ORiON, Vol. 1, No. 2, pp. 105-122

ASSESSMENT OF TECHNOLOGIES IN A GLOBAL ENERGY SYSTEM

P.J. VERMEULEN
Associate Professor, Department of Applied Mathematics
University of Pretoria and
Part-time Consultant, NRIMS of the CSIR

ABSTRACT

A limited research and development budget usually implies that decisions must be made regarding the distribution of the available funds among the most promising R & D projects. The MARKAL model [4] is used to describe a national energy system where existing and new energy conversion and process technologies compete for a market share in satisfying exogenously specified demand patterns. A measure is introduced which may be used to rank the relative importance of a technology in the energy system. Several scenarios depicting different restrictions on the energy system are used in the analysis.

1. INTRODUCTION

After the major oil crisis in 1973 there seemed to be a unified desire in the Western world to reduce its dependence on imported energy, especially oil. This new awareness resulted in a series of predictions on the energy future of the world. A major price hike by the oil producers in 1978/79 again emphasized the problematique of the energy-hungry world and gave rise to a further outpouring of explanations, solutions and prophecies of doom.

Most of the technologically advanced countries have survived the apparent energy crisis, and at this stage there even seems to be a glut of certain primary energy sources. Ruttley [1] explains that the rationale behind the energy problem has remained the same it has been for decades, but that the economics has changed.

The apparent success of the developed countries in countering the effects of the unstable supply and escalating prices of imported oil probably lies in a two-pronged action taken by these countries, i.e.

(a) an intensive domestic energy conservation programme, and

(b) an accelerated research and development programme for developing new alternative energy technologies.

Energy conservation is a vast potential energy source that is being researched and employed, with great success, all over the industrialized world. The aim of this paper, however, is to investigate the impact of new energy conversion, process and demand device technologies on a national energy system.

2. RESEARCH AND DEVELOPMENT PROGRAMMES

Governments, through their departments of energy, are usually in a position to consider and implement different policy options, which will influence the evolution of their national energy system. The policy options, usually constrained by a limited budget, may include regulatory measures, financial incentives, and research and development funding. It has been said that of the above-mentioned options only research and development is capable of creating possible new options [2].

Decision-makers in government have to seek an optimum research and development strategy, which means a distribution of available funds in a manner that will best satisfy a variety of policy objectives. These objectives may include some of the following:

to secure the availability of energy to meet the demand;

to improve foreign trade balances;

to enhance public health and safety;

to minimize the risk of technical and commercial failure.

In order to pursue these objectives, policy decisions must be made concerning the extraction, importation and exportation of raw fuels, the introduction of new technologies for the processing and conversion of primary energy sources to secondary energy forms, and the development and introduction of new end-use devices.

A hypothetical image of a South African energy system is used in this paper to demonstrate how a computer model (described in paragraph 3) may be used to assist the decision-makers in government to allocate research and development funds to the development of the most promising new technologies.

In the case of South Africa the '*decision-makers in government*' referred to in this paper may include persons from the upper hierarchy of the Department of Mineral and Energy Affairs (DMEA), as well as the National Programme for Energy Research (NPER) of the Council for Scientific and Industrial Research (CSIR). The close relationship that exists between the CSIR and the DMEA with regard to research and development in the non-nuclear energy field is reported on by Garbers [3].

Research and development (R & D) actions have in recent years been responsible for the development of various new energy technologies; these can be categorized as electric power generation, primary energy conversion, and end-use demand device technologies.

Table 1 indicates a few of the technologies being developed in each of the categories mentioned above.

TABLE 1. New Energy Technologies

Electric Power Generation	Primary Energy Conversion	Demand Device Technologies
Fluidized bed combustion systems	Coal to syngas	Transport:
	Coal to methanol	(a) electric cars (b) hydrogen aeroplanes (c) methanol cars (d) nuclear ships
Fuel cells	Direct coal liquefaction	
Magneto-hydrodynamic power plants	Natural gas to methanol	Industry:
Advanced nuclear technologies	Biomass to liquid fuels	(a) solar processing heat (b) improved furnaces
(a) fast breeder (b) fusion		Residential:
Renewable technologies		(a) improved space and (b) water heating
(a) solar (b) wind (c) geothermal		

Many new technologies offer the possibility of moderating the rising costs of energy while at the same time reducing the dependence on imported oil. The problem of deciding which technologies have the greatest advantage is complex and requires an analysis of the competition between new and existing technologies in the market-place over a long time-span. This competition can occur under a variety of future situations affecting energy resources, costs and technology availability. Limited R & D budgets imply that choices must be made regarding the distribution of available funds among the most promising R & D projects.

