FOOD AND ENERGY CHOICES FOR INDIA

A Programming Model with Partial Endogenous Energy Requirements

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PREFACE

The global modeling effort of the IIASA Food and Agriculture Program envisages a model of international interactions among different national models. This is a significant departure from earlier global models in that the policy makers are clearly identifiable with various suggested policies and that they pursue their own national objectives. As part of this effort a model for the agricultural policy of India, along with models for other countries, is to be built. For this purpose it would be useful to explore the choices available for the development of Indian agriculture to see whether development should be land intensive, irrigation intensive, or fertilizer intensive. Since land can also be used for growing firewood, irrigation needs energy, and since fertilizer feedstocks are also important fuels, these choices can be best explored together with choices in energy supply and energy-intensive uses. This study attempts to do this.

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SUMMARY

This paper explores India's choices in the food and energy sectors over the coming decades. For a poor, large and densely populated country like India, many choices in energy intensive sectors are still open, as the present level of energy consumption is low and large resources are not yet committed to particular technologies. The choices in energy supply and energy intensive sectors can be explored simultaneously. Also, this will determine a substantial part of the demand for energy.

India's energy consumption per capita is very low, being of the order of 700 kg of coal replacement. Nearly 50 percent of the energy consumed in India is obtained from noncommercial sources such as firewood, agricultural wastes, and animal dung. The transport, agriculture and household sectors of the Indian economy account for more than 55 percent of the commercial energy consumption and almost all of the noncommercial energy consumption. The alternatives available to these sectors are explored in detail, and these choices are then investigated along with those for energy supply.

The choices in agriculture arise from the following substitutions and complementarity possibilities: given the sown area, output can be increased only be increasing yield per unit area. In increasing the yield per unit area, however, alternative combinations of irrigation and fertilizers can be applied. Alternative land intensive, irrigation energy intensive and fertilizer intensive techniques of food production are identified using a nonlinear programming model. The land saved is devoted to growing firewood.

Ten alternative activities are identified, all of which meet the projected demand for food grains for the target year 2000-2001. These activities range from one that needs 4.6 million tons of nitrogen and 41.5×10^9 kWh of energy for pumping, to one that needs 7.3 million tons of nitrogen but only 32.45×10^9 kWh of energy for pumping and also releases enough land to provide annually 60 million tons of firewood.

Also, there are choices available for the production of nitrogenous fertilizers for which the following feedstocks are considered: naphtha, fuel oil, and coal. Nitrogen available from dung processed through biogas plants is taken into account.

Based on econometric studies, the demand for transport services are projected in terms of goods per ton per kilometers, urban passenger

kilometers, and regional passenger kilometers. In the case of goods transport, a distinction is made between different density classes, density being defined as the number of net ton kilometers carried per kilometer of route length per day. This distinction enables one to examine the relative economics of different tractions such as steam, diesel and electric and the number of tracks on a route. The optimal combination of railway (steam, diesel, and electric traction) and road (automobiles, diesel trucks, and diesel and petrol buses) transport is determined for these demands.

The cooking energy needs of rural and urban households are considered separately, the alternatives available being firewood, softcoke, biogas, kerosene, and LPG. With respect to lighting energy, the choice is between kerosene and electricity.

For the oil sector are included two alternative sources of supply of crude oil and petroleum products, namely, domestic production and imports. Process choices in the production of petroleum products are introduced by means of alternative refinery processing activities. These include a number of secondary processing activities such as vacuum distillation, visbreaking, hydrocracking, catalytic cracking, and coking.

The optimal choice is determined through a linear programming model. While the model is basically a static one, designed to determine the optimal choice for the target year of 2000-2001 certain intertemporal detail is incorporated for electricity generation.

The model minimizes the costs of meeting the needs for food, transport in terms of passenger kilometers and goods per ton per kilometers, energy needs for domestic cooking and lighting, and the energy needs of the rest of the economy.

The results of the various runs of the model indicate certain choices. A land and irrigation saving agricultural technology which is likewise fertilizer intensive is preferred. Fertilizer production is mainly based on coal and, to a lesser extent, on naphtha. However, these choices are sensitive to the price of crude oil.

Electric trains are preferred for passenger transport as are diesel buses for goods transport. The choice of traction depends upon the density of traffic, and a mix involving steam, diesel and electric traction is indicated.

For the domestic sector a mix of fuels emerges. Biogas is always selected to its full potential. Large amounts of kerosene are also used for cooking.

For the indicated product mix, secondary refinery processes are selected for all alternative runs.

Though coal based plants provide the bulk of electricity, the sizable development of CANDU and FBR plants is also indicated.

Food and Energy Choices for India

INTRODUCTION

The energy problems of a large, densely populated country with a low per capita income such as India are different from those of the rich countries. The latter have been analyzed both in theory and empirically by a number of researchers in the last few years. In this paper we take a look at the choices available to India over the next three decades in the energy and agricultural sectors.

India's energy consumption per capita is very low, being of the order of 700 kg of coal replacement while that of the USA is over 11,000 kg. The per capita consumption in Western Europe is in the range of 3000 to 6000 kg. Nearly 50 percent of the energy consumed in India is obtained from noncommercial sources such as firewood, agricultural wastes, and animal dung whereas in high income countries this proportion is negligible. The pattern of end use of energy in India is also quite different from that of advanced countries. Nearly 90 percent of the energy required for household cooking is supplied by noncommercial sources in India. Petroleum products account for a little over 70 percent of the energy needs of the transport sector in India while in advanced countries this proportion exceeds 90 percent. Another feature of the Indian energy scene is the use in agriculture--mainly for irrigation and partly in terms of chemical fertilizers--of significant amounts of electricity and oil, amounting to nearly 10 percent of the total electricity use and 5 percent of oil. Altogether the transport, agriculture, and domestic sectors of the Indian economy account for more than 55 percent of commercial energy consumption and almost all of noncommercial energy consumption. In this paper we explore the alternatives available to these sectors only.

Briefly stated the choices in agriculture arise from the following substitution and complementarity possibilities: given the sown area, output can be increased only by increasing yield per unit area. In increasing the yield per unit area, however, alternative combinations of irrigation and fertilizers can be applied. While some modes of lift irrigation such as through tubewells are users of energy, other modes such as irrigation from major storage reservoirs often provide energy in the form of hydroelectric energy (Hydel). Availability of irrigation, to the extent it makes it possible to grow more than one crop during a year, in effect, also increases the availability of land. In the production of fertilizers there are energy choices in terms of feedstock: coal, fuel oil, naphtha, or hydrogen obtained from water through electrolysis. Further, in a country as large as

India, where the potential for producing agriculture products varies from region to region, there is a choice between the strategy of concentrating production in a few regions and transporting final products to others, and the strategy of regional self sufficiency. While the latter strategy may save energy used in transportation, it is conceivable that it may require more total energy in terms of irrigation needs and fertilizer use (and its transportation, in case its production is concentrated because of considerations of economics of scale).

Though the agricultural sector covers all crops grown in India, over 75 percent of the cropped area is devoted to the cultivation of foodgrains, with rice and wheat accounting for more than 30 percent. The irrigated area, accounting for less than 30 percent of the total cropped area, is even more concentrated on foodgrains, with nearly 80 percent of the irrigated area devoted to foodgrains, and rice and wheat accounting for over 60 percent. For these reasons and for the more important reason that data on yield response to fertilizer use are more extensively documented for rice and wheat, in this paper we confine ourselves to choices in respect of these crops. We have also not explored the choice between extensive and intensive cultivation mentioned above.

In the production of nitrogenous fertilizers the following feedstocks are considered: naphtha, fuel oil, and coal. Also nitrogen available from dung processed through biogas plants is taken into account.

We have included two alternative sources of supply of crude oil and petroleum products, namely, domestic production and imports. Process choices in the production of petroleum products are introduced by means of alternative refinery processing activities. These include a number of secondary processing activities such as vacuum distillation, visbreaking, hydrocracking, catalytic cracking, and coking. In deriving these we have extensively drawn on the work of Bhatia (1974).

In the transport sector the optimal combination of railway (steam, diesel, and electric traction) and road (automobiles, diesel trucks, and diesel and petrol buses) transport is to be determined in respect of goods transport as well as regional and urban passenger transport. In the case of goods transport, we distinguish between different density classes, density being defined as the number of net tonn kilometers (ntkm) carried per km of route length per day. This distinction enables us to examine the relative economics of different tractions such as steam, diesel, and electric, and the number of tracks on a route.

In the generation of electricity the alternatives considered are conventional coal-based thermal plants, CANDU-type nuclear reactors, fast breeder reactors (FBRs), and high temperature reactors (HTRs).

The cooking energy needs of rural and urban households are considered separately, the alternatives available being firewood, softcoke, biogas, kerosene, and liquified petroleum gas (LPG). With respect to lighting energy, the choice is between kerosene and electricity.

