AN INITIAL FRAMEWORK FOR DESCRIPTION OF REGIONAL POLLUTION EMISSIONS IN THE IIASA INTEGRATED ENERGY SYSTEM RESEARCH PROGRAM

R. Dennis and K. Ito

June 1975 WP-75-61

This informal working paper is one of a series describing an IIASA research program on Integrated Energy System Modelling and Policy Analysis. Papers in the series are:

(1) Foell, W.K. "Integrated Energy System Modelling and Policy Analysis: A Description of an IIASA Research Program" IIASA Working Paper WP-75-38, April 1975.

(2) Dennis, R.L. and Ito, K. "An Initial Framework for Describing Regional Pollution Emissions in the IIASA Integrated Energy System Research Program"

An Initial Framework for Description of Regional Pollution Emissions in the IIASA Integrated Energy System Research Program

R. Dennis and K. Ito

Contents

I. Introduction

A brief overview of the environmental impact analysis for the Integrated Energy System Research Program is given in Foell (1). Three major pathways of environmental impact were identified and are shown in Figure 1. These are: (1) the impacts due to the emission of pollutants from the direct combustion of energy in the region, (2) the impacts due to the physical presence and use of the combustion machinery, e.g. cars and power plants, and (3) the impacts along the fuel chain (from extraction of raw material to the point of end use of the fuel). The content of this paper is concerned with the first pathway - the impact of emissions within the region. Three levels of within-the-region impact analysis break out naturally, where each increasing level represents an increase in the complexity of the analysis of about an order of magnitude.

(1) First Level: calculation of emissions
(2) Second Level: emissions with simple dispersion to obtain a dosage
(3) Third Level: dosage and health effects (dose-response) to obtain health impacts

This paper describes two models both at the First Level, for calculating emissions of pollutants due to the use of energy, on an annual basis, over a given study period. Both models assume some measure of energy use is available as input.

The first model, the Regional Emissions Model, is a universal approach, using the Japanese experience, for calculating the total emissions of pollutants for a given region. The second model, the Subregional Emissions Model, is the Wisconsin model

