appear to have received little attention to date. The first, conceptual, problem concerns the issue of weighting values in statistical analysis of areal data; and, as predicted by Robinson's classic discussion [28], experimentation showed that regression estimates were indeed affected measureably by the weighting scheme chosen. The second difficulty concerns sampling variability; as indicated by Table 3, which compares estimates based on complete census tract samples with those based on limited samples, variability does indeed appear high. And, finally, there is the purely computational problem of

Table 3

COMPARISON OF α-ESTIMATES

City	Year	All Tracts	25 Tracts	50 Tracts
Akron	1960	.370[a]		.19
Columbus	1950	.548[b]	.190	.40
	1960	.421[b]		.32
Dayton	1950	.467[b]	.320	.51
	1960	.354[b]		.37
Hartford	1950	.800[b]		.70
	1960	.597[b]		.51
Miami	1950	.336[b]	.240	.32
	1960	.210[b]		.18
Milwaukee	1960	.359[a]		.10
Portland	1960	.087[a]		.16
Syracuse	1950	.494[b]	.92	.72
	1960	.437[b]		.46
Toledo	1960	.292[a]		.14

[a]from Martin [16]
[b]from Treadway [30]
[c]from Muth [23]
[d]from Guest [10]

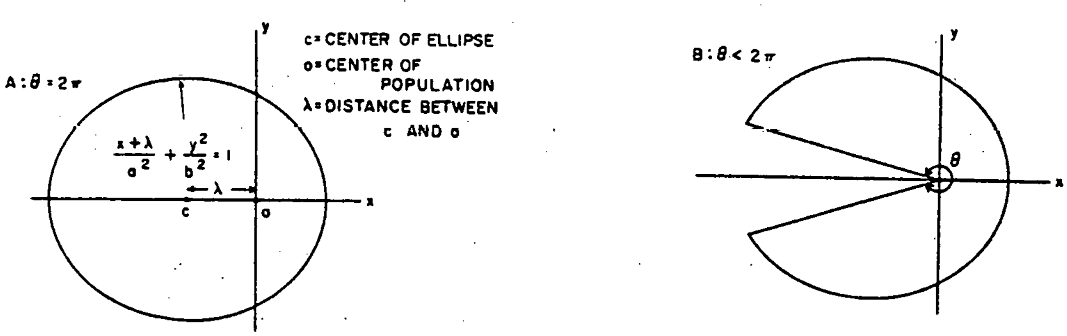

Figure 7: Definition Sketch: Elliptical SMSA

making census tract area[12] and distance determinations, especially, as in our case, when several hundred such estimates are required.

An alternative approach, suggested originally by Mills [21] and developed by Edmonston [8], rests on integration of (8) over appropriate spatial limits. For a circular city of sectoral angle θ, the integration of (8) to a distance R from the center can be shown to yield

$$(32)\qquad P(R) = \frac{\theta d_0}{\alpha^2}\left[1 - (1 + \alpha R)\, e^{-\alpha R}\right]$$

Applying (32) to, say, the entire SMSA, of average radius R_A, and known population $P(R_A)$, and the central city of radius R_C and population $R(R_C)$, results in two simultaneous equations in the two unknowns α and d_0, which, although no explicit solution exists, can be solved numerically; again it can be shown [19] that α is given by the root of

$$(33)\qquad f(\alpha) = \frac{P\left(R_C\right)\left|1 - \left(1 + \alpha R_A\right) e^{-\alpha R_A}\right|}{P\left(R_A\right)\left|1 - \left(1 + \alpha R_C\right) e^{-\alpha R_C}\right|} - 1 = 0$$

However, a difficulty in the Mills-Edmonston approach is the assumption of circular or near circular topology, and it was found that direct application of (33) to many of the elliptically shaped urban areas in the Northeast introduced substantial error. Consider, therefore, the general case of an elliptical SMSA (Figure 7). Any point on such an ellipse, in polar coordinates (ϕ, R), is given by the equation[13]

$$(34)\qquad \frac{1}{a^2}(R\cos\phi + \lambda)^2 + \frac{1}{b^2}(R\sin\phi)^2 = 1$$

which may be solved for R to yield

$$(35)\qquad R = \frac{-\frac{\lambda}{a^2}\cos\phi + \sqrt{\frac{1}{a^2}\cos^2\phi + \frac{1}{b^2}\left(1 - \frac{\lambda^2}{a^2}\sin^2\phi\right)}}{\frac{1}{a^2}\cos^2\phi + \frac{1}{b^2}\sin^2}$$

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[12] Census tract areas are not in the commonly available published statistics. There are some proprietory data basis, but these are expensive to use; and U.S. Bureau of the Census Computer Packages require very sophisticated software. The most common method reported in the literature (even the most recent) is a manual determination using tracing graph paper [30,17].