The optimal choice is determined through a linear programming model. While the model is basically a static one, designed to determine the optimal choice for the target year 2000-01, certain intertemporal detail is incorporated with respect to electricity generation.

In order to clarify the solution procedure and to indicate how the various sectoral models may be interconnected to maintain consistancy, a schematic block diagram is given in Figure 1.

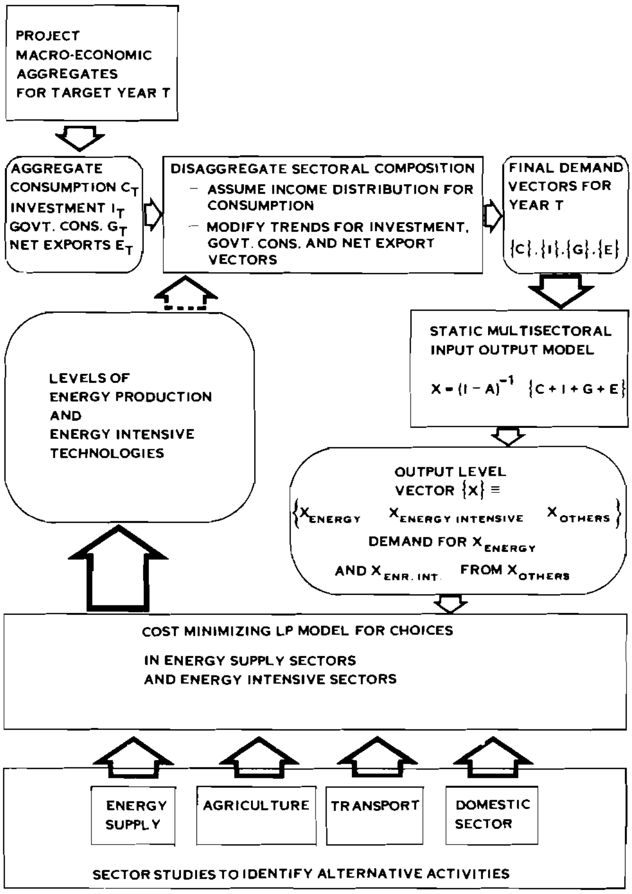

Figure 1. Solution procedure.

Rectangular boxes indicate models, and round blocks show the interfaces or information that is passed on from one box to another. However, we have not implemented all the steps shown in the figure. The static multisectoral input output model was not implemented, and the final demands for the output of energy-intensive sectors and the demand for energy from sectors other than those studied in detail were projected from other studies.

We now describe our model.

THE MODEL

For the target year 2000-01, the alternatives in food production, fertilizer production, modes of transport, domestic energy for cooking and lighting, refining techniques, and electricity generation are explored in an activity analysis model. The alternative activities for each of these sectors are described in greater detail in subsequent sections. Though these choices are posed for the target year, the choices for electricity supply techniques cannot be satisfactorily examined for only one period. The extent of availability of FBR or HTR technologies depends on the availability of plutonium, which has to be produced in first generation nuclear power plants. In order to explore these choices the problem of electricity supply has to be posed in an intertemporal model of plutonium accumulation. Such intertemporal considerations are introduced in the model only for the supply of electricity, confining other alternatives only for the target year.

The total demand for electricity for the target year consists of two parts--that which is oxogenously prescribed, and that which is endogenously determined. For the earlier periods the demand corresponding to the endogenous portion is assumed to grow exponentially over the planning period. To achieve this, we assume a value for the target year endogenous demand, prescribe the demand for an earlier year on that basis, and solve the problem. If the resulting solution value in the first iteration for the target year endogenous demand differs from its assumed value then a new assumed value equal to the solution value of the first iteration is prescribed for the second iteration. This iterative process is continued until convergence is achieved.

The linear programming model is described below. The equations of the model are given in Appendix 1. Separate constraints are written for each time period only for the electricity sector. For all the other sectors constraints are written only for the temporal period T. Consequently, the costs of capital investment are annualized for all activities except for the electricity generation activities for which capital and operating costs are kept distinct. A credit is taken for the stock of power plants surviving at the end of the planning period. This is done on the basis of the discounted value of the operating cost advantage over the remaining life offered by that plant compared to the plant with highest operating cost (coal-based plants).

The objective function is to

(1) Minimize the discounted:

(a) Costs of the capacity and energy of CANDU, FBR, HTR, and coal-based power plants installed in periods 1,2,...,T;

less (b) The credit for terminal capital stocks and the post terminal operating cost advantage of CANDU, FBR, and HTR plants over the coal plants;

less (c) The credit for surplus plutonium;

plus (d) The cost in period T of agriculture excluding the cost of irrigation energy and nitrogenous fertilizers;

plus (e) Nonfuel costs in period T of passenger transport by electric, diesel and steam trains, and buses run on diesel and motor gasoline (mogas);

plus (f) Nonfuel costs in period T of goods transport by electric, diesel and steam trains, and diesel trucks;

plus (g) Cost in period T of coal;

plus (h) Costs in period T of domestic and imported crude oil, of imported kerosene, diesel, light diesel oil (LDO), mogas, naphtha, fuel oil and other oil products, and of refining processes;

Subject to the following constraints:

(2) Demand for electricity, for domestic lighting, for urban and regional passenger transport, and for goods transport, for irrigation and exogenous demand $\leq$ supply from coal, FBR, HTR, and CANDU plants for the period T;

(3) Exogenous demand for electricity $\leq$ supply for periods 1,2,...,T-1;

(4) Electricity generated in period $\leq$ capacity in period for periods 1,2,...,T;

(5) Demand for uranium over the life time of all CANDU plants installed $\leq$ supply from known reserves;

(6) Demand for plutonium in the period for FBR and HTR $\leq$ supply from domestic accumulation until the period from past CANDU and FBR operations.

(7) Demand for plutonium for the post terminal life of installed HTR $\leq$ supply;

(8) Demand for coal for fertilizer feedstock, for rural and urban cooking, for trains for regional passenger and goods transport, and for electricity generation $\leq$ supply of coal for period T;

(9) Nitrogenous fertilizer required by food activities $\leq$ fertilizer produced using coal, naphtha, fuel oil, and biogas in period T;

(10) Demand for food $\leq$ supply of food in period T;

(11) Domestic lighting energy requirement $\leq$ lighting energy from kerosene and electricity in period T;

(12) Rural domestic cooking energy requirements $\leq$ cooking energy from coal, kerosene, biogas, and firewood in period T;

(13) Urban domestic cooking energy requirement $\leq$ cooking energy from LPG, kerosene, coal, and firewood in period T;

(14) Demand for firewood $\leq$ exogenous availability plus availability from land saved from agriculture by increasing fertilizer and/or irrigation intensity in period T;

(15) Demand for biogas $\leq$ supply from families with adequate animal dung to install their own plants in period T;

(16) Demand for urban passenger transport $\leq$ supply by diesel and mogas buses, electric trains, private automobiles, and scooters in period T;

(17) Urban passenger transport by electric trains $\leq$ demand in large metropolises;

(18) Demand for regional passenger transport $\leq$ supply by diesel buses, and electric, diesel and coal trains in period T;

(19) Demand for goods transport in each of six traffic density class $\leq$ supply by diesel trucks and electric, diesel and coal trains in period T;

(20) Goods transport required as feeder traffic $\leq$ goods transport by diesel trucks in period T;

(21) Demand of each petroleum product $\leq$ supply from domestic refining and imported products in period T;

(22) Demand for crude $\leq$ domestic availability and imported in period T.

We turn next to a description of the procedure of demand projections as well as of the production activities in each of the major sectors.

DEMAND PROJECTIONS

Our model assumes that the demands in the target year for rice, wheat, and transport as well as those for energy for cooking and lighting are exogenously determined. We now describe the basis of our exogenous projections of demand.

Demand for Rice and Wheat

We first project the likely population in India in the target year 2000-01, using 1971 government census data and on the basis of age-specific fertility and mortality rates computed by the Census Commission of the Government of India. The assumed time pattern of gross reproduction and fertility rates is given in Table 1.

Table 1. Gross reproduction rate and fertility rate for India.

Source: Census Commission, Government of India.

	1971-1976	1976-1981	1981-1986	1986-1991	1991-1996	1996-2001
Gross Reproduction Rate	2,409	2.168	1.952	1.759	1.662	1.590
Gross Fertility Rate Births per 1000 Females (15-44 years of age)	168.0	150.1	135.6	124.0	118.0	112.1

The projected population in India in 2000-01 is then 960 million, of which 30 percent are assumed to live in urban areas. The corresponding 1971 census figures are 547 million and 20 percent.