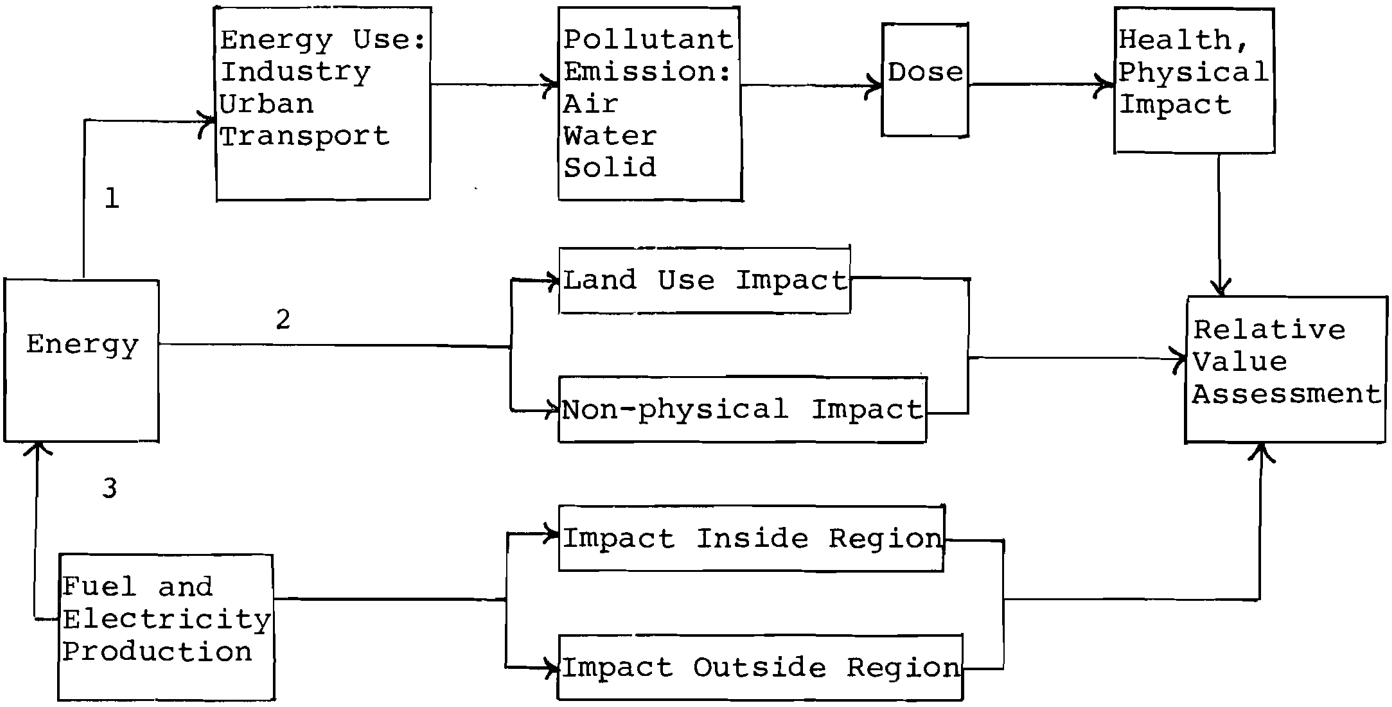


Figure 1 Pathways for Environmental Impact Analysis

for calculating air pollution emissions at the subregional level (Wisconsin is composed of 72 subregions: counties). Finally, a simple method is presented for displaying relative emission impact comparisons between different subregions. The main emphasis in this paper is on air pollution emissions, however the first model also includes water and solid waste emission pathways to give a broader overall sense to the system of impacts.

II. Regional Emissions Model

A. Model Overview

The following model is a simplified version, for presentation purposes, of a much more detailed model that is used in Japan (2). The conceptual structure of the model is shown in Figure 2, showing the major component parts of the model. Definitions of the terms in the figure are listed directly below as they represent the data needs of the model. They are:

X : pollution sources

Y : amounts of pollutants generated by source (tons/year)

Z : amounts of pollutants emitted (tons/year)

P : environmental impact indicators

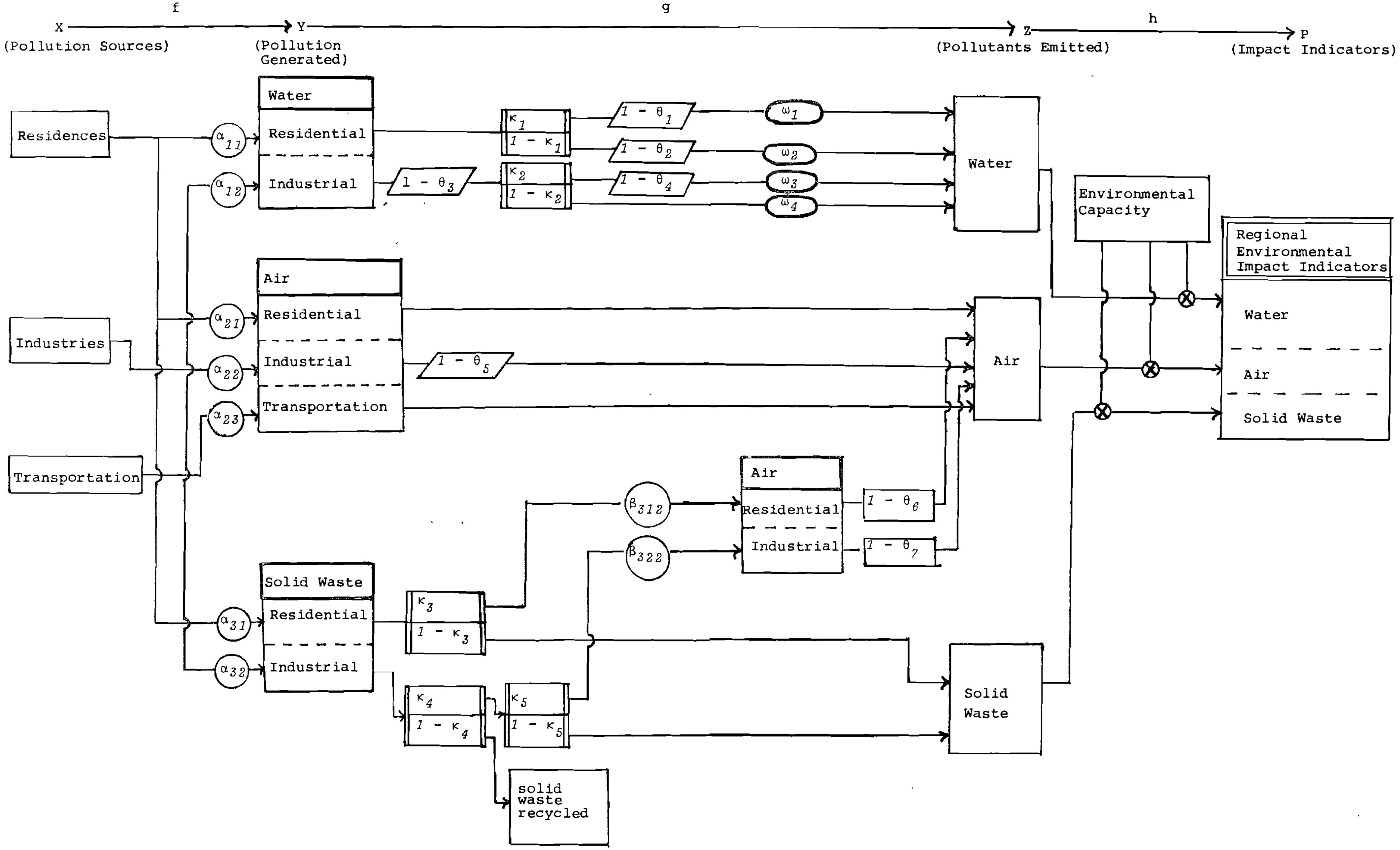
α_{ij} : primary generation factor of pollutant, where i is the type of pollutant and j is the source of pollutant (economic sector)