In order to determine priorities for energy technology R & D, the International Energy Agency (IEA), which consists of fifteen Western countries, established a multinational systems analysis group in 1976 to assess the relative merits of candidate new technologies. A mathematical model, MARKAL [4], which describes a national energy system, was developed. MARKAL models the flow of unprocessed primary energy through conversion and transformation technologies and end-use demand devices to meet exogenously specified demands for useful energy in each consuming sector of the economy.

The flexible programming code incorporated in MARKAL allows individual countries to construct their own energy models according to the primary energy sources, transformation technologies and end-use facilities available to them.

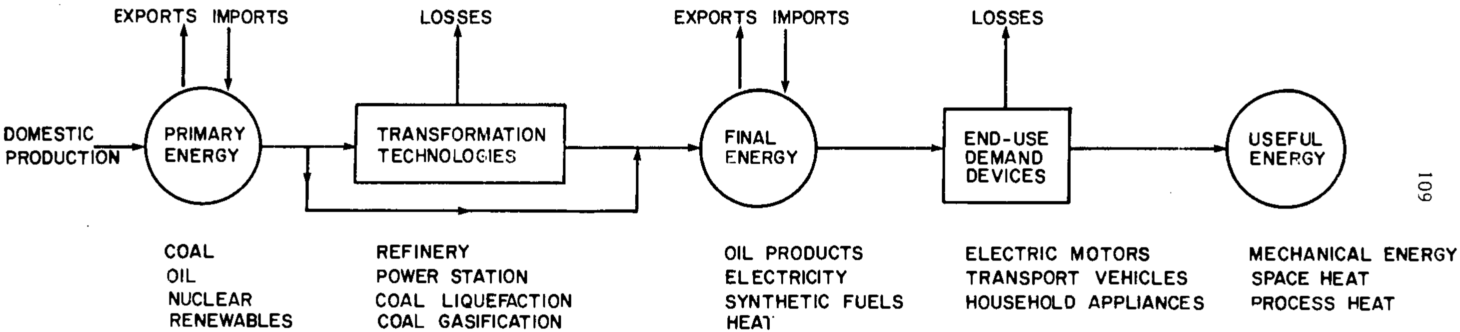
This energy network is outlined in Figure 1.

The technologies competing for such funds have widely varying characteristics, which relate to costs and benefits, technical performances, environmental effects, etc. It is necessary to analyse these effects in some detail before decisions on technology programmes can be made. A complete assessment of the possible value of a particular technology cannot be made on an individual basis. Instead, many technologies, which are competing against each other for various shares of the energy market, must be considered simultaneously. The MARKAL model is capable of evaluating competing technologies and has been used for this purpose by the IEA countries.

The aim of this paper is to indicate how modelling, specifically the MARKAL model, can contribute to the decision of how the limited R & D funds should be distributed among competing new technological developments in the energy field.

FIGURE I -

ENERGY SYSTEM AS MODELLED BY 'MARKAL'



3. THE MARKAL MODEL

MARKAL is a demand-driven, time-phased, multiperiod, linear program of energy supply and demand. Basically MARKAL uses exogenously specified useful energy projections and determines the optimal energy supply and end-use device and transformation technology network that can meet the demand. The exact nature of an optimal solution depends both on the criterion of optimality and the ensemble of technological and economic data or estimates supplied by a user to characterize a country's energy technologies. A feature of the model is the use of various objective functions, such as minimum discounted costs, oil imports, or environmental effluents. These objective functions can be used individually or in combination in trade-off situations.

The model can determine the specific combination of old and new technologies that satisfies the projected energy demands for the given time-frame at the minimum value of an objective function. The question arises how the model's results can be used to rank, in order of merit, the new extraction, conversion and end-use technologies and thereby assist in the allocation of R & D funds.

The MARKAL model, which forms the basis of the investigation to determine the merits of new technologies, is employed to generate optimal solutions for the energy system by using the following objective functions:

(i) the minimization of total cost (P), discounted to a present value,

(ii) the minimization of total oil imports (S) during the time-span of the model, and

(iii) the minimization of a linear combination of oil imports and cost ($Q = P + qS$).

The factor q in the last objective function represents the marginal change in the system cost (P) with respect to a unit change in the oil imports (S) and can therefore also be interpreted as the shadow price for imported oil.

Different energy scenarios can also be assumed, each with the same set of exogenous energy demands but with, for instance, different assumptions regarding the value of the surcharge on oil, different rates of market penetration of new technologies, a variety of future primary energy prices and future restrictions on the development of nuclear or fossil energy technologies.