We next project the average aggregate consumption expenditure at 1970-71 prices in the target year by assuming a 5 percent per annum growth for the period 1975-1991, and a 6 percent per annum growth thereafter. The ratio of urban per capita consumption expenditure to that in rural areas in the target year was set at 1.25. Given this ratio, the projected urban and rural population, and the aggregate consumption expenditure, we calculated that the urban per capita consumption expenditure would be Rs 1378* and the corresponding value in rural areas would be Rs 1098.

*The 1970-71 exchange rate is 7.5 Rs to US$1.

The pattern of distribution of rural and urban households among 13 per capita expenditure classes was derived by assuming this distribution to belong to the two parameter log-normal family in each case. The projected average per capita consumption expenditure (rural and urban), together with an assumed Lorenz ratio of 0.3, determine completely the distribution. By using data from the 1970-71 round of the National Sample Survey on the per capita consumption (in physical units) of rice and wheat by rural and urban households in each of the 13 expenditure classes, in conjunction with the distribution of the households among these classes in the target year, the total private consumption of these two foodgrains was obtained. By adding a customary 12.5 percent margin for feed, seed, and wastage, and assuming net foreign trade as well as stock changes in the target year to be negligible, the output target for foodgrains and, in particular, for rice and wheat were determined.

Demand for Passenger Transport

Two different kinds of passenger transport were distinguished. The first, urban passenger transport, consisted essentially of traffic within cities and towns. The demand in terms of passenger kilometers (pkm) of this kind of transport was assumed to grow in proportion to the growth of urban population. The second regional passenger transport consisted of all other passenger transport. This category included all long-end medium distance passenger traffic, for which demand was assumed to grow in proportion to the growth in total population. This procedure resulted in the following projections for 2000-01 (in 10^9 pkm): 960 for urban, and 2020 for regional.

Demand for Goods Transport

We first estimated on the basis of past data the following regression relation between tkm of goods carried by the railways (Y) and real gross national product (GNP) originating outside agriculture (X_1), the stock of trucks (X_2), and a time trend (X_3). We have

$$Y = 3387 + \underset{(2.12)}{13.401X_1} - \underset{(2.155)}{0.331678X_2} + \underset{(3.717)}{3940X_3}$$

$$\bar{R}^2 = 0.9839 \qquad \text{DW (Durbin Watson)} = 1.784 \ .$$

By assuming both a stock of a million trucks in 2000-01 and projected values of GNP outside agriculture, a forecast of Y for

2000-01 was made, amounting to 660 x 10^9 tkm. To this was added 400 x 10^9 tkm that would be carried by the million trucks, and 1070 x 10^9 tkm representing the projected demand for goods transport in 2000-01 given this projection, in the model we did not in anyway constrain the division of the total between railways and trucks. In many ways this procedure is rather unsatisfactory, since it implies that a projection based on a past relationship and the projection of the numbers of trucks in 2000-01 are used to determine the total demand, which is then subsequently optimally divided between railways and trucks. But the number of trucks implied by the optimal amount of truck traffic need not equal the number used in the projection. We have not attempted to iterate in this respect, preferring to assume consistency to emerge through changes in the efficiency of trucking.

Energy Demand for Cooking and Lighting

These projections were derived on a normative basis. A target of energy consumption for cooking and lighting of 0.38 kg of coal replacement per person per year was set for rural areas. The corresponding target for urban areas was set at 0.40 kg. The lighting component of these targets was set at 5 kg of kerosene or 40 kWh per person per year for both rural and urban areas.

PRODUCTION CHOICES

Choices in Foodgrain Production

The production of only rice and wheat is treated in the model. The choices available were summarized in terms of ten activities included in the programming model. In deriving these activities we adopted a quadratic programming model developed earlier by us. In the earlier model, India is divided into 57 agro-climatic zones, based on soil characteristics and rainfall. For each zone for which sufficient data from experiments on farmers' fields were available, a quadratic response function relating yield of a particular variety of a crop to applications of fertilizers was estimated. The varieties included a number of high yielding ones (usually dwarf varieties developed and propogated by agricultural scientists) and local varieties. The responses were separately estimated for irrigated, rainfed, and dry (less than 90 cm average rainfall in a year) areas of a zone. The interested reader is referred to Parikh and Srinivasan et al. (1974) for more details about this model.

The programming model works as follows: given the area (irrigated, rainfed and dry portions separately) in each zone and the exogenously specified demand for the output of each crop for the country as a whole, the model determines the varieties to be grown and the cost minimizing amount of chemical fertilizers (nitrogen, phosporous, and potassium) to be applied in each zone in respect of each crop that will result in production being at least as large as demand. In executing the model, we had to face the problem that experimental response data were not available in some zones in respect of some crops. In our earlier study referred to above, we circumvented this problem by substituting the *minimum* observed response of a crop over all zones for which data were available for the nonavailable response (keeping, of course, the irrigated, rainfed and dry area district). In the present paper the substitute response function is the *weighted average* of observed responses in the zones with data, the weights being the area under the crop in each zone. Thus the basic data specified are the areas devoted to each crop in each zone (separately for irrigated, rainfed and dry) and the demand for output.

The procedure by which we obtained the Indian demand for rice and wheat has already been described. While keeping the demands the same, our ten activities were obtained by varying the gross area and the irrigated portion of it. In "gross sown area", hectare of land is treated as 2 ha gross if it grows 2 crops a year, whereas in "net sown area", each hectare of land is included only once, regardless of the number of crops grown on it in a year. Thus the net sown area can be increased only by bringing more land under cultivation, while gross sown area can be increased both by increasing net sown area and by cultivating more crops in a year on the same piece of land, that is, by increasing the cropping intensity. In a country such as India, where agriculture has been practiced for millennia and where population growth has been substantial, very little area is available to be brought under cultivation for the first time. Hence the scope for increasing gross sown area lies mostly in increasing cropping intensity. While the availability of irrigation is essential for such multiple cropping, provision of irrigation to a previously unirrigated piece of land need not, and often does not, lead to more than one crop since the irrigation provided may not be sufficient to grow more than one crop. Thus the availability of irrigation may mean simply shifting from growing a single unirrigated crop to a different, perhaps more profitable crop with irrigation. While we allow some increase in gross sown area to result from an extension of irrigated areas, we permit cropping intensity to change for other reasons as well. In fact, we assume three alternative values for additions to gross sown area by 2000-01: 0, 10, and 20 million hectares for the country as a whole.

The Irrigation Commission in its report (1972) has provided state-wide estimates of ultimate irrigation potential. We adjusted these figures for certain obvious biases of underestimation in their procedure and assumed six alternatives in the 65 to 85 percent for the proportion of the ultimate potential to be realized by the year 2000-01. The assumed alternative values for additions to gross sown area for the country as a whole were then allocated between states in proportion to the addition to irrigated area arising from the assumed proportion of the ultimate irrigation potential to be realized. The statewide projections thus obtained for gross sown area and irrigated area were then allocated to the 57 agro-climatic zones and crops within a zone using a procedure adopted in the earlier study.

Table 2 lists the ten combinations considered used in the model.

Table 2.

	Activity									
	1	2	3	4	5	6	7	8	9	10
Addition to Cross Sown Areas (10^6 ha)	20	20	20	10	0	0	0	0	0	0
Realized Irrigation Potential (%)	85	75	65	75	85	80	75	72	68	65

For each combination the food sector submodel was run to obtain the minimum amount of nitrogen (together with phosporous and potassium, assumed used in fixed proportion to nitrogen) needed to produce the specified amount of rice and wheat. For example, activity 10 represents a fertilizer-intensive strategy of food production, since with no additions to gross sown area and the irrigated area fixed at its minimum permissible value, the required output of food can be produced only by increasing the use of fertilizers. By contrast, activity 1 is a fertilizer-saving strategy, while activities 1 and 5 are irrigation intensive ones. Activities 4 to 10 require less net land compared to activities 1 to 3, which are land intensive. The land saved could be devoted to growing firewood. Credit for firewood available from this land is taken for activities 4 to 10. The resulting 10 activities in Figure 2 thus represent the spectrum of choices with respect to energy in food production. The activity coefficients are given in Appendix 2.

Choices in Modes of Transport

The alternatives considered in transporting goods are electric, diesel, and steam traction on the railways and diesel and petrol trucks. The alternatives for passenger transport were, in addition to the three modes of traction on the railways, diesel and petrol buses. The technological details are given in Tables 3 and 4.