β_{ijk} : secondary generation factor of pollutant, where i is the original pollutant, j is the source of pollutant, and k is the final pollutant

θ_i : coefficient of pollution control effect (percent)

κ_i : treatment ratio of pollutant (percent)

ω_i : rate of run-off (percent)


f
g
h
X
(Pollution Sources)
Y
(Pollution Generated)
Z
(Pollutants Emitted)
P
(Impact Indicators)
Residences
Industries
Transportation
α_{11}
α_{12}
α_{21}
α_{22}
α_{23}
α_{31}
α_{32}
Water
Residential
Industrial
Air
Residential
Industrial
Transportation
Solid Waste
Residential
Industrial
$1 - \theta_3$
κ_1
$1 - \kappa_1$
κ_2
$1 - \kappa_2$
$1 - \theta_1$
$1 - \theta_2$
$1 - \theta_4$
ω_1
ω_2
ω_3
ω_4
$1 - \theta_5$
κ_3
$1 - \kappa_3$
κ_4
$1 - \kappa_4$
κ_5
$1 - \kappa_5$
solid waste recycled
β_{312}
β_{322}
Air
Residential
Industrial
$1 - \theta_6$
$1 - \theta_7$
Water
Air
Solid Waste
Environmental Capacity
Regional Environmental Impact Indicators
Water
Air
Solid Waste

There are three major functional relationships in the model between the major variables of X, Y, Z and P.

(1) Raw pollution generation: $Y = f(X) = \alpha X$, which in matrix form can be written as $y_{ij} = \alpha_{ij}x_j$.

(2) Actual pollution emission after controls and treatment: $Z = g(Y)$, where g is a function of β, θ, and ω.

(3) Indication of impact: $P = h(Z)$.

Some examples of the relationships (1) and (2) will be discussed below for each pollution phenomenon - water, air and solid waste. Relationship (3) will be discussed in the fourth section of the paper, Regional Emission Impact Indicators.

B. Examples of the Relationships in the Model

Water Pollution

There are many items which indicate the level of water pollution such as pH, BOM, COD, TOC, TOD, SS, DO, and heavy metals. As our interest is not to investigate the very special and very localized water pollution phenomenon, it will be sufficient to investigate such items as BOD, COD, and (if possible) SS.

