An Integrated Framework for Analysis of Korea's Electric Sector Investment

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I. Introduction

The motivation for this paper is the major finding of the "Final Report of Korea Energy Policy Study Mission" prepared in May, 1979 by the UNDP/IBRD. According to this paper, the Koreans' existing electric program depends excessively on nuclear energy which is expected to account for over 75% of total energy output (377,000 Gwh), and approximately 60% of total generating capacity (80 Gwe) by the year 2000. The report notes that such ambitious nuclear plans would face significant problems of man-power, natural resource and capital requirements, even if "optimal" in the narrow sense of minimum direct engineering cost. No approach for the quantitative analysis and assessment of these issue is offered, however. The proposed research therefore seeks to develop a framework in which these issues may be analyzed *quantitatively*.

The problem noted in the UNDP/IBRD report stems from the quite widespread practice of analyzing electric sector expansion problems in terms of the direct costs to the planning agency (or electric authority) charged with responsibility for that sector; mathematical tools used to identify optimal expansion plans are formulated only in terms of minimization of total present worth. Thus constraints on capital, on foreign exchange, on availability of

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sufficient trained manpower, etc., are not included in such modelling frameworks as WASP,[1] used by the Korean electric utility.

It follows from all of this that a more comprehensive analytical framework is required to adequately analyze these issues when the electric sector has a significant impact on macroeconomics. In particular the framework must account for the relationship of electric demand with overall economic development, and for the relationships between the investment capital required to meet stated levels of electric demand with overall investment planning and balance of payments (or foreign exchange requirements). An explicit link to manpower and development is also required, since different expansion plans differ in their labor intensity and the mix of skills required for construction and operation.

The continued rise in the real price of oil since the 1973 oil embargo has raised energy problem throughout the world. Most developing countries have experienced pressing problems in accommodating their economies to this new situation. They are incurring increasing difficulties resulting from increased payment for imported energy.

A variety of resources are used to satisfy the demand for energy in Korea. They are coal (anthracite, bituminous), oil, hydro, nuclear and firewood, accounting for 27.5, 61.2, 1.3, 1.6, and 8.4% respectively, of the primary energy consumed in 1978. The consumption of all energy resource in that year was about 1.512×10^{18} joules (242 million bbl oil equivalent). The total primary energy consumption has risen at an 8.8% annual rate during the 1965-1978 period. The demand for electrical energy has been growing at an even more rapid rate of approximately 20% over the same interval. About 20.1% of the resources consumed in 1978 were in the generation of electricity. Coal, oil, nuclear, and hydro are the resources, accounting for 4.1, 81.6, 8.1, and 6.2% respectively, of fuel consumed for generation in 1978. If the present growth rates were to persist to the year 2000, a total resource consumption of 9.67×10^{18} joules (1550 million bbl oil equivalent) would be reached at that time and electric utilities would account for about 56% of that total.

1 See Jenkins and Joy (1974)

The high degree of dependence on oil is an important characteristic of LDC energy use.[2] The vast majority of the developing countries depend in varying degrees on imported oil. For example, Brazil and Korea — industrialized LDCs — have a growing demand for oil and could become increasingly dependent on imports unless they develop alternative sources. Korean's oil consumption accounted for only 10% of total primary energy consumption until 1965, growing to 61% in 1978. In Brazil, oil consumption accounted for 33.8% of primary energy in 1967, growing to 41.7% in 1977. In addition, heavy investments in electric power will be necessary in such countries because the industrialization that is an inescapable aspect of economic development will greatly increase their reliance on electric power. Electric power is generally capital intensive, but it will be even more so if oil, gas, and coal are not available, and nuclear and hydroelectric power (or, in the more distant future, solar energy) must be used. It seems likely that the developing countries as a whole will concentrate their investments in nuclear and hydroelectric power and that they will have to import increasing amounts of oil and uranium.

As a result of the increased oil import burden, oil-importing LDCs have run large balance of payments (current account) deficits, have seen their terms of trade deteriorate, and have incurred increasing amounts of debt to finance decreasing rates of economic growth. Furthermore, LDCs' needs for massive investments in the electric sector will greatly magnify their financial problems.