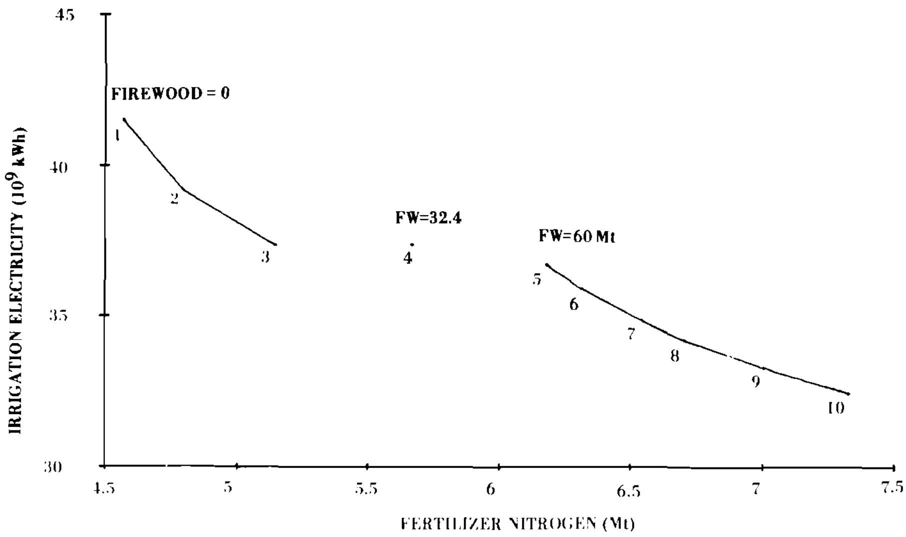

Figure 2. Food activities isoquants (all activities produce the same food output).

Table 3. Choices in passenger transport.

	Urban Passenger Transport					Regional Passenger Transport			
	Trains (Elec)	Buses (Diesel)	Buses (Petrol)	Private Auto-mobiles	Prvt. Scoot-ers	Buses (Diesel)	Trains (Diesel)	Trains (Elec)	Trains (Coal)
Costs* 10^6Rs/ 10^9pkm	11.05	32.5	32.5	240	40	78.125	27.62	27.62	27.62
Energy: Electricity 10^9kWh/10^9pkm	.017	-	-	-	-	-	-	.016	-
Diesel 10^6t/ 10^9pkm	-	.008225	-	-	-	.006854	.004308	-	-
Petrol 10^6t/ 10^9pkm	-	-	.015	.0473	.025	-	-	-	-
Coal 10^6t/ 10^9pkm	-	-	-	-	-	-	-	-	.057

*Includes capital charges but excludes energy costs.

Table 4. Choices in goods transport.
(activities are shown row-wise.)

Activity					Fuel Required		
No.	Traction	Single/ double tracks	Density class	Costs excluding energy 10^6Rs/ 10^9tkm	Electrical energy 10^9kWh/ 10^9tkm	Diesel 10^6t/ 10^9tkm	Coal 10^6t 10^9tkm
1	S	s	1	122.93	-	-	.109
2	S	s	2	60.73	-	-	.109
3	S	d	3	58.85	-	-	.109
4	S	d	4	56.59	-	-	.109
5	S	d	5	56.59	-	-	.109
6	S	d	6	56.59	-	-	.109
7	D	s	1	187.00	-	.004308	-
8	D	s	2	72.66	-	.004308	-
9	D	s	3	59.60	-	.004308	-
10	D	s	4	53.37	-	.004308	-
11	D	s	5	49.80	-	.004308	-
12	D	d	6	47.35	-	.004308	-
13	E	s	1	231.10	.031	-	-
14	E	s	2	82.47	.031	-	-
15	E	s	3	65.48	.031	-	-
16	E	s	4	57.37	.031	-	-
17	E	s	5	52.74	.031	-	-
18	E	d	6	49.56	.031	-	-
19	Truck			112.30	-	.04112	-

Notes: Density class defines the traffic density in terms of ntkm/day per km of route

The following density classes have been considered:

Class 1	0 - 10000
2	10001 - 20000
3	20001 - 30000
4	30001 - 45000
5	45001 - 60000
6	60001 and above

The proportion of total route km belonging to each density class and the goods traffic to be carried in the class are assumed as follows:

Table 4. (continued)

	Fraction of total route km	10^9 ntkm/year carried
Density Class 1:	.10	20
2:	.15	110
3:	.30	270
4:	.30	270
5:	.20	190
6:	.10	140
All Classes	1.00	1000

Trucking for local distribution is constrained to be at least 70×10^9 ntkm. Further trucking if found desirable is assumed to be distributed evenly on all routes.

For each density class, the number of tracks are determined for each traction to minimize costs.

The costs include costs of track including electrifications and rolling stock, but not the fuel costs.

Traction code: S (Steam), D (Diesel) and E (Electric).

Track code: s (single), d (double).

Choices in Cooking and Lighting Energy

The alternatives are: LPG, coal gas, firewood, kerosene, and biogas for cooking and electricity, and kerosene for lighting. The details are shown in Tables 5 and 6.

Table 5. Energy choices for cooking.

Fuel Units	LPG a/ (10^6 t)	Coal gas b/ ($10^9 m^3$)	Firewood (10^6 t)	Kerosene (10^6 t)	Coal (10^6 t)	Biogas b/ $10^9 m^3$
Cost 10^6 Rs/10^6 t or $10^9 m^3$	c/	240	10 d/	c/	95	196.7
Coal Replacement Factors	8.3	2 (t/1000m^3)	0.95	8.3	1.0	2.60 (t/1000m^3)
Nitrogen produced 10^6 t/$10^9 m^3$	-	-	-	-	-	.032

Table 5. (continued)

a/ LPG and coalgas are considered options only for urban areas, and biogas is confined to rural areas.

b/ Biogas coefficients refer to small family-sized units. The nitrogen produced is additional to what would be obtained by composting animal dung instead of feeding it in the plant.

c/ Costs determined by the model from prescribed crude and refining costs.

d/ Nonland costs.

Table 6. Choices in energy for lighting*

	Kerosene	Electricity	Biogas
Requirement per person per year	5 kg	40 kWh	220 m^3

*Progress of rural electrification is exogenously specified. Other substitutes are not strictly comparable to electricity.

Choices in Refinery Processes

Nine types of crude oil are considered--two from domestic fields, and seven imported crudes. The secondary processes include vacuum cracking, visbreaking, hydrocracking, and catalytic cracking. The choices considered are shown in Figure 3; details of activities are given in Appendix 3.

Choices in Electricity Generation

India is well endowed with coal, but the coal is of inferior quality and the reserves are geographically concentrated. The known reserves of oil and uranium are meager, but a vast amount of thorium is available. Thus a long-term development strategy has to be geared to the use of thorium either in HTRs or in FBRs. However, both these reactors require plutonium, which has to be produced as a joint product with electricity in a first generation nuclear power plant. For a country with small reserves of uranium (about 30,000 t), a neutron efficient path of CANDU reactors using natural uranium is attractive. In order to explore the choices in electricity generation which involve plutonium accumulation a multiperiod treatment is required. We have therefore treated electricity generation choices in a multiperiod framework. The choices available are shown in Table 7.