[13] This approach is discussed in some detail in [18].

denoted by $R(\phi)$. Thus the SMSA population is given by the integral

$$(36) \qquad P_{SMSA} = \int_0^{\pi} \int_0^{R(\phi)} d_0 \, e^{-\alpha r} r \, dr \, d\phi$$

which can be shown to yield

$$(37) \qquad = \frac{\theta d_0}{\alpha^2} - \frac{2d_0}{\alpha^2} \int_0^{\theta/2} [1 + \alpha R(\phi)] \, e^{\alpha R(\phi)} \, d\phi$$

defining an analogous expression for the central city, α is then given by the root of

$$(38) \qquad f(\alpha) = \frac{P_C \left\{ \theta - 2 \int_0^{\theta/2} \left[1 + \alpha R_A(\phi)\right] e^{-\alpha R_A(\phi)} \, d\phi \right\}}{P_A \left\{ \theta - 2 \int_0^{\theta/2} \left[1 + \alpha R_C(\phi)\right] e^{-\alpha R_C(\phi)} \, d\phi \right\}} - 1 = 0$$

which is readily obtained by the Newton-Raphson technique. The differences between (33) and (38) and α and d_0 estimates are illustrated on Table 4. Note that in the special case of circularity in both SMSA and central city, (38) reduces to (32).

Table 4

THE EFFECT OF ESTIMATING TECHNIQUE

	1970 α-Estimate		1970 d_0 - Estimate (in 1000's)	
SMSA	Eq. (31)	Eq. (36)	Eq. (31)	Eq. (36)
Altoona	.65	.70	18.28	18.28
Lancaster	.36	.56	13.13	13.04
Manchester	.93	.83	15.21	12.96
Newark	.21	.19	27.28	26.00
Norwalk	.50	.43	11.23	9.76
Scranton	.37	.41	10.13	8.40
Ultica-Rome	.19	.26	3.89	3.74
Wilmington	.25	.24	9.87	8.57

Using this technique for all of the 69 SMSA's and urban areas in the Northeast allowed a rapid estimation of model parameters for both 1960 and 1970, avoiding the tedium of numerous regression computations for complete census tract sets.

8. SOME RESULTS

All of the above mathematics has been integrated into a single computer program, and Table 5 is an extract from the output listing, showing, for the case of direct firing in a coal boiler with landfill as the alternative disposal method, the optimum radii R*, the SMSA radius R-SMSA, the central city radius R-CC, and the breakeven refuse price P_E.

In making projections for future refuse energy conversions, it should be clear that one must consider future values of α and d_0. In the Northeast, where many SMSA' are already contiguous and without much scope for further territorial expansion, an assumption of constant SMSA area seems not unreasonable. But given this assumption, it is clear that population growth in our model can only be accomodated by adjustment in the α and d_0 parameters, an argument well developed by Winsborough [34]. Two specific cases were examined in detail; one assuming a continuation of current urban sprawl trends, in which we extrapolate the 1960-1970 trend for α (in most cases, of course, implying continuing decrease in α value), and then, using

TABLE 5

OPTIMUM RADIUS FOR ALTERNATIVE DISPOSAL AT $5.00/TON

(Direct Firing in Utility Boilers, PE-Coal Price, $/ton)

SMSA	R*	R-SMSA	P-CC	PR
Albany	20.5*	26.6	3.6	3.3
Allentown	14.6*	18.6	3.7	1.2
Altoona	14.6	13.0	1.7	1.2
Atlantic City	33.1	19.0	2.8	8.0
Baltimore	30.1*	35.1	6.5	6.9
Binghampton	20.5*	25.7	1.9	3.3
Boston	24.4	19.9	4.3	4.8
Bridgeport	24.4	11.1	2.3	4.8
Bristol	24.4	4.0	2.9	4.8
Brockton	24.4	7.2	2.6	4.8
Buffalo	10.5*	26.0	4.2	3.3
Erie	24.6*	22.8	2.5	1.2

denotes R < R-SMSA, implying that only part of the SMSA refuse would be economically converted.