The financing constraint is the essence of the energy problem for LDCs. Another constraint which is likely to be a serious problem is the availability of skilled construction and operating manpower. Physical, social and institutional infra structure bottlenecks are likely to be also severe constraints for these countries.

The literature on electric sector investment planning is of varying quality. The state-of-the art is essentially summarized in Anderson,[3] and Turvey.[4] Much effort has been devoted to the use of mathematical programming models for power system planning

2 See Palmedo and Nathans (1978)
3 See Anderson (1972)
4 See Turvey and Anderson (1977)

problems; including linear programming (LP),[5] simulation techniques,[6] mixed-integer programming (MIP),[7] non-linear programming (NLP),[8] the use of dynamic programming (DP),[9] and probabilistic simulation and dynamic programming.[10] All of these are for the problem referred to as the "generating mix optimization" problem in the narrow sense of minimum direct engineering cost.

Because of lack of compatibility and integration, however, those models are clearly no longer appropriate to the developing countries faced with the overall economic, capital, and resource problem. This has led to the evolution of another approach of integration by considering the interactions of economic feedback to electric sector planning. For example, the BNL-Harvard-University of Illinois group developed a model used by ERDA for long-range planning in 1977. That effort linked the BNL LP version of RES, called BESOM, the University of Illinois 110-sector national IO model, and the Hudson-Jorgenson macroeconomic growth model.[11] Alan Manne developed the ETA-MACRO model,[12] which integrates a process analysis of energy technology assessment with a macroeconomic growth model providing for substitution between capital, labor, and energy inputs. The electric sector investment problem examined in this paper is based on an analysis of the integrated framework performed by the author at BNL over the period 1979-1981.

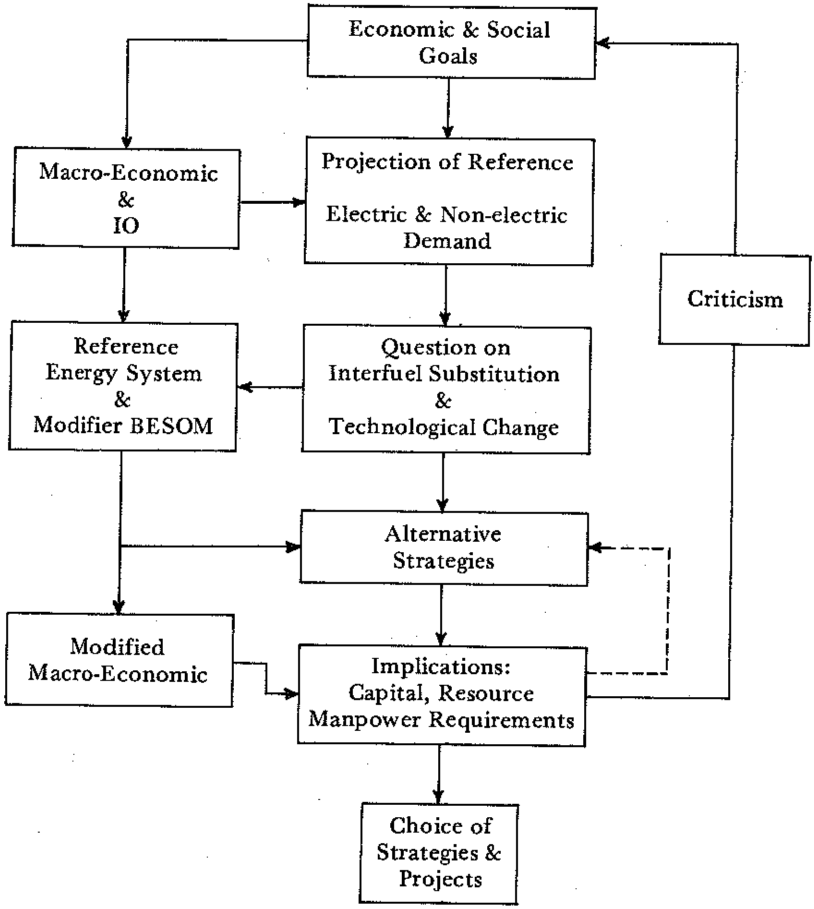
II. Methodology

The framework (see Figure 1) will account for the important strategic decision problem in electric sector investment planning which concerns the installation of new generating plants. The decision parameters in this problem include selecting the size, type, and date of installation of the new generating plants.