1. Pollution Sources

Two pollution sources are given as an example of the methodology:

Residential:	number of inhabitants (persons)
Industrial:	annual industrial production amounts for 20 industries in terms of dollars, (see Appendix I for a list of the industrial categories).

2. Pollutants Generated

The α_{ij}'s are the generation or emission factors, where i is the type of pollutant and j is the source of pollutant. For example:

α_{11} : is the generation coefficient for water pollution from residents. It depends on the standard of living and lifestyle of the population and is in units of pollution generated per unit of source, (e.g. generation factor of BOD in West Germany is 54 gm/person/day).

α_{12} : is the generation coefficient for water pollution for industry. It depends on the type of industry, the level of technology, etc., and is in units of tons of pollutant per dollar of production.

3. Pollutants Emitted

To estimate water pollutants emitted, the following factors must be taken into account:

residential: κ_1 (diffusion rate of public sewage),
θ_1 (treatment ratio of sewage),
θ_2 (night soil treatment ratio),
ω_1 and ω_2 (rates of run-off)

industrial: θ_3 (coefficient of waste water control effect within each industry),
κ_2 (diffusion rate of public sewage for industrial waste water),
θ_4 (treatment ratio of sewage),
ω_3 and ω_4 (rates of run-off).

Air Pollution

The critical pollutants are particulates, sulfur oxides (SO_x), nitrogen oxides (NO_x), hydrocarbons (HC), and carbon monoxide (CO). The scheme to estimate the emissions is very similar to the one in the Wisconsin model described below; however the model of Figure 1 includes the air pollutions caused by incinerating solid waste. In this section, a detailed explanation of the air pollution caused by transportation components will be given to illustrate the overall scheme.

1. Pollution Sources

As the transportation sources of air pollution we will consider only motor vehicles and airplanes classified into nine groups according to the possible combinations between the two following categories.

$$a \begin{cases} \text{passenger car (personal carrier)} \\ \text{truck} \\ \text{bus and vehicle with special uses} \end{cases}$$

$$b \begin{cases} \text{vehicle with gasoline engine} \\ \text{vehicle with LPG engine} \\ \text{vehicle with Diesel engine} \end{cases}$$

2. Pollutants Generated and Emitted

Motor Vehicles: Taking into account the average driving distance, the average driving speed for each type of vehicle mentioned above and the age mix of the motor vehicles, the generation factor of each pollutant, α_{23} (gm/day/car), is estimated. No pollution control devices are considered here, that is, we assumed that both the amounts of generation and emissions are equal to each other ($Y = Z$). Otherwise, there would also be a $(1 - \theta)$ term.

Airplanes: The annual total number of LTO cycles (landing and take-off cycle; 1100 m $\longrightarrow$ 0 m $\longrightarrow$ 1100 m) is used to estimate the amount of emissions considering the type of engine and number of engines. Again no pollution control is assumed.

Solid Waste

1. Pollution Sources

There are many kinds of solid wastes and problems to be taken into account. However, since the main purpose of the project is to investigate the regional environmental impacts related to regional energy uses, it does not seem necessary to study the problem in great detail.

Let us focus our attention on the problem of plastic waste, which is one of the typical and important solid wastes generated by residences and industry.

2. Pollutants Generated and Emitted

Up to now, generation factors of solid wastes, α_{31} and α_{32} have been investigated in many regions in Japan, and the percentage of the plastic waste included within solid wastes is well estimated. The factors involved are:

κ_3 and κ_5 : treatment ratios by incineration

κ_4 : recycling ratio of plastic waste

β_{312} and β_{322} : secondary generation factors of air pollution from residences and industries by incineration

θ_6 and θ_7 : coefficients of air pollution control effect

In the investigation of solid wastes, it is generally necessary to take into account the time-lag problem into the system, but the available data in this direction is still very poor and limited at this stage.