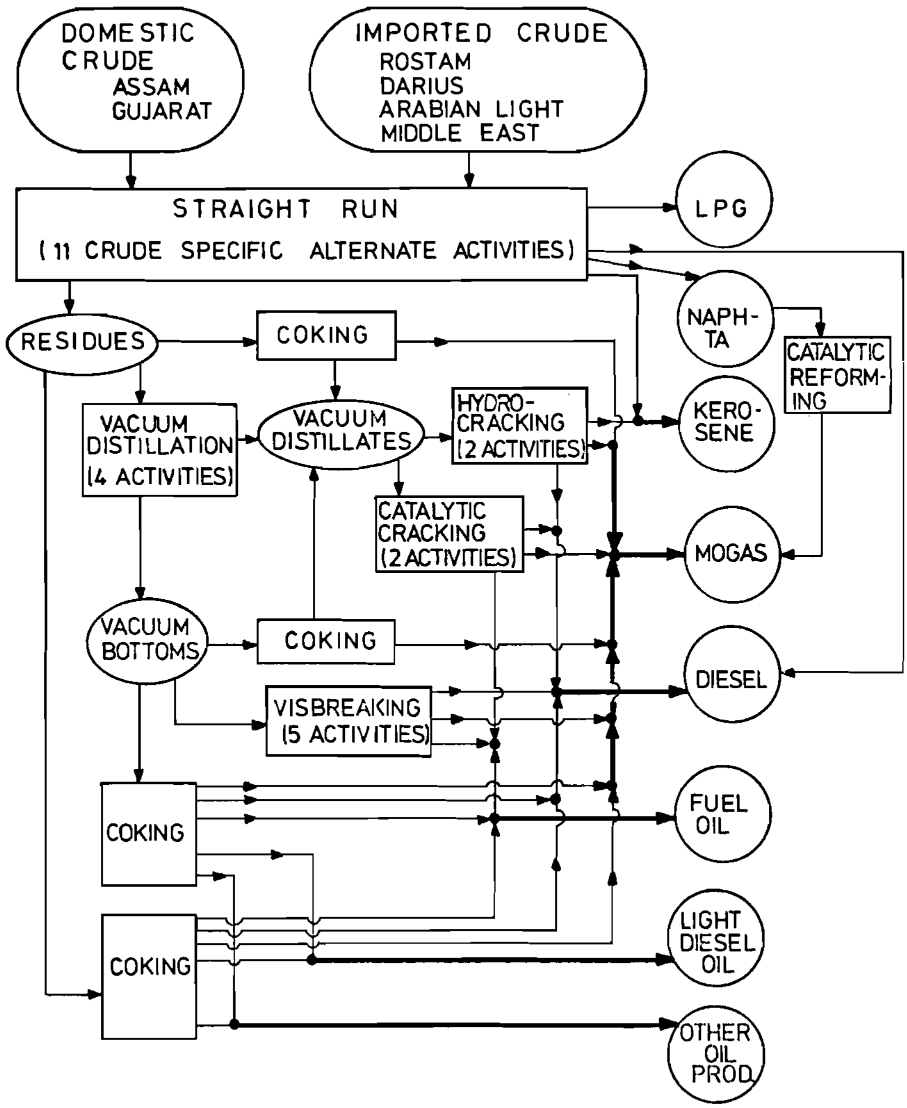

Figure 3. Choices in refining and secondary processing.

Table 7. Choices in electricity generation.

	Coal-Based Thermal Plant	CANDU Natural Uranium Based Nuclear Plant	Fast Breeder Reactor (FRR)	High Temperature Reactor (HTR)
Capital Cost (10^6 Rs/GW(e))	2050	3650	3100	3100
Operating Cost[a/] (10^6 Rs/10^9kWh)	32	12.3	10	10
Load Factor	0.8	0.85	0.85	0.85
Fuel Input Uranium (Natural)	-	-	-	-
(t/10^9kWh)	-	19.7	-	-
Coal (4500 kcal/kg)	-	-	-	-
10^6t/10^9kWh)	0.55	-	-	-
Plutonium (t/10^9kWh)	-	-	0.208	0.068
Fuel Inventory:				
Uranium (t/10^6 kw(e))	-	260	-	-
Fissile Plutonium (t/10^6kW(e))	-	-	3.5	-
Fuel Recovery:				
Fissile Plutonium (t/10^9kWh)	-	.0565	.276	-

[a/] Excluding plutonium credit.

Hydel development is assumed to be fixed exogenously. While a large number of good sites still remain to be developed, the pace of development is constrained primarily by construction capability. However, it is assumed that hydel plants in future will be used mainly for peaking and would have a load factor of 0.3 compared to the present hydel load factor of 0.6

Similarly the power available from the LWR reactor at Tarapore is taken as given, as the fuel for it comes from the USA under a special agreement.

The assumed availabilities of power from these sources are shown in Table 8.

Table 8. Availability of electricity from hydel plants and light water reactors (LWRs)

Mid-year	Hydel (10^9kWh)	LWR (10^9kWh)
1975-76	46	2
1980-81	66	2
1985-86	88	2
1990-91	109	2
1995-96	135	2
2000-01	158	2

Choices in Fertilizer Production

The main chemical fertilizers used in India are nitrogenous, phosphastic, and potassic fertilizers and their mixtures. Indian farmers tend to use relatively more nitrogenous fertilizers than would be optimal if they were to base their decisions on the experimental yield response functions. We have assumed that the potassic and phosphatic fertilizers are used in fixed ratios to the amount of nitrogenous fertilizers, these ratios being based on past behavior.

There are alternative ways of producing nitrogenous fertilizers while there is not much of a technological choice in the others. Further, animal dung is also a source of nitrogen. We assume that the amount of dung that was being composted before 1975 will in the future be put through biogas plants, and the extra nitrogen obtained by processing the dung through a biogas plant as compared to composting is a net addition to the supply of nitrogen.

The technological choices in the production of nitrogen (other than from dung) are described in Table 9.

Table 9. Choices in fertilizer feedstock[a].

	Fertilizer Plants Based on Feedstock		
	Naphtha	Fuel oil	Coal
Cost[b] 10^6 Rs per 10^6t of Nitrogen	848	935	1143.8
Feedstock Required (incl. fuel) 10^6 t/t of N)			
Naphtha	1.0724	-	-
Fuel Oil	0.3980	1.404	-
Coal	-	-	3.974

[a] Biogas fertilizers produced as joint product. For details see Table 5 on energy choices for cooking.

[b] Excluding cost of feedstocks.

RESULTS

The results of our various runs are presented in Tables 10, 11, and 12.

Table 10. Summary of fuel choices.

	Base Case	Oil Prices Doubled	Coal Costs Reduced 20%	Exogenous Availability Firewood Set at Zero	Domestic Crude Availability Increased 75%
Case No:	(1)	(2)	(3)	(4)	(5)
Total Consumption					
Coal[a] (10^6t)	593.322	647.781	627.029	650.322	574.765
Electricity[b] (10^6kWh)	467.907	476.277	*	*	459.060
Agriculture Sector					
Food Activity No.	10.	*	*	*	*
Fert. Nitrogen (10^6t)	7.328	*	*	*	*
From Coal	4.018	6.848	6.203	*	1.763
From Biogas	0.480	*	*	*	*
From Naphtha	2.830	0	0.645	*	5.085

Table 10. (continued)

Case No.			(1)	(2)	(3)	(4)	(5)
Transport Sector							
Urban Passenger (10^9 pkm)							
Electric Trains			320.0	*	*	*	*
Diesel Buses			640.0	608.182	*	*	*
Mogas Buses			0	31.818	*	*	*
Regional Passenger (10^6 pkm)							
Diesel Trains			0	*	*	*	552.911
Electric Trains			2020.0	*	*	*	1467.089
Goods Transport (10^9 tkm)[c/]							
Trains							
Traction	Tracks	Density class					
Steam	single(s)	1	20.0	*	*	*	*
"	double(s)	2	110.0	*	*	*	*
Diesel	s	3	270.0	*	*	*	*
"	s	4	270.0	0	*	*	*
Electric	d	4	0	270.0	*	*	*
"	d	5	190.0	*	*	*	*
"	d	6	140.0	*	*	*	*
Trucks Diesel		1	70.0	*	*	*	*
Domestic Sector							
Cooking							
Biogas ($10^9 m^3$)			15.000	*	*	*	*
Firewood (10^6t)			120.000	*	*	60.000	*
Coal (10^6t)			27.034	65.028	52.058	84.034	22.381
Kerosene (10^6t)			13.253	8.889	10.540	*	13.285
LPG (10^6t)			1.949	1.734	1.646	*	2.477
Lighting							
Kerosene (10^6t)			0.670	*	*	*	*
Electricity (10^9kWh)			38.400	*	*	*	*

* Indicates that the value is the same as in the base case.

a/ Includes coal for electricity generation.

b/ Excludes energy from hydel and LWR.

c/ For details regarding density classes see Table 4.

Table 11. Electricity generation.

	Base Case	Oil Prices Doubled	Coal Costs Reduced 20%	Exogenous Firewood Availability Set at Zero	Domestic Crude Availability Increased 75%
Case No:	(1)	(2)	(3)	(4)	(5)
Energy Generated (in 10^9kWh/year)					
CANDU (in period)					
1	2.234	*	*	*	*
2	5.957	*	*	*	*
3	6.739	*	*	*	*
4	85.122	*	*	*	79.190
5	85.122	*	*	*	87.642
6	85.122	*	*	*	87.642
FBR (in period)					
5	60.131	*	*	*	56.566
6	60.131	*	*	*	56.566
Thermal (in period)					
1	27.054	28.183	*	*	24.058
2	62.023	64.009	*	*	56.757
3	125.121	128.364	*	*	116.527
4	140.234	145.164	*	*	133.152
5	197.249	201.968	*	*	179.727
6	338.454	347.945	*	*	329.467
New Capacity Created (in GW(e))					
CANDU (in period)					
4	10.292	*	*	*	9.495
5	0	*	*	*	1.135
6	0	*	*	*	*
FBR (in period)					
5	8.076	*	*	*	7.597
6	0	*	*	*	
Coal (in period)					
4	1.012	1.714	*	*	0
5	8.134	8.106	*	*	6.646
6	20.149	20.830	*	*	21.367

* Indicates that the value is the same as in the base solution.

Table 12. Oil imports and refinery processes (10^6t).