5 See Anderson and Tarkan (1972) and PIES Documentation (1976)
6 See Jacoby (1967)
7 See Gately (1971)
8 See Noonan (1974)
9 See Dale (1966)
10 See Joy and Jenkins (1971)
11 See Hoffman (1971), Cherniavsky (1974) and Hudson and Jorgenson (1977)
12 See Monne (1977)

Figure 1

OVERALL FRAMEWORK OF STUDY



The framework will ensure that each capacity expansion alternative is linked quantitatively, and consistently, with a given economic development plan. The feasibility of any particular GNP/economic/electric scenario will, in general, depend largely on the feasibility of the implied balance of payments and the overall ability to raise the necessary capital.

The framework will also provide a quantitative basis for analyzing capital shortage and manpower requirements in electric sector investment planning. Within this framework the equilibrated investments in the electric sector and other sectors with balanced GNP will also be calculated.

The modelling approach for this study employs an integrated set of technological and economic models to explore the national energy and economy response to electric sector expansion planning. The integrated system is composed of three component models: a macroeconomic model of economic growth, an energy input-output (IO) model, and an energy network flow model.

The macroeconomic model developed by the Korea Development Institute (KDI) was chosen to reflect the structure and trends of economic growth of Korea and is dynamic in structure. The energy input-output (IO) model for Korea developed in this study is used to estimate detailed sectoral outputs, consistent with basic energy demand responding to changes in final demand. The energy network flow model is used to optimize energy allocation of primary energy supplies to conversion and end-use activities. In order to implement energy network flow analysis, the Fortran version of BESOM LP model, structured around a Reference Energy System (RES), is used.

In this study, two integrated models — model 1 and model 2 — will be described which differ primarily in terms of algorithmic structure. The contribution of this paper may be viewed as the development of integrated modelling framework linking energy and the rest of the economy, and the calibration of the economic impact of electric sector planning in developing countries.

2.1. The KDI Macroeconomic Model

The South Korea macroeconomic model of inflation and growth is composed of 1) a set of macroeconometric behavioral equations which are expressed in terms of variables in percentage change (growth rate) form, and 2) macroeconomic identities. Its structure is recursive for each time period. The principal endogenous variables of the model are output, the price level, the wage rate, imports, fixed investment, inventory investment, savings consumption, employment, and migration. The model projects variables in both current and constant prices. The sample period for estimation is taken to be 1960-1979, with earlier years used for lagged values as required. The main instruments of the model are the exchange rate, the nominal money supply, and the farmer's selling price for agricultural products. The main exogenous variables are the level of gross agricultural output, net factor income from abroad, population, and some perspectives on world economy such as growth of world trade volume.

The basic concepts underlying the model specification are as follows:

a) Output is determined by expectations and by the availability of domestic credit, subject to the existing stock of fixed capital. The relevant expectations include prices and effective demand levels, e.g., the governments' annual export target.

b) Prices are determined mainly by the relative levels of nominal money supply and the real demand for money, plus movements in the primary price — the price of imports.

c) Consumption expenditures are determined by permanent disposable income, wealth, and price level, while investments are determined by output growth and by foreign capital inflows together with domestic credit availability.

d) Export level is determined partly by the volume of world trade and partly by the exchange rate and income of major trading countries, where import requirements are responsive to the level of output and exchange rate.

In essence, it is a "demand-dominated"[13] model in a double sense:

- demand expectations help determine output.
- output determines the increment in capital stock.
- the capital increment, plus foreign savings behavior, determine domestic savings.

The KDI version is a 3-sector model, consisting of agriculture, industry, and services sectors. The energy sector is not disaggregated so that the KDI model lacks the capability to analyze the energy sector quantitatively. In the version, the non-electric sector (coal mining, petroleum refining, and coal products) is aggregated into the industrial sector, and the electric sector is aggregated into the service sector.

13 See Oh and Yoo (1975)

The KDI model has been modified in this study by taking out the energy sector, which is called the "modified" version.