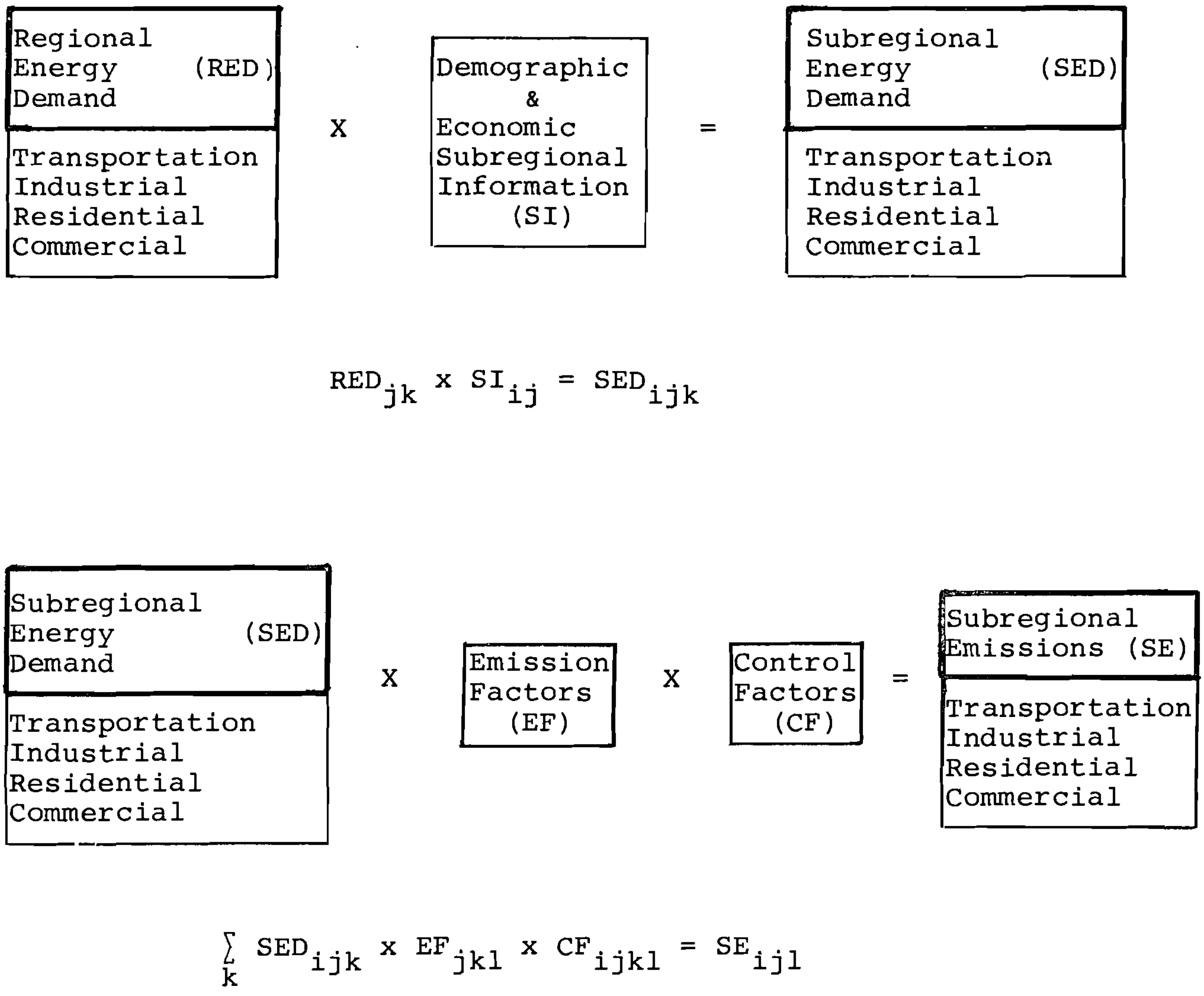
III. Subregional Emissions Model

A. Model Overview

The Wisconsin model has been developed to deduce, with the help of subregional non-energy data, the annual subregional (county) air pollution emissions due to energy use from the total regional (state) energy demand. In Wisconsin the subregions are the 72 counties in the state, but the methodology is completely general and only depends on the fineness of the data. Figure 3 shows a schematic of the model in both diagramatic and matrix form. The subscripts are identified in Section B, C, and E below. The first part, below, describes the regional energy demand data that is required as input to the model, followed by a section describing the methodology to calculate the subregional energy demand. The third part outlines the demographic and economic subregional data required by the model, and the fourth part describes the methodology to calculate the subregional emissions. The final section notes the type of data required to calculate the subregional emissions.