	Base Case	Oil Prices Doubled	Coal Costs Reduced 20%	Exogenous Firewood Availability Set at Zero	Domestic Crude Availability Increased 75%
Case No:	(1)	(2)	(3)	(4)	(5)
Domestic Crude	40.000	*	*	*	70.0
Imported Crude	23.813	14.284	8.390	*	0
Imported Petroleum Products					
Fuel Oil	0	*	9.240	*	*
Others	13.320	*	13.306	*	*
Product Availability					
LPG	1.949	1.734	1.646	*	2.477
Kerosene	13.923	9.559	11.210	*	13.955
Diesel	15.469	14.044	*	*	17.851
Naphtha	6.035	3.0	3.692	*	8.453
Fuel Oil	14.026	12.9	13.157	*	14.924
Mogas	4.4	4.877	*	*	*
LDO	4.4	*	*	*	*
Others	15.0	*	*	*	*
Refinery Processes					
Straight Runs of Crude					
Assam 2	10.000	*	*	*	20.000
Gujarat 1	0	*	*	*	25.524
Gujarat 2	30.000	*	*	*	24.476
Middle East 1	0	14.284	8.390	*	*
Middle East 4	23.813	0	*	*	*
Cat. Refor, of Naph.	1.736	3.030	1.637	*	2.380
Hydrocrack. of Vac. Dist. 1	0	2.512	9.761	*	*
Hydrocrack. of Vac. Dist. 2	5.280	0	0	*	1.472
Vac. Dist. of Residues 3	8.756	9.961	0	*	13.083
Vac. Dist. of Residues 4	7.197	2.326	16.323	*	0
Visbreaking of Vac. Bott. 1	10.664	0	0	*	11.611
Visbreaking of Vac. Bott. 2	0	9.775	*	*	*
Coking of Residues 1	14.004	*	7.442	*	*
Coking of Vac. Bottoms 1	0	0	6.562	*	*

* Indicates that the value is the same as in the base solution.

In Table 10 we list the choices with respect to total energy, agriculture, transport, and domestic sectors. Case 1 is the base case to which all comparisons of other cases refer.

In the base case solution, food activity 10, which is a land-saving and fertilizer-intensive technology, is selected, and coal is preferred as feedstock for fertilizer manufacture. For urban passenger transport electric trains are selected up to the prescribed maximum and then diesel buses are selected. For goods transport trains with all three tractions, steam, diesel and electric, are selected depending upon the density of traffic on the route. Trucks are not selected beyond the prescribed minimum feeder traffic. For the domestic sector a mix of kerosene, LPG, coal, biogas, and firewood is selected.

Case 2 differs from case 1 in that the crude oil and product prices are doubled compared to the base case. This results in substantial reduction in the import of crude oil in case 2. The reduction of about 10 Mt in oil consumption is accomplished by increasing the consumption of coal by more than 54 Mt. Though the food activity 10 is still selected, naphtha is no longer used as a fertilizer feedstock. The saving in naphtha leads to increased availability of mogas, and mogas buses are used marginally for urban passenger transport. For goods transport in the density class 4, electric traction replaces diesel traction. In the domestic sector, as oil becomes more expensive in case 2, about 4.5 Mt of petroleum products are replaced by coal. As can be seen from Table 11, the increased requirement of electricity in case 2 comes from coal, and for nuclear plants the pattern of electricity generation in cases 1 and 2 are the same.

In case 3, the price of coal is decreased by 20 percent as compared to the base case. Naturally this results in an increase, over the base case, in the consumption of coal by nearly 34 Mt. Crude oil imports are reduced even more substantially than in case 2, but about 9 Mt of fuel oil are imported. The electricity generation remains unaltered. There is also no change in choices in the food activity and the transport sector. The bulk of the fertilizer manufacture is now coal based. In the domestic sector, coal replaces kerosene in rural cooking to a large extent. Since less of kerosene and diesel are consumed in cases 2 and 3, refinery processes get changed to accomodate this (see Table 12).

In case 4, the exogenous availability of firewood was set at zero instead of at 60 Mt. This reduction in the availability of an energy source for the domestic sector is made up entirely of coal, and no other change takes place in any of the sectors.

In case 5, availability of domestic crude was raised by 75 percent. As is to be expected, this eliminates the need for importing crude. Fertilizers are mainly produced with naphtha as feedstock but some coal is still used as feedstock. Regional passenger transport demand is now met partly by diesel trains. However, the choices in goods transport remain unaltered. In the domestic sector the relative proportions of coal, LPG, and kerosene change. The pattern of electricity generation is altered as slightly less electricity is required in this case compared to the base case.

In case 6, when the capital costs of FBR and HTR are increased by 20 percent over the base case, the solution is the same as in the base case and these results are not therefore tabulated separately.

As seen in Table 11, CANDU and FBR plants are installed in all cases, and the shadow price on uranium and plutonium constraints are positive. This is the case even when capital costs of FBRs are increased by 20 percent. However, the HTR is not selected in any of the cases.

The refinery processes vary from case to case as does the source of imported crude, depending upon the product mix that emerges. In all cases the product mix is such as to make economical secondary processing activities such as hydrocracking.

Family-sized biogas plants are found to be economical and in all cases are selected up to the prescribed limit of availability of animal dung.

In conclusion, we feel that the insensitivity observed, particularly in the agricultural sector, in food and fertilizer, production, in urban passenger, and in goods transport in the six cases treated indicates that the technological choices in these have to be modeled in greater detail. In particular, economies of scale in passenger transport should also be taken into account. Additional choices in the agricultural sector, such as those arising out of regional self sufficiency, should be introduced. Increasing costs in the production of coal is another improvement that can be made. Also our demand projections have not reflected the changes in costs arising from alternative production choices. This price inelasticity assumption should perhaps be revised, particularly with respect to transport choices. Finally, a truly dynamic version of the model has to be built.

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Appendix 1. The Mathematical Model

LIST OF SYMBOLS

r : Rate of annual discount.

t : Period from 1,2,..,T. (each period consists of 5 years, T = 6).

T : Terminal period, mid-year 2000-01.

Electricity Generation

k_i : Investment cost in 10^6 Rs/GW(e) of capacity for plant type i, i = CANDU, FBR, HTR, coal.

K_{it} : Capacity created at the beginning of t of plant type i in GW(e).

v_i : Operating cost in 10^6 Rs/10^9 kWh of plant type i.

E_{it} : Electricity generated in mid-year of period t from ith type plant in 10^9 kWh.

g_i : Energy that can be generated in one year from GW(e) of the ith type plant in 10^9 kWh/year.

p_{plut} : Price of plutonium in 10^6 Rs/t in mid-year of period 1.

$plut_i$: Plutonium produced or required per 10^9 kWh of generation from ith type of nuclear plant in t.

Pu_{inv} : Plutonium inventory required in t/GW(e) of installed capacity of FBR.

u_{inv} : Uranium inventory required in t/GW(e) of installed capacity of CANDU.

u_{CANDU} : Uranium required in t/10^9 kWh of generation from CANDU.

$elec_i$: 10^9 kWh of electricity required for ith need per year in period T.

$\overline{ELED}_t$: Exogenously specified demand for electricity for mid-year of period t in 10^9 kWh.

ELE_t : Demand for electricity in 10^9 kWh determined in the model.

$\overline{ELE}_o$: Base year demand for electricity in 10^9 kWh for agricultural use and for urban and rural lighting, urban and regional passenger transport by electric trains, and transport of goods by electric trains.

Food Production

i_j : Firewood produced per unit level food activity j.

a_j : Cost in Rs 10^6 for a unit level of food production activity j.

e_j : 10^9 kWh of energy required for pumping water for unit level of food activity $FOOD_j$.

$fert_j$: 10^6 t on N required for activity $FOOD_j$.

$FOOD_j$: Alternative activities to produce food. Unit level of any activity produces all the required food.

Fertilizer Production

f_i : Cost of ith type fertilizers, excluding the cost of fuel and feedstock, in 10^6 Rs/10^6 t of N from fertilizers $FERT_i$.

n : Naphtha required as feedstock per unit of nitrogenous fertilizers production.

$FERT_i$: Fertilizer produced by process using feedstock, i, i = naphtha (N) coal (C), biogas (BG), and fuel oil (FO).

β : Fuel oil required as feedstock per unit of nitrogenous fertilizer production.

Fuels

c_i : Cost of fuel type i in 10^6 Rs/10^6 t or 10^9 m^3.

$coal_i$: 10^6 t of coal required for ith need per year in period T.

$FUEL_i$: Fuel type i used, i = coal, electricity, kerosene, etc.

$\overline{COALD}$: Exogenous demand for coal in 10^6 t for mid-year of period T.

COAL : Total coal used other than for electricity production.

$\overline{U}$	: Uranium availability.
RCBG	: Animal dung used for biogas production for rural cooking.
$\overline{RCBGB}$	: Availability of animal dung for biogas production.