2.2 Modified Macroeconomic Model

As discussed previously, the primary motivation of this study is to analyze impacts of electric sector investments and energy imports on the macroeconomy in terms of changing GNP, trade balance (TB) and balance of payments (BOP). In order to perform this, we need a macroeconomic model which can give feedback effects of investment in the electric sector and energy imports, which are exogenous input to the macroeconomic model. However, within the KDI model, the electric sector is aggregated into the service sector and energy imports are aggregated into "commodity imports." To avoid double-accounting effects, we develop our "modified" macroeconomic model.

The major work done for developing our modified version was the separation of the energy sector from the original KDI model. The electric sector was removed from the service sector. Similarly, the energy imports were removed from the sector "aggregated commodity imports."

2.3 Energy Input-Output Model

The initial work on input-output analysis (or inter-industry accounts) was done by Leontief[14] in the 1930's.

The interindustry structure of an IO transaction matrix provides a significant degree of disaggregation. This permits detailed sectoral analysis within the context of the national economy. The IO accounting framework is particularly useful in ensuring intersectoral consistency of economic projections as well as consistency between sectors and more aggregate measures of economic activity such as GNP.

The basic supply/demand balance in the conventional IO Model is as follows:

$$AX + Y = X$$

where A = the matrix of technical production coefficients, obtained by dividing each entry in an industry

14 See Leontief (1966)

column by the gross output for that industry
X = vector of gross domestic outputs
Y = vector of final demands.

One obtains the solution for gross output

$$X = (I - A)^{-1}Y$$

where I = the identity matrix.

This solution may be used to estimate the effects of a change in one or more of the final demand levels. Policy-induced changes in the structure of GNP final demand as well as behavioral economic changes can then be evaluated as to their effects on sectoral demands for output. In the $(I - A)^{-1}$ matrix, the sum of column coefficients, a_{ij}, indicates the total increase in output for all industries that results from one unit change in the final demand for industry j.

The basic assumption associated with the static IO model is technological constancy. In input-output terms, the matrix of technical coefficients represents the technology of the economy, and the assumption that each element on the matrix does not change over time implies that technology used in the future will be identical to that today. It also implies that the economy will exhibit constant returns to scale in expanding output. The limitation of constant input coefficients in conventional IO models is improved by changing input coefficients of energy supply sectors defined in the energy IO model by using a coupled energy IO/LP model.

The initial U.S. energy IO model was constructed at the University of Illinoise.[15] Several distinguishing characteristics of the energy IO model developed here differentiate it from conventional interindustry IO models. The treatment of energy here represents a departure from conventional IO analysis. First, energy sector outputs are expressed in terms of physical units (Btu, Joules, etc.) rather than monetary units as are the non-energy sectors. Second, outputs of the energy supply/conversion sectors are distributed to non-energy sectors via "dummy" energy product sectors.

This structure allows the specification of transactions in terms of fuels and end uses. The dummy energy product sectors define end-use demands for energy exhibiting a limited degree of

15 See Herendeen (1973)

substitutability; coal-based feedstocks, oil-based feedstocks, motive power, industrial process heat, etc.

Finally, the framework of the energy IO model permits the addition of new energy technologies and revision of existing technologies by the user's specification of appropriate production functions derived from engineering data and technical relationships. The functional end-uses provide a basis for interfacing engineering concepts with economic behavior. By specifying energy input requirements to non-energy sectors in terms of energy products, substitution among fuel supplies is permitted. Furthermore, technological change associated with fuel substitution is captured in the production function of the energy supply/conversion sectors.

The development of the Korean version of the energy IO model developed by the author in this study is based on the 1975 conventional IO table of the Bank of Korea (BOK). The 1975 conventional IO table was the latest one which was available, and contains 60 sectors; 56 non-energy sectors and 4 energy sectors (coal, petroleum products, coal products, electric power). The 56 non-energy sectors were reaggregated into 21 non-energy sectors by considering technological homogeneity and degree of energy intensity.

2.4 The Energy Network Flow Model

Reference Energy System Analysis

A good starting point for any energy modelling is a base year energy balance that reconciles energy supply, conversion, distribution, and end use. The Reference Energy System (RES), developed by Hoffman, is a convenient graphical portrayal of the more usual energy balance table. It stresses the notion of energy flow through the economy, with an accounting of energy losses at each stage of conversion, distribution, and end use.