4. MEASURES FOR THE ASSESSMENT OF NEW TECHNOLOGIES

The principal purpose of this analysis is to identify those energy technologies most deserving of R & D funding. Ideally the benefits that might accrue from the use of each technology would be measured by the model. Development priorities would then be established in the light of these estimated benefits.

There are several ways in which the merits of candidate technologies can be assessed from the model's results:

4.1 The appearance of a technology in the solution

Unless a technology appears in the optimal mix, it is supposed to be inferior to one or more of the new technologies that do appear. The appearance of a technology in the optimal network is certainly an indication that it has merit. On the other hand, if a different objective function is used for the same scenario it may easily result in the exclusion of that particular technology from the optimal mix. This measure unfortunately favours the most marginal technologies and, due to the linear programming technique, employs the marginally better technologies to their limits in all cases.

4.2 Assessment of the amount of energy produced, converted or consumed by the technology

The amount of energy that a technology produces, converts or consumes is a direct and commonly used criterion for evaluating a technology. The dependence of the energy system upon a certain technology can be measured directly by this criterion. A shortcoming of this norm is, however, that the market penetration of different technologies is set by the modeller, and it can therefore be argued that the model can be set to promote the modeller's favourite technology. A second objection to the use of energy activity as a criterion is that it fails to reflect the availability of alternatives. For example, in the case of cost minimization the optimal mix may exclude a marginally more expensive technology while the same optimal mix would be obtained even if that technology were not considered as a substitute.

4.3 The shadow price of constrained activities

The dual variable, or shadow price, for each constraint forms part of the solution of a linear program. The shadow price measures the difference in the value of the objective function that would be obtained if one more unit of energy capacity of that constrained technology was made available. The shadow price can therefore be interpreted as the marginal value of that technology. However, shadow prices alone are not an acceptable measure. It is well known that if the installed capacity of a technology is increased to the point where it is no longer binding, the shadow price becomes zero.

In a multiperiod linear programming model such as MARKAL the shadow price of a certain technology may become zero in one or more of the time periods, indicating that the installed capacity of that technology is not binding in that time period. To assist in understanding shadow prices in this case, Dantzig [5] proposed that adjustments be made in the assigned constraints of the technologies in successive computer runs to eliminate the zero shadow prices. This procedure is very expensive in the case of the MARKAL model.

4.4 Comparing objective function values

An almost ideal measure of the value of a technology is the difference in the objective function between the energy system having access to and not having access to a new technology. This can be determined by solving the problem once by including the technology and once by excluding it. The difference in the total energy system costs and the level of oil imports in the two cases unambigously measures the benefits that can be attributed to the use of that technology. Unfortunately, the cost of obtaining this measure for n new technologies in m scenarios by running the model with and without each technology would require $2n \times m$ computer runs, which is a prohibiting factor.

4.5 The product of the bounded installed capacity and the shadow price

The shadow price, in general, is highest when the installed capacity approaches zero, and it becomes zero when the allowable installed capacity is so high that some other constraint becomes binding. If a low upper bound for a technology is specified, the value of the technology would seem low when measured by energy activity but high when measured by the shadow price. If a high upper bound is specified, the reverse is true. Thus, the product of the two will tend to compensate for the arbitrary nature of the assumed installed capacity. It can be assumed that this measure approximates the ranking that would be obtained if individual technologies were deleted from the system one at a time as described in 4.4. It should be noted that the units of this measure are the same as those of the objective function. This is advantageous in a multi-period model because the product measure, unlike the shadow prices, may be added over several time periods to obtain a single measure of the technology's value. This measure will be used in the analysis that follows.

5. SCENARIO SETTINGS

A scenario schedule is used to investigate the impact of different new technologies and to determine their relative importance in an energy system.

The scenario settings will be defined relative to a base case [6]. A minimization of the total discounted system cost using a medium oil import cost structure, as indicated by curve B in Figure 2, constitutes the base scenario. The other oil price schedules to be used in the investigation are also shown in Figure 2.