B. Required Input of Regional Energy Demand

As input the emissions model requires annual sectoral energy demand by region. At Wisconsin these data come from demand model projections of the regional energy demand, for



$$\mathrm{RED}_{jk} \times \mathrm{SI}_{ij} = \mathrm{SED}_{ijk}$$

$$\sum_{k} \mathrm{SED}_{ijk} \times \mathrm{EF}_{jkl} \times \mathrm{CF}_{ijkl} = \mathrm{SE}_{ijl}$$

Figure 3 Schematic of Regional Emissions Model various scenarios, over the study time period. For this model, the energy demand is required to be in the form of the quantity of fuel consumed (not its energy value).

1. Annual Residential Energy Demand
   - By residential type (these are: urban house, urban apartment, and rural house)
   - By fuel type (coal, oil, natural gas, and other)

     Fuel type is by quantity of fuel, e.g. tons of coal, 1,000 gallons of oil and 1,000 ft^3 of natural gas, or other units consistent with the emission factors used.
2. Annual Commercial Energy Demand
   - By fuel type

     The Wisconsin model bases the commercial energy demand on the cubic meters of commercial buildings in the state.
3. Annual Industrial Energy Demand
   - By 2-digit Standard Industrial Classification (SIC)*

     By fuel type

In 1, 2, and 3 the demand must be in terms of fuel quantity consumed.

4. Annual Transportation Demand
   - Miles traveled by transportation type (intracity car, intracity mass transit, intercity car, intercity mass transit, and inter and intracity freight).

The annual sectoral energy demand for the region as delineated in 1-4 above can be summarized in matrix form as

---

*See Appendix I for a list of the 20 "SIC"s in the model.

RED_{jk}, where j indexes the sector and k indexes the fuel. RED_{3k} is a function of the industry type as listed in Appendix I. Table 1 shows the sectors and fuels used in the Wisconsin model.

j	Sector
1	Residential
2	Commercial
3	Industrial
4	Transportation

k	Fuel
1	Coal
2	Oil
3	Natural Gas
4	Other

Table 1

C. Model for Apportioning Energy Use to Subregions

The breakdown into sectors for the Subregional Energy Demand (SED) is the same as for the regional demand sectors.

1. Residential

$$SED_{i1k} = \text{Residential Energy Use (subregion i, fuel type k)}$$

$$= \sum_{\substack{\text{residence}\\ \text{type}\\ r}} (\text{Regional Fuel Use } (k,r)) \times \frac{\text{Number of Residences } (i,r)}{\text{Regional Residence Number } (r)}$$

2. Commercial

$$SED_{i2k} = \text{Commercial Energy Use } (i,k) = \text{Regional Fuel Use } (k) \times \frac{\text{Cubic Meters of Commercial Buildings } (i)}{\text{Regional Cubic Meters of Commercial Buildings}}$$

3. Industrial

SED_{i3k} = Industrial Energy Use (i,k,SIC)

$= \text{Regional Fuel Use (k,SIC)}$

$\times \dfrac{\text{Value Added (i,SIC)}}{\text{Regional Value Added (SIC)}}$

This assumes fuel usage is directly proportional to value added.

4. Transportation

SED_{i42} = Miles Traveled (transport type t,i)

$= \text{Regional Miles Traveled (t)} \times \dfrac{\text{Population (i)}}{\text{Regional Population}}$

If more data is available, then the modal split may be more directly predicted for the subregions. This assumes a homogeneous transportation pattern in the urban areas of the region.

In matrix form, the model for subregional energy use can be written as:

$$SED_{ijk} = RED_{jk} \times SI_{ij},$$

where SI is the required subregional information.

D. <u>Required Subregional Information</u>

To implement the model in C, certain subregional data must be available in addition to the regional data. These data requirements are:

1. Residential Sector Requirements

- Numbers of residences (residence type r, subregion i)

This data may be generated by ascertaining that the ratio of the residence type does not change significantly across the region and thus the population fraction may be used.

- Alternatively, the data may be a table of projections for residences of each type in each subregion.

2. Commercial Sector Requirements

- Cubic meters of commercial buildings (subregion i)

- Alternatively some equivalent measure for determining commercial energy use can be used.