The RES is a network representation of the overall energy system encompassing all of the physical activities required in the supply and utilization of various forms of energy used to deliver energy services. Technologies are represented for all operations involving specific fuels, including their extraction, refinement, conversion, transport, distribution, and utilization. Each of these activities is represented by a link in the network for which efficiency, environmental residuals, and the cost coefficients may be specified. The network is quantified for a given year with the level of energy demands, and the energy flows through the supply activities that are required to serve those demands. The total environmental residuals, resource consumption, and costs for the energy system are tabulated for each planning year on the RES. It provides a compact information system that can be used directly, in a manual fashion or with computer assistance, for the evaluation of alternative policies and technologies. The Reference Energy System is designed to permit the assessment of individual technologies, or a broad set of technologies and policies ranging across all supply and utilization options, with emphasis on the potential markets for the technologies.

A major feature of the RES is the treatment of end-use devices as a part of the energy system, and the correlation of energy demands in these devices with functional definitions of energy services. That is, demands are defined in terms of vehicle-miles traveled and households to be heated, as examples. The levels of services, defined in a base year and projected to future years, thus serve as demand drivers for the energy system and are translated into energy units (Btu per year) needed to provide the required service levels.

The high level of technical details is necessary to permit the assessment of interfuel substitution strategies, analysis of conservation options, and analysis of the impact of introduction of advanced technologies. Additionally, this comprehensive framework provides the ability to analyze both centralized and decentralized technologies, since the detail associated with energy transmission and distribution systems is also included.

The Brookhaven Energy System Optimization Model

The Brookhaven Energy System Optimization Model (BESOM) is a linear programming model that was developed for the quantitative evaluation of energy technologies and policies within a systems framework. BESOM is structured around an RES that depicts the flow of energy from a resource to the point of actual end-use. BESOM is designed to examine interfuel substitution in the context of constraints on the availability of competing resources and technologies and their associated costs. BESOM is a static model that provides a "snapshot" of the energy configuration at a single year in time. However, BESOM can be applied in a sequential or time step mode; at each step additions to satisfy new demands and replacement of existing stock are optimized. The model's unified framework is particularly well suited to energy technology assessment and policy analysis since it emphasizes technological, economic, and environmental factors. BESOM's linear programming format lends itself to the investigation of alternative scenarios by minimizing different objective functions, such as total system costs, oil imports, capital requirements, environmental residuals, and natural resource use. The resulting linear program, BESOM, solves for z such that

$$\begin{aligned} &\min\ Cz \\ \text{subject to}\quad &Dz = d \\ &Sz \leq s \\ &Bz \leq b \\ &z \geq 0 \end{aligned}$$

where

- C = a vector of unit costs
- z = a vector of activities that represent the Btu flows in particular segments of the RES network
- d = a vector of end-use demands (the right-hand side of the RES)
- s = a vector of supply constraints
- b = a vector of all other constraints

and D, S, B represent the corresponding coefficient matrices. This model is described in more detail by Hoffman, and by Cherniavsky.

III. Integrated Analytical Framework

3.1 Integrated Model 1

The integrated model 1 is composed of the KDI macro model, a final demand linkage program, the Korea energy IO model, a linkage program from IO to LP, the BESOM LP model, a linkage program from LP to IO and our modified macro model. The starting point of integrated model 1 is the KDI macroeconomic model, which drives the final demand components: private consumption, government consumption, fixed investment, inventory change, exports and imports. The final demand linkage program calculates final demand to be used for the energy IO model. With final demand, the Korea energy IO model calculates gross outputs of the energy supply sector, energy product sector and non-energy sector. The gross output of the energy product sector, X_P, represents the energy demands categorized by the Korea energy IO model. The energy demands associated with BESOM LP demand categories are obtained by interface equations from the IO to LP. The BESOM LP is then solved, and the convergence is checked by termination tolerance. If convergence is not achieved, the Korea energy IO model is run again with revised energy IO coefficients and obtaining a revised final demand of the energy supply sector, which is interfaced by a linkage program from LP to IO. The whole procedure is then repeated until convergence is achieved.

The structure of the integrated model 1 framework is designed to analyze the national economic impact of capital requirements of the electric sector, and the energy imports comparing the gross national products (GNP), trade balance (TB), and balance of payments (BOP) before and after the expanded interaction of energy sector into the total economy.