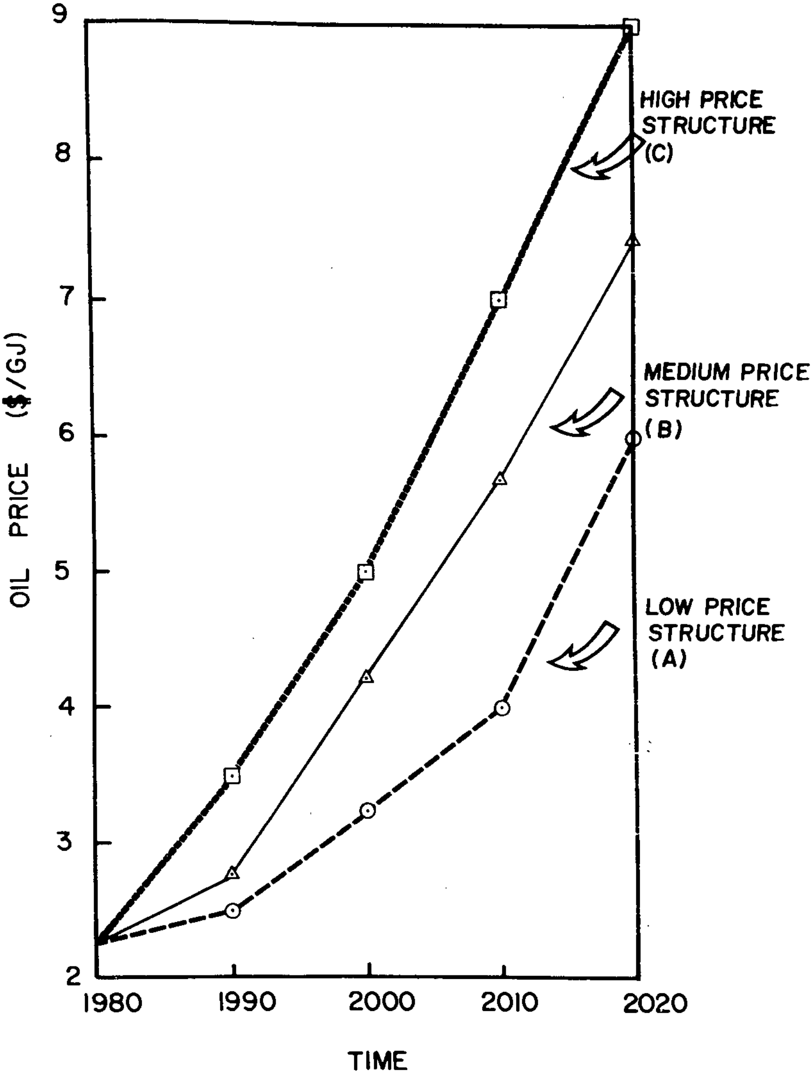
Table 2 describes the other scenarios that will be used to determine the sensitivity of the model's results to changes in the assumptions about the future state of the national energy system. The different scenarios range from the use of different oil prices to the impact of a surcharge on oil imports and from the effect of a constraint on the amount of fossil energy to the impact of accelerated market penetration of new technologies on the energy system.

The MARKAL results obtained from the ten scenarios in Table 2 may be used to analyse the effect of the different assumptions regarding the energy system.

Figure 3 depicts the trade-off between cost and oil imports for the base case and some of the other scenarios. Each scenario represents 45 years of activity. The label at each point indicates the assumptions behind each scenario, as listed in Table 2.

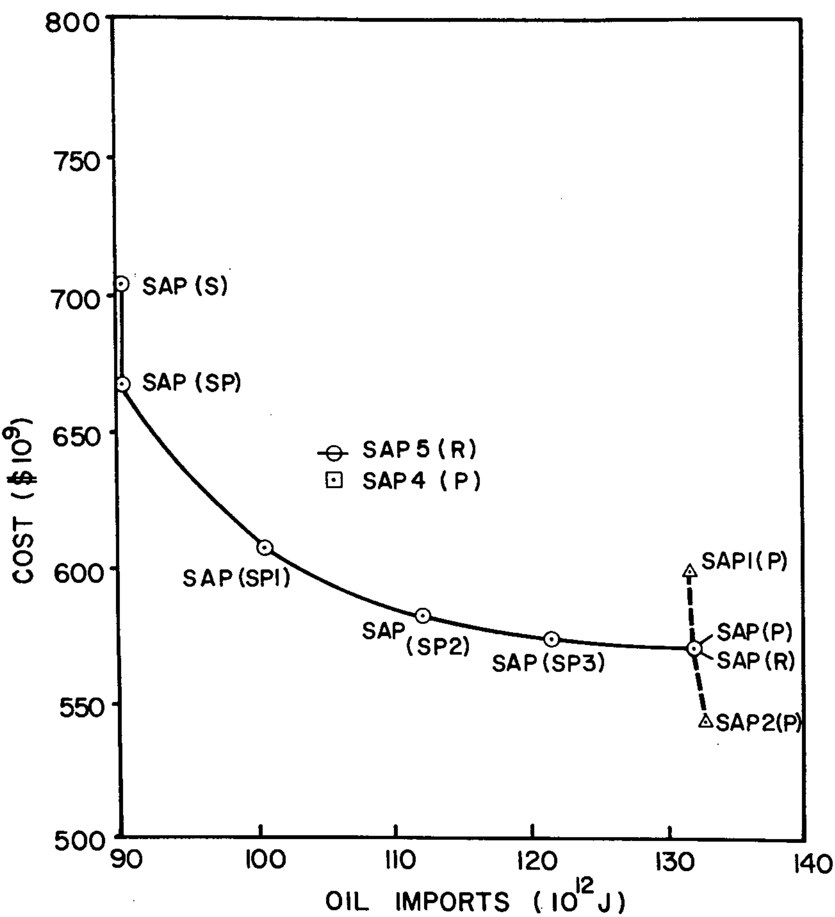
From Figure 3 we can see the consequences of different oil price trajectories, oil import surcharges, curtailment of energy from coal and oil, and a policy of maximizing the use of renewables.