3. Industrial Sector Requirements

- Industrial value added (subregion i, SIC)

- If need be, some equivalent measure of industrial activity or energy use for each Standard Industrial Classification can be substituted.

4. Transportation Sector Requirements

- The subregional fraction of the population in urban areas and the number of cities in different population classes.

- Some equivalent measure to apportion miles traveled to each subregion could also be used.

E. Model for Calculating Subregional Emissions

The following is the Wisconsin model for estimating the annual Subregional Emissions (SE) for each of the sectors. The emission factors used here all come from national averages and the USEPA. These emission factors are in units of tons of pollutants per quantity of fuel. In concept, these emission factors are the same as the α's used in the Regional Emission Model.

1. Residential

SE_{il1} = Residential Emissions (pollutant l, subregion i)

$= \sum_k$ Emission Factor (l,k) x Residential Energy Use (i,k)

This assumes no difference in efficiency of furnace operation between residence types.

2. Commercial

SE_{i21} = Commercial Emissions (l,i) = $\sum_k$ Emission Factor (l,k) x Commercial Energy Use (i,k) x Pollution Control Factor (l,i,k)

Here we allow for a pollution control factor for commercial buildings and allow for subregional differences.

3. Industrial

SE_{i32} = Emissions (l,i,SIC) = $\sum_f$ Emission Factor (l,k) x Industrial Energy Use (i,k,SIC) x Pollution Control Factor (l,i,k,SIC)

Again a control factor is included

4. Transportation

SE_{i41} = Emissions (l,t,i) = Emission Factor (l,t) x Miles Traveled (t,i)

In equation form, the subregional emissions model is

$$SE_{ijl} = \sum_k SED_{ijk} \times EF_{jkl} \times CF_{ijkl},$$

where EF and CF are the emission factor and control factor respectively.

F. Emission Data Needs

1. All emission factors for E 1,2,3,4 for each of the fuels. It is most helpful if these factors are in a time series, past and future, for example, to reflect changes in automobile population.

2. All control factors for each type of control device to be possibly used in the study period, e.g. efficiency.

3. All fuel characteristics required such as the percent ash content and percent sulfur content of coal or the percent sulfur in oil, and the Btu content of the fuel if quantities of fuel use must be estimated.

This completes the description of the two emission models and their data needs. The next section outlines a simple means for comparing and displaying pollutant by pollutant comparisons of different subregions, once emissions are known.

IV. Regional Emission Impact Indicators

In this section, to consider what is the environmental capacity, some first approximation regional environmental impact indicators will be introduced for water, air pollution and for solid waste ($P = h(Z)$).

Water Pollution

As an indicator of environmental capacity, the combination of low water discharge and mean water discharge can be meaningful. It is necessary to take pollution load which flows down from the surrounding subregions into account. As the regional environmental impact indicators of water pollution, two indicators will be acceptable, i.e. emitted load of pollutant divided by both low and mean water discharges.

Air Pollution and Solid Waste

As an environmental capacity measure for both air pollution and solid waste, the land use, broken into three categories (metropolitan, rural and wilderness), of each subregion will be roughly applied. For air pollution it is of course necessary to take into account the meteorology as part of the environmental capacity, but this will be omitted in this first level regional environmental impact analysis. However, the results which will be carried out by the first level model will indicate the relative pollution level of each subregion, and using this result, we can select some relatively more polluted subregions in which more detailed investigations should be carried out.

Indicator Diagrams

Let us omit the influence of pollutants from outside, and also exclude the wilderness areas (mountains, woods, and forests) from the area of consideration.

As there are great differences of pollution level between urban and rural parts in each subregion, we divide the habitable area of each subregion (HA) into two areas: metropolitan area (MA) and rural area (RA), such that HA = MA + RA.

Accordingly, let us introduce the following three regional environmental impact indicators:

(1) Indicator I_1 : (Pollutants emitted in HA)/HA

(2) Indicator I_2 : (Pollutants emitted in MA)/MA

(3) Indicator I_3 : (Pollutants emitted in RA)/RA

Standardizing by the indicator I_1 of the total region, we can compare the relative environmental pollution level of each subregion for the emitted pollutants as shown in Figure 4.