The iterative solution procedure for the integrated model 1 is summarized as follows:

1. Run the KDI macro-economic model.
2. Final demand components are obtained from the KDI model.
3. The linkage program calculates final demands for energy product sector (Y_P) and non-energy product sectors (Y_N).
4. Run the energy IO model.
5. Gross output of energy product sectors (X_P) are mapped by the function g(.) into D, the vector of the right-hand-side (RHS) value of demand constraints in BESOM LP.
6. Run the BESOM LP.
7. Check convergence of integrated framework. For the application study,

$$\left| \frac{D_i^k - D_i^{k-1}}{D_i^{k-1}} \right| < 0.0005,$$

has been used as a convergence criterion, where D_i^k represents energy demand level of the ith demand category in BESOM LP at the kth iteration.

8. If convergenc is not achieved, go back to step 4 with new energy IO coefficients and final demands of energy supply sectors ($\hat{Y}_S$), interfaced by the linkage program.
9. If convergence is achieved, run the modified macroeconomic model with capital requirements of the electric sector and energy imports.
10. Compare the GNP, trade balance (TB), and balance of payments (BOP) between KDI and Modified models.

The comparison of GNP, TB, and BOP before and after energy-economic interaction can be done in terms of implicit judgemental criteria. There is no linkage of explicit quantitative analysis of the comparison.

3.2. Integrated Model 2

The Integrated Model 1 results of the economic impact of electric in terms of level of GNP, TB, and BOP. Suppose, however, that the resulting GNP level is not feasible by the policy maker's judgement. Then the immediate question arises "What would be the 'macroeconomic-balanced' level of investments in the electric and non-energy sector, energy imports, and consumption, which would satisfy the policy-determined level of GNP?" In order to address this question, we develop a second model.

The structure of the framework of integrated model 2 is designed to determine the 'macroeconomic balanced' level of investments of electric and non-electric sectors and energy imports by compensating adjustment in personal consumption, hence maintaining a constant (or policy-determined) level of GNP, government consumption, inventory changes, non-energy sector exports and imports. This framework does not need the KDI macro-economic model, since the final demand components, together with GNP, are specified exogenously as input by model users.

The starting point of the integrated model 2 is a linkage program, the "MKLEE PROGRAM 1," which sets the initial level of final demands of the energy IO model. The energy IO model then calculates and delivers energy demands to the BESOM LP model.

With energy demands linked, the BESOM LP is then solved and derives the least-cost optimal supply mix to satisfy energy demands. Next the convergence of energy demand associated with the BESOM LP demand categories is checked by termination criterion, which is exactly the same as used in the integrated model 1. The inner loop of the combined model of the energy IO/BESOM LP is iterated until convergence is achieved. After convergence of the inner loop, the "MKLEE PROGRAM 2" calculates capital investments of the electric sector, non-energy sector, and energy imports by linking the results of the BESOM LP. The majority of the algorithm in the "MKLEE PROGRAM 2" is based on the capital investment linkage, GNP identity constraint, checking routine for convergence of outer loop and feedback to the internal loop. After convergence of the outer loop, the integrated model 2 ends by running the reporting program, which is called the "MKLEE PROGRAM 3."

The iterative solution procedure for the integrated model 2 is as follows:

1. Initialization of GNP, final demand components.
2. Run the linkage program, "MKLEE PROGRAM 1," for final demand calculation.
3. Run the energy IO model.
4. Run the BESOM LP with the interfaced demand constraints energy IO model (same as in integrated model 1).
5. Check convergence of inner loop in the combined IO/LP system.
6. If convergence is not achieved, go back to step 3 with new energy IO coefficients and final demands of the energy supply sectors ($\hat{Y}_S$) interfaced by linkage program.
7. If convergence is achieved, update the investment of the electric sector and energy imports from the solution file of BESOM LP, and update the investment of non-electric sector calculated by the investment linkage program, "MKLEE PROGRAM 2."
8. Calculate current consumption level, C, from the identity equation of GNP.
9. Check convergence of outer loop by comparing the current value to the previous value of C. For the application study,

$$\left| \frac{C^k - C^{k-1}}{C^{k-1}} \right| < 0.005$$

has been used as a convergence criterion, where C^k is consumption level at kth iteration.