FIGURE 2 -



OIL PRICE STRUCTURES

FIGURE 3-



PRICE - SECURITY TRADEOFFS FOR DIFFERENT SCENARIOS

TABLE 2. · Scenario Definitions

Scenario Reference	Primary Objective Function	Oil Price Schedule	Description
SAP(P)	Price minimization	Medium Price (B)	Base case
SAP(SP1)	Price minimization	Medium Price (B)	High surcharge on oil imports
SAP(SP2)	Price minimization	Medium Price (B)	Medium surcharge on oil imports
SAP(SP3)	Price minimization	Medium Price (B)	Low surcharge on oil imports
SAP(S)	Oil import minimization	Medium Price (B)	No surcharge on oil imports
SAP(R)	Maximization of renewables	Medium Price (B)	Preference to renewable technologies
SAP1(P)	Price minimization	High Price (C)	High oil price scenario
SAP2(P)	Price minimization	Low Price (A)	Low oil price scenario
SAP4(P)	Price minimization	Medium Price (B)	Oil imports curtailed at 80% of base case value
SAP5(R)	Maximization of renewables	Medium Price (B)	Combination of coal and oil import reductions with preference for renewable technologies

The effect of the oil price schedule can be seen by the broken line in Figure 3, connecting the points SAP(P), SAP1(P) and SAP2(P). With the oil imports at a low price (price structure A in Figure 2), a marginally higher level of oil imports is justified. A high oil price structure reduces the oil imports by a small margin. There is a significant increase in system cost of about 10%, between the low and high oil price scenarios, while the reduction in oil imports is only 0,8%. This indicates that the modelled energy system is very rigid and insensitive to the price of imported oil.

The solid line in Figure 3, connecting SAP(P) with SAP(S), shows a series of solutions in which an increasing premium is paid to reduce oil imports, assuming a medium oil price schedule (B). The points SAP(SP1), SAP(SP2) and SAP(SP3) represent three solutions in which more expensive substitutions for imported oil are made in order to reduce its level of import. A fairly substantial reduction in oil imports (8% below the value of the base case SAP(P)) is obtained in scenario SAP(SP3) for a minimal cost increase of 0,6% above the system cost of the base case. Further increases in the surcharge on oil imports, however, give rise to a more substantial increase in system costs. The point SAP(SP) represents a solution in which every conceivable step has been taken to reduce oil imports, regardless of the cost. Under these circumstances oil imports can be reduced no more than 32% of the level at SAP(P), with an increase in system cost of about 17%.

The effect of accelerating technologies in the modelled energy system is disappointingly small. This is probably due to the stringent constraints imposed on the modelled system. It has been found, however, that the introduction of methanol conversion plants at an earlier stage has a marginal effect on the quantity of imported oil. Wind energy technology also entered the optimal mix sooner than in the base case, but with virtually no effect on the cost and oil import levels. This scenario is not shown in Figure 3.

The effect of curtailment on imported oil was investigated by reducing the oil imports obtained in the base case by 20%. As a result, for a price minimization, the cost rose by 11% (point SAP4(P), Figure 3).

Another scenario, SAP(R), was studied to evaluate the effect of the use of renewable resources. For optimization purposes the mix of technologies was established by assuming initially that the capital cost of renewable technologies was zero and then minimizing total discounted system cost; subsequently their cost was accounted for in determining the total energy system cost. The trade-off point SAP(R) virtually coincides with the base case, point SAP(P). This points to the fact that the modelled system has a high inertia level when the use of renewable technologies is stimulated.