Haul Cost Parameters

Truck size, tons (t)	=	5.50
Unload time, hr (u)	=	0.25
Average speed mph (s)	=	20.00
Optimum cost, $/hr ($\gamma_h$)	=	20.00

the OBERS projection for total SMSA population, solve for d_0, by substitution in (30); this will result in generally decreasing d_0 values also, As an alternative, we also considered a postulated revitalization of city centers, in which we keep constant the d_0 value, and then solved for α again by substitution (30). α values still decline somewhat, but much less so than in the urban sprawl case; and of course α must be sought again by numerical means as (30) does not allow explicit derivation of α.

The results of this analysis not unexpectedly indicated that by 2000, the revitalization case yielded increases over the sprawl case in potentially recoverable energy by as much as 15%. However, many of the smaller SMSAs show little or no increase with this scenario,[14] whereas the larger SMSAs show a much higher increase.[15] The reason is that in the smaller SMSAs, all or most of the refuse would be economically hauled to the central facility, even in the base case, whereas in the larger ones, the optimal collection radius does not encompass the entire population and hence concentration of the population results in a greater proportion of the total refuse being economically recoverable. Thus we note yet a further energy benefit to limiting current suburban expansion - in addition to the usually cited gains to transportation energy savings or waste heat utilization/district heating potential.

Several other sensitivity analyses were performed details of which are noted elsewhere [20]. The most important results however, do bear mention here: Table 6, for example, shows an analysis of the total regional contribution to electricity demands as a function of different load growth scenarios (derived in [18]) and different assumptions for refuse generation rate. The low case is based on no increase in current rates; the median case on a constant 1.5% annual growth rate in accordance with trends in non-durable goods consumption [9]; and the high case by application of a regression equation prediction, reflecting current trends. Another analysis showed remarkably little sensitivity to refuse composition, with the predominant variation in Btu yield due to population growth and per capita generation levels.

[14] Reading, Scranton and Waterbury, for example, show increases of 1.78, 4.0 and 0.6% respectively.

[15] New York and Boston, for example, show increases of 29 and 44%, respectively.

Table 6

PERCENTAGE OF REGIONAL ELECTRIC DEMAND POTENTIALLY CONTRIBUTED BY REFUSE

		1985 Electricity Demand		
		Low (480×10^6 Mwh)	Median (555×10^6 Mwh)	High (638×10^6 Mwh)
1985 Refuse Generation	Low (28.5×10^6 tons)	5.9%	5.1%	4.5%
	Median (33.1×10^6 tons)	6.9%	5.9%	5.2%
	High (38.9×10^6 tons)	8.1%	7.0%	6.0%

		2000 Electricity Demand		
		Low (681×10^6 Mwh)	Median (900×10^6 Mwh)	High (1158×10^6 Mwh
2000 Refuse Generation	Low (36.0×10^6 tons)	5.2%	4.0%	3.1%
	Median (52.0×10^6 tons)	7.6%	5.7%	4.5%
	High (90.7×10^6 tons)	13.3%	10.1%	7.8%

9. CONCLUSIONS

Despite a recent resurgence of analysis on the validity of the negative exponential model of urban population density [13, 17, 26] and despite Dacey's fears that extensions of the negative exponential model might lead to intractable analytical formulations [6], use of this model in an energy policy analysis context appears appropriate, useful and not unduely complex. To be sure, the reasons for successful application are practical rather than theoretical (and we have no argument with those who question the exponential model on theoretical grounds); but in policy analysis studies, necessarily involving the participation of non-technical decision makers, clarity of assumptions and plausibility of models are important factors to be considered in the selection of an analytical approach.

As to the substantive findings, there can be little doubt as to the merit of exploiting the energy in refuse in the heavily urbanized Northeast. Recent setbacks to implementation of refuse energy projects are due almost entirely to institutional obstacles, amenable to resolution given appropriate planning and political leadership, rather a result of technical difficulties. Moreover, the precarious Northeastern supply situation mandates a comprehensive energy policy based on a synthesis of many options, each of which by themselves would make only a marginal contribution, but which together could make the difference between serious shortages (and all that that portends for an already declining industrial base) and tolerable balance.

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