10. If convergence is not achieved, calculate final demands of energy product (Y_p), non-energy product sectors (Y_N), and go back to step 3.
11. If convergence is achieved, run the reporting program and stop.

3.3 Final Demand Linkage

The final demand vector drives the energy IO model and hence, represents a major component in the solution of a combined IO/LP system. The methodology used in this study to estimate final demands utilizes six final demand components determined by the macro-economic model: personal consumption expenditure (CP), government consumption expenditure (CG), gross private fixed investment (IF), changes in inventories (IV), exports (EX), and improts (IM). Subsequently, each of these final demand components is divided into the 39 sectoral purchases defined in the extended energy IO model. The incorporation of disaggregation of final demand components into 39 sectors involves the estimation of sectoral share (composition ratio) by type of purchaser.

Energy supply sectors' final demands are usually divided into three purchasing components: inventory changes, exports and imports. Final demands of the energy product sector are not usually divided into more than two purchasing components: personal consumption and government consumption. Final demands of the non-energy industry sector are divided into six GNP components.

3.4 Linkage from Energy IO to BESOM LP

The linkage from IO to LP is essential to interface the demand constraints for the LP. The vector of gross outputs of energy products coming from the solution of the energy IO model is used to calculate demand constraints for the LP. These calculations are made on the basis of the BESOM LP demand category and energy IO product sector correspondence. The interface equations for the demand categories are mostly one-to-one correspondence. The disaggregation of motive power into three demand categories: non-electric transport, electric rail and auto. The disaggregation of residential electricity into four demand categories, miscellaneous residential electricity, space heating, air conditioning, and cooking, plus pumped storage. The demand for pumped storage was added to residential electricity for convenience. The residential non-electric is disaggregated into space heating and cooking.

The linkage from LP to IO is required to interface revised IO coefficients and final demand for the energy supply sector (Y_s). The solution to the BESOM LP, the set of Z_K's, is used to calculate coefficients and final demand for the energy supply sector. The IO coefficients calculated in this manner can be partitioned into two submatrices, A_{SS} and A_{SP}. A_{SS} coefficients represent fuel flows (coal, oil) and traditional energy form flows (coal products, refined oil, electricity, etc.) plus conversion and distribution losses within or between the eleven energy supply/conversion sectors. However, the conversion and distribution losses are represented by the diagonal elements and their coefficients are not changed through iterations. A_{SP} coefficients represent fuel and traditional energy form flows into the seven dummy energy product sectors.

3.5 Capital Investment Linkage

The linkage of capital investment for the non-electric sector (IF_N), electric sector (IF_e) and calculation of energy imports (IM_F) is important to the integrated model 2.

Calculation of Non-Electric Sector Investment

Define the capital/output ratio, KO, as

$$KO^t = \frac{\text{Fixed Investment}}{\text{Value Added}} = \frac{IF^t}{Y^t}$$

Then, we define the capital/output ratio for three sectors:

$$KO^t_A = \frac{IF^t_A}{Y^t_A}, \qquad KO^t_I = \frac{IF^t_I}{Y^t_I}, \qquad KO^t_S = \frac{IF^t_S}{Y^t_S}$$

where

KO^t_A = capital/output ratio for agricultural sector, year t

KO_I^t = capital/output ratio for industrial sector, year t

KO_S^t = capital/output ratio for service sector, year t

IF_A^t = fixed investment for agricultural sector, year t

IF_I^t = fixed investment for industrial sector, year t

IF_S^t = fixed investment for service sector, year t

Y_A^t = value added for agricultural sector, year t

Y_I^t = value added for industrial sector, year t

Y_S^t = value added for service sector, year t

The values of KO_A^t, KO_I^t and KO_S^t are obtained from the KDI macro-economic model.

One must also adjust the sectoral classification to calculate value added of the aggregated three sectors from the gross output vector created by the combined energy IO/BESOM LP system.