A last scenario, SAP5(R), was included to determine the effect of a combination of coal and oil import reductions of the above-mentioned magnitudes on total system cost and quantity of oil imports when the capital cost of renewable technologies is neglected in a price minimization run. A comparison of points SAP(R) and SAP5(R) reveals that a considerable price has to be paid when both coal extraction and oil imports are curtailed even when the development costs of renewable technologies are not considered. What amounts to a subsidy for renewables might in this modelled system be better spent in reducing the oil imports in the base case at a much lower cost increase. While renewable resources may justify themselves in the very long run, they do not deserve priority development on the basis of their direct costs during the modelled period of 45 years.

6. CHOICE OF TECHNOLOGIES

The lesson of Figure 3, which shows the cost-security trade-offs, is that the choice of technologies is important. It is far more important to accelerate the technologies that are effective in reducing cost or oil imports than to introduce every new technology at a low level. An important question still remains: which are the most valuable technologies?

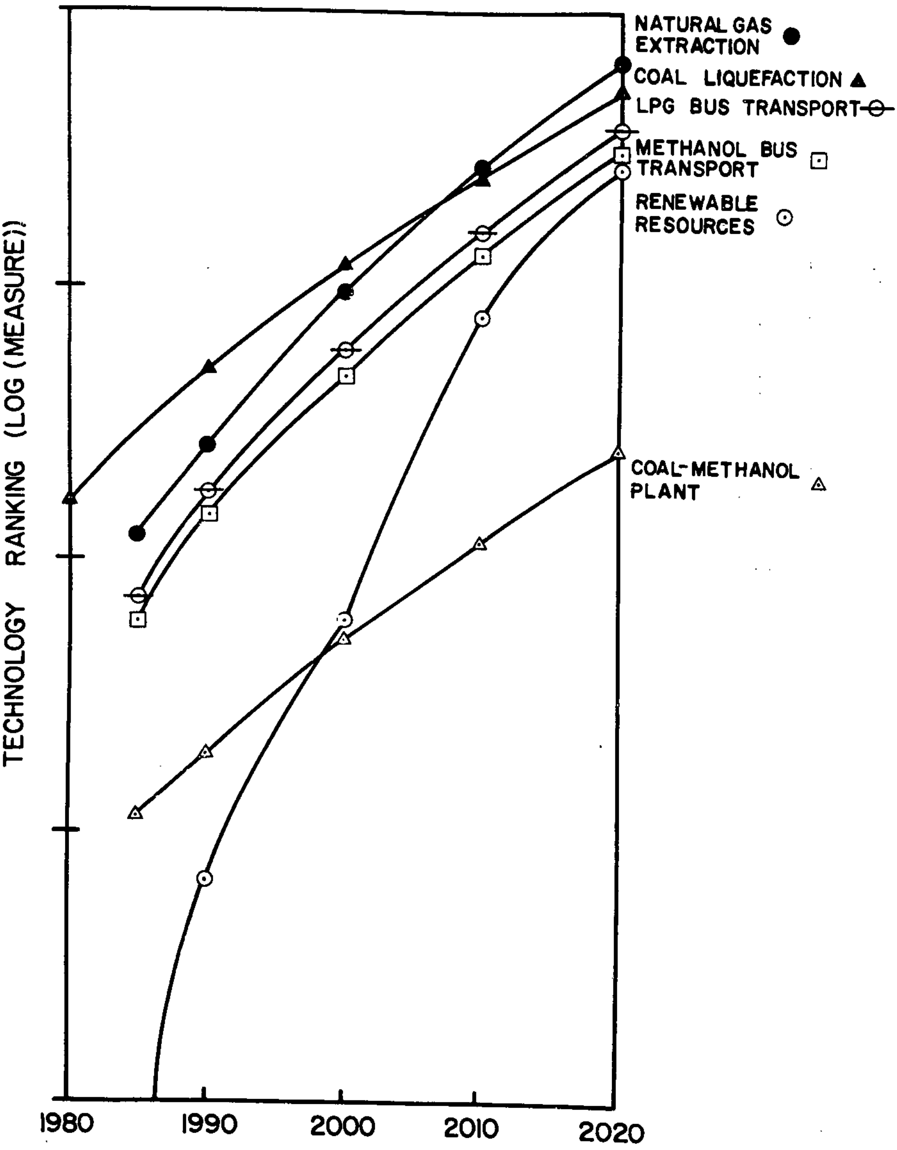
In Figures 4 and 5 the approximate measure, as described in paragraph 4.5, is used to illustrate, for a number of technologies, how the benefits vary in several scenarios.