Energy

s_i^L, s_i^C	: Fuel to energy conversion ratios in 10^9 kWh/10^6 t or 10^9 m^3; for example s_{KER}^L converts kerosene to lighting energy.
R, U	: Prefixes stand for rural, and urban, respectively.
L,C	: Stand for lighting, and cooking, respectively.
E, KER,BG FW, C	: Stand for electricity, kerosene, biogas, firewood, and coal, respectively.
Example	: Rural lighting kerosene (in 10^6 t): RLKER.
$\overline{RLED}$	: Demand for energy for rural lighting.
$\overline{ULED}$	: Demand for energy for urban lighting.
$\overline{RLEE}$	: Exogenous supply of electrical energy for rural lighting.
$\overline{ULEE}$	: Exogenous supply of electrical energy for urban lighting.
$\overline{RCED}$	: Demand for energy for rural cooking.
$\overline{UCED}$	: Demand for energy for urban cooking.
$\overline{RCAW}$	: Exogenous supply of energy from agricultural wastes used in rural cooking.

Passenger Transport

$(up)_i$, $(rp)_i$	: Cost of urban passenger and regional passenger transport by mode i, excluding the cost of fuel, in 10^6 Rs/10^9 pkm.

UPK_i, RPK_i : Urban and regional passenger transport in 10^9 pkm carried by mode i, i = petrol buses, diesel buses, automobiles, scooters, electric, diesel and steam trains.

$\overline{UPKD}$, $\overline{RPKD}$: Urban and regional passenger transport in 10^9 pkm.

Goods Transport

$(gt)_{ij}$: Cost of goods transport by mode i for density class j in 10^6 Rs/10^9 tkm.

α_j : Fraction of rail route kilometer with traffic density of class j.

GTK_{ij} : Goods carried by trains of traction i in density class j, in 10^9 tkm, i = diesel (D), electric (E), steam (S).

$TRUK_c$: Goods tkm (10^9) carried by diesel trucks, competing with goods transported by rail, in 10^9 tkm.

$TRUK_f$: Volume of feeder traffic to be carried by diesel truck.

$\overline{TRUKD}$: Exogenously specified volume of feeder traffic.

$GTKD_j$: Goods carried in density class j in 10^9 tkm.

Petroleum and Oil Products

p_j : Price of crude oil in 10^6 Rs/10^6 t.

m_q : Price of imported oil product q in 10^6 Rs/10^6 t.

r_h : Cost of refinery process h in 10^6 Rs/10^6 t of processing per year.

$(rp)_h$: Coefficients of refinery process activity h.

$REFIN_h$: Level of refining activity hm 10^6 t of input.

d_{rb}, d_{ub}, d_{rt}, d_{gm}, d_{gt} : Diesel required for regional and urban passenger transport by buses, for regional passenger transport by trains, and for goods transport by trucks and trains per unit per year.

pet_a, pet_b, pet_s	: Petrol required by automobiles, buses, and scooter per unit per year for passenger transport.
$OILPR_q$	: Oil product q imported, q = mogas, naphtha, kerosene diesel, fuel oil, light diesel oil, and other products.
$CRUD_j$	: Crude used, j = domestic (D), imported (M).
$\overline{CRUDD}$	: Exogenously specified domestic crude availability.
MOGAS	: Motor gasoline
DIESEL	: Diesel
KERO	: Kerosene
$\overline{KEROD}$	: Exogenously specified portion of kerosene demand.
NAPHTHA	: Naphtha.
$\overline{NAPTHAD}$	: Exogenously specified portion of naphtha demand.
FOIL	: Fuel oil.
$\overline{FOILD}$	: Exogenously specified portion of fuel oil demand.
LDO	: Light diesel oil.
$\overline{LDOD}$	: Exogenously specified portion of light diesel oil demand.
OOPS	: Other oil products in 10^6 t.
$\overline{OOPSD}$	: Exogenously specified portion of other oil products demand.

(1) Objective Function: Minimize

$$Z = \sum_{t=1}^{T} (1+r)^{-(5t-5)} \sum_{i} (K_{it} + 5v_i E_{it})$$

Costs of capacity K_{it} and energy E_{it} of plant type i installed at t.
i = CANDU, FBR, HTR, and coal.

$$- \sum_{t=1}^{T} \sum_{j=1}^{30-5(T-t+1)} (1+r)^{-(5T-5+j)} \sum_{i} (v_i - v_{coal}) g_i \, K_{it}$$

Credit for post terminal cost advantage
i = CANDU, FBR, HTR, and coal.

$$- p_{plut} \sum_{t=1}^{T} \sum_{j=5t}^{30+5t-1} (1+r)^{-(j-5)} \left\{ \sum_{i} plut_i E_{it} - plut_{htr} E_{htr,t} - Pu_{inv} K_{fbr,t} \right\}$$

Credit for plutonium surplus
i = CANDU, FBR.

$$- 5(1+r)^{-(5T-5)} \left[\sum_{j=1}^{10} a_j \, FOOD_j + \sum_{i} f_i \, FERT_i \right]$$

Nonfuel and fertilizer feedstock cost in agriculture
i = naphtha, coal and fuel oil.

$$+ \sum_{i} (up)_i \, UPK_i + (rp)_i \, RPK_i$$

Nonfuel cost of passenger transport, i = electric trains, diesel trains, steam trains, petrol, and diesel buses.

$$+ \sum_{j=1}^{6} \sum_{i} (gt)_{ij} \, GTK_{ij} + (gt)_{truck} \, (TRUK_f + TRUK_c)$$

Nonfuel costs of goods transport, i = electric, diesel, and steam trains.

$$+ \sum c_i\ FUEL_i + \sum_j p_j\ CRUD_j + \sum_q m_q + \sum_{h=1}^{30} r_h\ REFIN_h \Big]$$

Fuel, crude, oil products and refining costs i = coal, kerosene, diesel, mogas, LPG, fuel oil, biogas, and firewood
j=domestic, imported
q=imported kerosene, HSDO, LDO, mogas, naphtha, fuel oil, and OOPS.

Subject to:

(2) $\overline{ELED}_t + ELE_t \leq \sum_i E_{it}$

Demand ≤ supply constraint for electricity t = 1,...,T.
i = CANDU, FBR, HTR, coal.

(2a) $ELE_T = \sum_{j=1}^{10} e_j\ FOOD_j + \sum_i elec_i$

i = urban lighting, rural lighting, electricity for transport of urban passenger, regional passenger, and goods.

(2b) $ELE_t = \overline{ELE}_o \dfrac{(ELE_T - \overline{ELE}_o)^{t/T}}{\overline{ELE}_o}$

(3) $\overline{COALD} + \sum_i coal_i \leq COAL$

Demand ≤ supply constraint for coal i = fertilizer, urban cooking, rural cooking, goods per tkm regional pkm carried by steam traction.

(4) $\sum_{j=1}^{10} fert_j\ FOOD_j \leq \sum_i FERT_i$

Demand ≤ supply constraint for fertilizers i = naphtha, fuel oil, coal, biogas.

(5)	$\sum_{j=1}^{10} FOOD_j \geq 1.0$	Supply of food ≥ requirement.
(6)	(a) $\sum_i s_i^L RL_i \; \overline{RLED} - \overline{RLEE}$	Domestic energy for lighting ≥ demand (a) Rural: i = electricity, kerosene, and biogas.
	(b) $s_{Elec}^L ULE \geq \overline{ULED} - \overline{ULEE}$	(b) Urban: i = electricity.
(7)	(a) $\sum_i s_i^C RC_i \geq \overline{RCED} - \overline{RCAW}$	Energy available for cooking ≥ demand (a) Rural cooking: i = firewood, biogas, coal, kerosene.
	(b) $\sum_i s_i^C UC_i \geq \overline{UCED}$	(b) Urban cooking: i = firewood, coal, kerosene, LPG.
(8)	$RCFW + UCFW \leq \sum_{j=1}^{10} l_j \; FOOD_j$	Availability of firewood ≥ demand.
(9)	$RCBG \leq \overline{RCBGB}$	Availability of animal dung for biogas ≥ dung used for biogas production.
(10)		Passenger transport carried by all modes ≥ demand.
	(a) $\sum_i UPK_i \geq \overline{UPKD}$, $UPKTE = 0.3 \; \overline{UPKD}$	Urban: i = buses (diesel and petrol) electric trains automobiles and scooters.