The diagrams then give a relative indication of emission densities and land use densities for the different habitable areas considered. To make the necessary divisions into MA

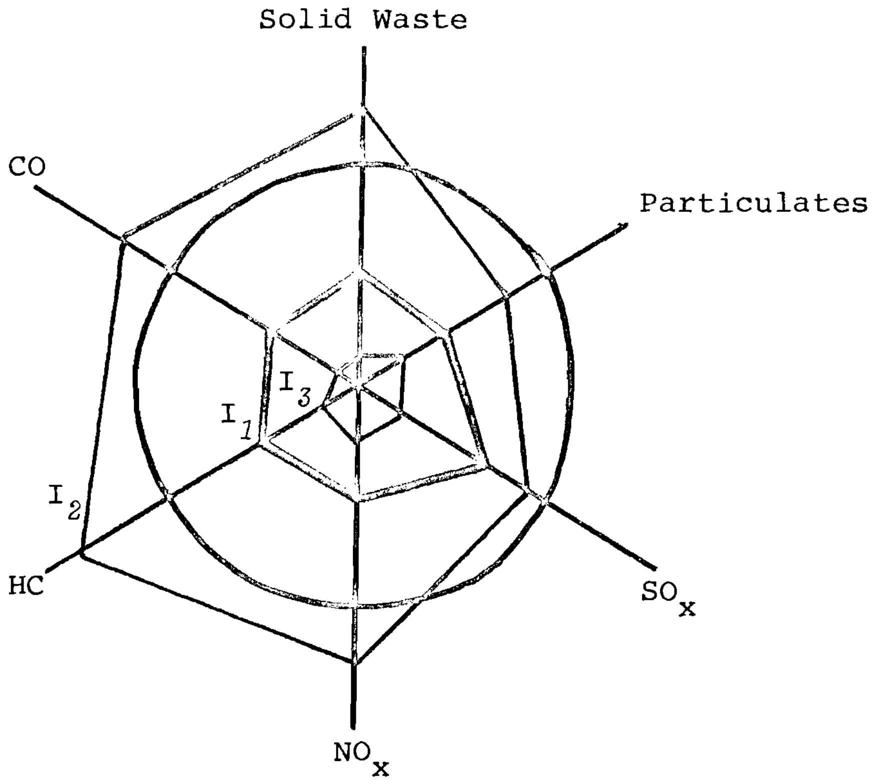


Figure 4 Indicator Diagram of Each Subregion

and RA requires some non-energy data. These data are:

1. land use data dividing the region or subregion into wilderness, rural and metropolitan land areas;
2. population data for each of the three land use categories in 1; and
3. industrial activity in both the rural and metropolitan areas by SIC. (Commercial and transportation activity is assumed to apportion by population.)

It may be possible to apply meteorological data to these diagrams and arrive at some relative comparisons of average dose. This is being presently investigated, but the diagrams cannot at present be used to relate relative pollution levels.

Appendix I

Standard Industrial Classifications

SIC Code	SIC Industry
20	Food and Kindred Products
21	Tobacco Manufactures
22	Textile Mill Products
23	Apparel and Related Products
24	Lumber and Wood Products
25	Furniture and Fixtures
26	Pulp, Paper, and Products
27	Printing and Publishing
28	Chemicals and Allied Products
29	Petroleum and Coal Products
30	Rubber Products
31	Leather and Leather Goods
32	Stone, Clay, and Glass
33	Primary Metal Industries
34	Fabricated Metal Products
35	Machinery, except Electrical
36	Electrical Machinery
37	Transportation Equipment
38	Instruments and Related Products
39	Miscellaneous Manufactures

References

(1) Foell, W.K., "Integrated Energy System Modelling and Policy Analysis: A Description of an IIASA Research Program." Int. Inst. for Applied Systems Analysis, IIASA, WP-75-38, April 1975.

(2) T. Ono, K. Ito, Y. Suzuki, "Interrelation Between Production, Consumption and Pollution as a Complex System - For the Kinki Region." _Preprint of the Symposium on Environmental Pollution Control, Special Research Project supported by the Ministry of Education in Japan, March, 1975, Tokyo (in Japanese)_.