Figure 4 illustrates how some of the assumed new technologies rank over time in the base case SAP(P). The logarithm of the measure defined by the product of the shadow price and the installed energy capacity summed over the nine five-year time periods appears along the vertical scale. The marks on the vertical axis represent factors of ten.

Five of the six new technologies, indicated in Figure 4, only penetrate the energy market in the 1985 time period because these technologies were modelled to be available only after 1985. The liquefaction of coal provides the greatest benefit for the modelled energy system until 2005 when it is overtaken by the extraction of natural gas, which was modelled as a new technology. It is interesting to note that the utilization of renewable resources accelerates from a non-ranking 'technology' in 1985 to one of the most promising sources of energy in the later time-span of the model. Bus transport, fuelled by liquid petroleum gas and methanol, is high on the priority list of new technologies. The coal to methanol plant also features in Figure 4 but has a low profile throughout the time-span, with the ranking measure being at least a factor of 10 lower than the next rival technology, i.e. the methanol bus transport.

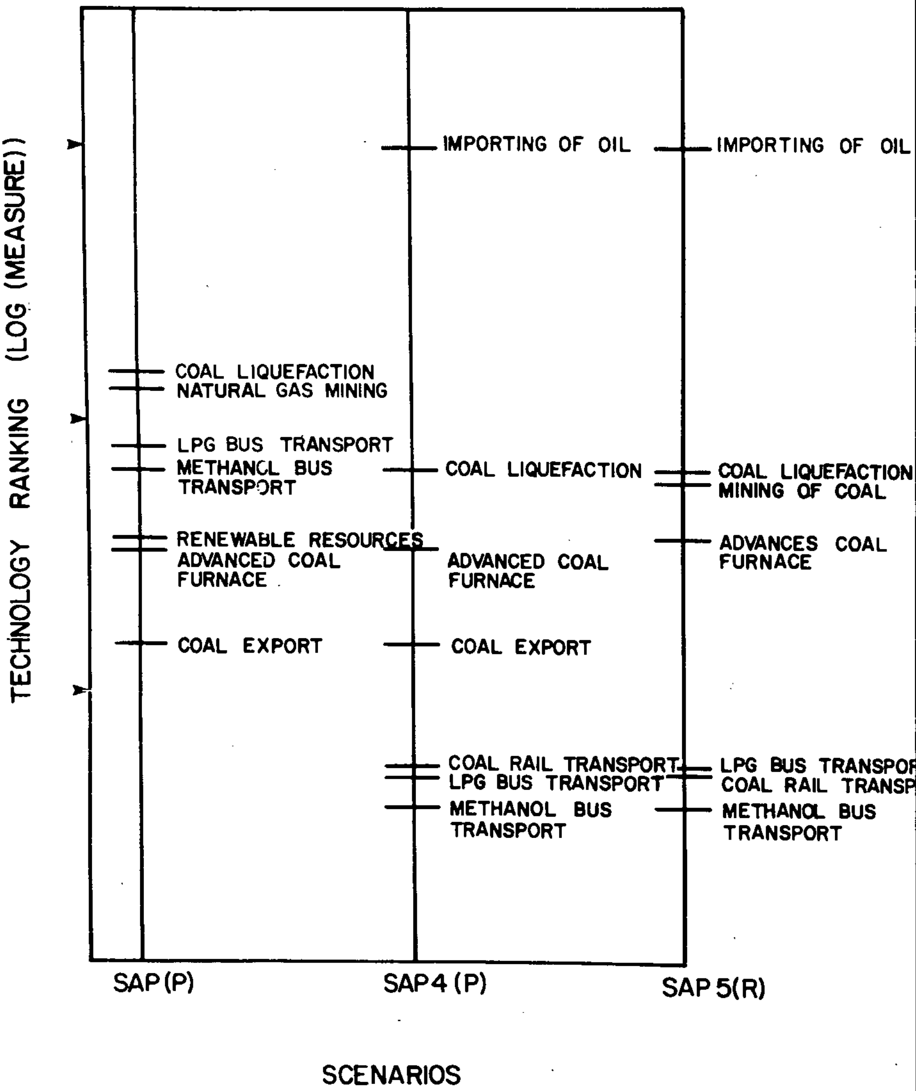
Figure 5 compares the benefits of a sample of promising technologies for three different scenarios. The vertical scale again shows factors of ten, representing the logarithm of the approximate measure. The time dependence is eliminated by summing the measure over the total time-span and discounting the result by a 6% discounting rate to obtain a current value.