(b) $\sum_{i} RPK_i \geq \overline{RPKD}$	<u>Regional</u>: i = diesel buses and trains, electric and steam trains.
(11) $\alpha_j\ TRUK_c + \sum_{i} GTK_{ij} \geq \overline{GTKD}_J$	Goods transport carried by all modes ≥ demand i = trains (electric, diesel, and steam) j = density class
j = 1,..., 6 density classes	
$TRUK_f \geq \overline{TRUKD}$	
(12)	Supply for oil products ≥ demand
(a) $MOGAS \geq PET_b UPKBP + pet_a UPKA + pet_s UPKS$	Motor gasoline (mogas)
(b) $DIESEL \geq d_{ub} UPKBD + d_{rb} RPKBD + d_{rt} RPKTD +$	Diesel
$+ d_{gt} \sum_{j=1}^{6} GTKD_j + d_{gm} \left\{ TRUK_f + TRUK_c \right\}$	
(c) $KERO \geq RCKER + UCKER + RLKER + \overline{KEROD}$	Kerosene
(d) $NAPHTHA \geq n.\ FERTFO + \overline{FOILD}$	Naphtha
(e) $FOIL \geq \beta\ FERTFO + \overline{FOILD}$	Fuel oil
(f) $LDO \geq \overline{LDOD}$	Light diesel oil
(g) $OOPS \geq \overline{OOPSD}$	Other oil products

(13) CRUDE $\geq$ CRUDD + CRUDM — Refinery balances

CRUDD $\leq \overline{\text{CRUDD}}$

$$\begin{Bmatrix} \text{CRUDE} \\ \text{LPG} \\ \text{NAPHTHA} \\ \text{KERO} \\ \text{DIESEL} \\ \text{LDO} \\ \text{RESIDUE} \\ \text{FOIL} \\ \text{MOGAS} \\ \text{OOPS} \end{Bmatrix} \leq \left[\quad rp \quad \right] \begin{Bmatrix} \text{REFIN}_1 \\ \\ \\ \text{REFIN}_{30} \end{Bmatrix} + \begin{Bmatrix} \text{OILPR}_1 \\ \cdot \\ \cdot \\ \text{OILPR}_q \\ \cdot \\ \cdot \\ \cdot \end{Bmatrix}$$

The refining processes $(rp)_1,\ldots,(rp)_{30}$ are described in Appendix 3.

(14) $E_{it} \leq g_{it} K_{it}$ — Output $\leq$ capacity electricity generation, i = CANDU, FBR, HTR, coal, t = 1,...,T.

(15) $\sum_{t=1}^{T} u_{inv} K_{candu,\ t} + \sum_{t=1}^{T} 5u_{candu} E_{candu,\ t} \leq \overline{U}$ — Uranium $\leq$ availability

(16) $\sum_{t=1}^{T} \Big[Pu_{inv} K_{fbr,\ t} + 5plut_{htr,t} E_{htr,t} - 5plut_{fbr} E_{fbr,t-1}$ — Plutonium availability $\geq$ plutonium used

$$- 5plut_{candu,t-1} E_{candu,t-1} \Big] \leq 0$$

$t' = 1,\ldots,T$

$$\sum_{t=2}^{T} \sum_{j=t+1}^{t+5} + 5 \Big[plut_{htr}\, g_{htr}\, K_{htr,t} - \sum_{i=candu,fbr} plut_i\, g_i\, K_{it} \Big] \leq 0$$

Appendix 2. Alternative activities to produce required output of food.

Item	Food Activities									
Irrign. Potential realized (%)	85	75	65	75	85	80	75	72	68	65
Addl. Area (10^6 ha)	20	20	20	10	0	0	0	0	0	0
Activity	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Wheat output: (78 Mt)										
Nitrogen (10^6 t)	1.222	1.417	1.635	1.562	1.413	1.513	1.630	1.706	1.846	1.965
Land (10^6 ha)	26.617	26.617	26.617	26.066	25.606	25.606	25.606	25.606	25.606	25.606
Irrigated area (10^6 ha)	23.364	19.619	17.966	19.443	20.623	19.417	18.211	17.487	16.522	15.798
Paddy output: (180 Mt)										
Nitrogen (10^6 t)	2.435	2.418	2.483	2.975	3.532	3.543	3.606	3.657	3.758	3.897
Land (10^6 ha)	50.268	50.268	50.268	47.700	45.566	45.566	45.566	45.566	45.566	45.566
Irrigated area (10^6 ha)	33.318	31.137	28.051	29.059	29.555	28.313	26.991	26.178	25.075	24.141
All Food Crops										
Nitrogen (10^6 t)	4.571	4.794	5.148	5.671	6.181	6.320	6.545	6.704	7.005	7.328
Irrigated area (10^6 ha)	70.850	63.445	57.521	60.628	62.723	59.663	56.503	54.581	51.996	49.924
Elec. energy for										
Irrigation (10^9kWh)	41.5	39.2	37.35	37.4	36.7	35.9	34.85	34.2	33.3	32.45
Firewood (10^6 t)	0	0	0	32.4	60.0	60.0	60.0	60.0	60.0	60.0
Annual Cost (10^6 Rs)										
Discounted	3166	2896	2693	2871	2987	2890	2791	2725	2652	2607
Undiscounted	34303	31377	29178	31107	32363	31312	30240	29525	29734	28246

Notes:

Area and nitrogen requirements for wheat and paddy assumed to be 80 percent of the total.

Cropping intensity taken to be 1.67 for irrigated land.

Lift irrigation assumed to decrease at the rate of 2.5% for every increase of 10% in the irrigation potential, from a value of 50% for 65% irrigation potential.

Energy required per hectare of lift irrigation is 1300 kWh/year.

A ha of land gives 12.35 t of firewood per year.

Appendix 3. Refining and secondary processing activities (rp_h)
(typed row-wise for convenience).

Products: / Activities	Crude	Gas	Naph-tha	Kero-sene	HSDO	LDO	Resi-due	Vacuum disti-lates	Vacuum bottom	Fuel oil	Motor gas	Other oil products
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Assam crude (AS)												
1	-1.0	.0160	.1440	.1900	.2760	.0	.3740	-	-	-	-	-
2	-1.0	.0290	.0970	.1690	.2750	.0	.4300	-	-	-	-	-
Gujarat crude (GU)												
1	-1.0	.0350	.2410	.2470	.2600	.0	.2170	-	-	-	-	-
2	-1.0	.0410	.1120	.1480	.1700	.0	.5290	-	-	-	-	-
Middle East crude (ME)												
1	-1.0	.0150	.1190	.1750	.2625	.0	.4285	-	-	-	-	-
2	-1.0	.0150	.1400	.1900	.2300	.0	.4250	-	-	-	-	-
3	-1.0	.0220	.1590	.1530	.1790	.0	.4870	-	-	-	-	-
4	-1.0	.0180	.1445	.2295	.1970	.0	.4110					
Aga Jari (AJ)	-1.0	.0345	.1605	.1400	.2020	.0	.4630	-	-	-	-	-
Rostam (ROST)	-1.0	.0150	.1520	.1970	.2350	.0	.4010	-	-	-	-	-
Arabian Light (ARL)	-1.0	.0330	.1300	.1900	.1860	.0	.4610	-	-	-	-	-
Darius (DAR)	-1.0	.0170	.1780	.1780	.1960	.0	.4310	-	-	-	-	-
Vacuum Distillation of Residue (VACRD)												
1	0	0	0	0	0	0	-1.0	.5702	.4293	-	-	-
2	0	0	0	0	0	0	-1.0	.5037	.4959	-	-	-
3	0	0	0	0	0	0	-1.0	.1125	.8875	-	-	-
4	0	0	0	0	0	0	-1.0	.5980	.4020	-	-	-

Appendix 3. (continued)

Activity	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Visbreaking of Vacuum Bottom (VBVB)												
1	0	0	0	0	0	0	0	0	-1.0	.9480	.0520	-
2	0	0	0	0	.0297	0	0	0	-1.0	.9190	.0396	-
3	0	0	0	0	.0323	0	0	0	-1.0	.9226	.0297	-
4	0	0	0	0	0	0	0	0	-1.0	.8791	.0906	-
5	0	0	0	0	0	0	0	0	-1.0	.9479	.0520	-
Catalytic Reforming of Naphtha (CATRF)	0	0	-1.0	0	0	0	0	0	0	0	.8410	-
Hydrocracking of Vacuum Distillate (HCVD)												
1	0	0	0	.3700	.4500	0	0	-1.0	0	0	.1492	-
2	0	0	0	.4400	.3600	0	0	-1.0	0	0	.1547	-
Catalytic Cracking of Vacuum Distillates (CATVD)												
1	0	0	0	0	.1931	0	0	-1.0	0	.5238	.1401	-
2	0	0	0	0	.1931	0	0	-1.0	0	.5238	.1402	-
Coking of Vacuum Bottom (CVB)												
1	0	0	0	0	.0731	.3142	0	0	-1.0	.2797	.1119	.1200
2	0	0	0	0	0	0	0	.80	-1.0	0	.0300	0
Coking of Residues (CR)												
1	0	0	0	0	.0731	.3142	-1.0	0	0	.2797	.1119	.1200
2	0	0	0	0	0	0	-1.0	.80	0	0	.0300	0