Defining the ratio of value added to gross output, R, as

$$R_A^t = \frac{Y_A^t}{X_A^t} \quad ; \quad R_I^t = \frac{Y_I^t}{X_I^t} \quad ; \quad R_S^t = \frac{Y_S^t}{X_S^t}$$

Then, the investment for each sector is expressed as:

$$IF_A^t = X_A^t * R_A^t * KO_A^t$$

$$IF_I^t = X_I^t * R_I^t * KO_I^t$$

$$IF_S^t = X_S^t * R_S^t * KO_S^t$$

Thus, the total investment requirements of the non-electric sector are given as

$$IF_N^t = IF_A^t + IF_I^t + IF_S^t$$

The calculation of electric sector investment and energy imports, however, can be obtained from the BESOM LP solution variables.

3.6 Convergence Properties of the Integrated Model

The formal analytical convergence proof for the iterative procedure of the combined energy IO/LP, was developed in M. Swift's dissertation, upon which the integrated model 1 is based. His work proved the convergence of the iterative algorithm of the combined IO/LP, which showed the convergence of sequence (Z^K) and (X^K), the solution vector of the LP and the gross output vector of the IO, respectively. Experience has demonstrated that the integrated model 1 converges in three to five iterations. The numerical results for three iterations in this study has shown 0.05% of error based on the following criterion of

$$\left| \frac{D_i^k - D_i^{k-1}}{D_i^{k-1}} \right| < 0.0005 \text{ for all } D_i^k$$

where

D_i^k = RHS value of demand constraint for category i in BESOM LP, at K^{th} iteration

The BESOM LP portion of this integrated model 1 in this study had approximately 280 constraints, of which 12 were variable, and approximately 210 variables, while the IO portion had 39 sectors. Convergence by the above criterion was obtained in 40 CPU seconds on a CDC 7700 at Brookhaven National Laboratory.

The formal convergence proof for integrated model 2 is shown in Appendix A. The numerical results show a rapid tendency of the algorithm to converge towards limiting values. The six iterations in this study have shown less than 0.02% of error for sequential value of C^K based on the following criterion of

$$\left| \frac{C^k - C^{k-1}}{C^{k-1}} \right| < 0.005$$

where C^K = consumption level at K^{th} iteration

Convergence using the 0.005 criterion for the integrated model

2 was obtained in 137 CPU seconds on a CDC 7700 at Brookhaven National Laboratory.

4. Findings

The computational results of integrated model 1 and model 2 are presented in Table 1. The level of GNP in model 1 came out

Table 1

COMPARISON OF RESULTS FOR YEAR 2001
BETWEEN INTEGRATED MODEL 1 AND 2

Unit: Billions of Won in 1975 price

	Model 1	Model 2
Private Consumption	43,956.16	32,711.10
Government Consumption	7,315.44	7,315.44
Investment	50,330.27	32,533.85
Agricultural Sector	2,153.27	796.75
Industrial Sector	16,338.22	12,771.70
Service Sector	30,459.76	18,486.30
Electric Sector	1,379.02	479.10
Nuclear Capacity	(30 Gwe)	(20 Gwe)
Inventory Change	3,229.76	3,229.76
Exports	39,883.03	39,883.03
Imports	45,757.22	57,690.90
Non-energy Imports	31,330.38	47,917.30
Energy Imports	4,426.84	9,773.60
GNP	98,957.44	57,982.28
TB (Trade Balance)	−5,874.19	−17,807.87
BOP* (Balance of Payments)	−7,253.21	−18,286.97

BOP* = $TB + IF_e$

to be unrealistic from the view point of Korea's economic growth. For this reason, assuming a plausible GNP level exogenously, the "macroeconomic balanced" level of final demand components have been recalculated by the use of integrated model 2.

Comparing the results between two models, note that the GNP level of model 1 is almost twice of model 2. In model 2, the private consumption, and investment levels have been reduced by 20% and 40% respectively compared to that of model 1. Furthermore, the imports level of model 1 has been increased by about 25% of that in model 2. As an aggregated results, the acceptable cumulative nuclear capacity until year 2001, would be 20 Gwe (about 20 nuclear units) based on the capital (foreign exchange), natural resource and manpower limitations.

The major conclusions that may be drawn from this work are:

(1) The integrated modelling approach to overall energy sector planning as well as electric sector for Korea within the context of energy-economy interactions is both necessary and feasible.

(2) Within the integrated model 2, the reductions in consumption levels provide insight into energy conservation potentials in the manufacturing industry and household sector.

(3) However, the lack of explicit linkage with balance of payments is a serious limitation to this study.

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