FIGURE 4 -



COMPERATIVE BENEFITS OF LEADING TECHNOLOGIES

FIGURE 5-


TECHNOLOGY RANKING (LOG (MEASURE))
IMPORTING OF OIL
IMPORTING OF OIL
COAL LIQUEFACTION
NATURAL GAS MINING
LPG BUS TRANSPORT
METHANOL BUS TRANSPORT
COAL LIQUEFACTION
COAL LIQUEFACTION
MINING OF COAL
RENEWABLE RESOURCES
ADVANCED COAL FURNACE
ADVANCED COAL FURNACE
ADVANCES COAL FURNACE
COAL EXPORT
COAL EXPORT
COAL RAIL TRANSPORT
LPG BUS TRANSPORT
METHANOL BUS TRANSPORT
METHANOL BUS TRANSPORT
SAP(P)
SAP4 (P)
SAP 5(R)
SCENARIOS

The base case ranking is depicted on the left-hand side of Figure 5 (SAP(P)), whereas the ranking of technologies, when the oil import is curtailed at 80% of the base case value, is shown in the centre of the figure (SAP4(P)). On the right-hand side of Figure 5 the ranking obtained from a renewable resource optimization, run SAP5(R), is shown while the oil imports and coal extraction were simultaneously constrained to 80% and 90% respectively of the base case values.

It can be seen that coal liquefaction and the extraction of natural gas are highly rated technologies in the standard case. The exporting of coal, which contributes to the cost structure of the energy system and which was modelled as a technology, also appears in the ranking of promising technologies. Careful consideration should therefore be given to the policy formulation concerning the exporting of coal.

The ranking in the case of scenario SAP4(P) indicates that the curtailment of oil imports alone propelled the oil import strategy, which was modelled as a primary source technology, into top position. It is also interesting to note that the exporting of coal maintained its position, whereas the bus transport technologies lost ground in the ranking as compared to the standard scenario.

The right-hand side, depicting the ranking of scenario SAP5(R), shows the same trend as scenario SAP4(P) regarding the oil import strategy and bus transport technologies, but the simultaneous curtailment of coal extraction resulted in the ranking of coal mining as a promising technology.

7. CONCLUSIONS

Figures 3, 4 and 5 illustrate that the relative importance of energy technologies varies over time and depends upon future circumstances. Without prescience, therefore, no single ranking of technologies is possible. Some technologies tend to dominate in many of the scenarios and the circumstances that favour others can be identified.

The performance of the coal liquefaction technology in all the scenarios of the modelled energy system is salient. The only demand device technologies that do appear in the ranking list are the methanol and liquid petroleum gas bus transport, but with a relative low priority.

The appearance of the oil-importing technology, whereby oil is made available as a primary energy source, in the oil curtailment scenarios, SAP4(P) and SAP5(R), is intuitively correct, but its top priority ranking by such a large margin should result in the re-evaluation of the national oil import policy.

The results of the analysis reported in this paper are determined by assumptions and numerical parameters set by the analyst. The model represents a hypothetical but realistic image of a global energy system. The different scenarios enable the analyst to perform sensitivity tests on the modelled energy system. The operation of the model is computationally and mathematically undisputable, but the conclusions drawn from such results are solely those of the analyst.

8. ACKNOWLEDGEMENT

This project was done under the auspices of the National Programme for Energy Research (NPER) at the National Research Institute for Mathematical Sciences (NRIMS) of the Council for Scientific and Industrial Research (CSIR), Pretoria.

9. REFERENCES

[1] RUTTLEY, E. World Energy Prospects, *Proc. of South African Energy in Perspective*, CSIR Conference Centre, Pretoria, 24-25 January 1983.

[2] LAMONTAGNE, J. The Role of Large Scale Energy Systems Models in R & D Planning, *Proc. of ORSA/TIMS Conference*, Colorado Springs, CO, November 1980.

[3] GARBERS, C.F. Research for Energy, *Proc. of South African Energy in Perspective*, CSIR Conference Centre, Pretoria, 24-25 January 1983.

[4] ABILOCK, H. et al. MARKAL, A Multiperiod Linear Programming Model for Energy Systems Analysis, IEA Energy Systems Analysis Report, BNL 26390, Brookhaven National Laboratory, Upton, NY, 11973, 1979.

[5] DANTZIG, G.B. *Linear Programming and Extensions*. Princeton University Press, New Jersey, 1963.

[6] VERMEULEN, P.J. Market Allocation for Energy Technologies in the Energy System, UP TW 32, Department of Applied Mathematics, University of Pretoria, 1983.