A SIMPLE MODEL OF ENERGY DYNAMICS

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ABSTRACT

This paper discusses the impact of the energy supply transition on the U.S. economy. An energy supply transition occurs when one resource base is replaced by a new source of energy due to some shift in the comparative economic attractiveness of the two sources. The effects of an energy transition on an industrial economy are long-term and far-reaching. The recently witnessed depletion of the 1970s may foreshadow a major turn in the path of economic development.

Our analysis focuses on a disequilibrium system dynamics model and takes a primary interest in the response of GNP to the changes in key energy variables, such as energy price, associated with an energy supply transition. The model is simple and aggregate to illustrate the dynamics during the transition. The model structure contains one sector for factors of energy production and another sector for factors of total production. Energy is a direct factor input to overall production (GNP). Feedback occurs because part of GNP must be returned as a factor of energy production in the form of capital investment. Another important feedback mechanism is responsible for economic growth, whereby part of GNP is reinvested to support the nonenergy factors of production. A household sector makes a consumption and saving decision. Capital stocks adjust to desired levels with delays, and resource allocation is treated dynamically.

An energy supply transition can inflate the investment demands of the energy sector, slicing deeply into consumption and nonenergy investment. A rough transition, characterized by high real energy prices, decreased growth in GNP, and reduced household consumption, is likely to occur when the transition is driven by a rise in the cost of the old source, until the new source becomes economically viable through default. A smooth transition occurs when the new source becomes cheaper, perhaps through technical advancement, until it becomes more viable than the old source; this smooth transition may place the economy on an accelerated path of development.

The model sheds light on the implications of alternative policy choices, particularly with respect to how the impact of a rough transition can be minimized. We found that the goal of an aggressive policy would be to turn a rough transition into a mixed transition, whereby the desirable charcteristics of a smooth transition, especially accelerated economic growth, mask the rough characteristics. The increased energy investment required during the initial years of a rough transition should be channeled into development of the new energy source instead of maintenance of the old. The cost of producing energy from the new source will drop, and the crossover point of viability will be met sooner. The key to the success of this policy is anticipation of a transition with investment in the development of new energy sources during the "energy-rich" times precedingthe transition.

INTRODUCTION

In the past century, the U.S. economy has gone through two full transitions in its basic form of energy production. Figure 1 shows the characteristic life cycle of three forms of energy previously utilized in the U.S. economy. In the 1880s, over ninety percent of the nation's energy demands were met by the burning of wood. At the turn of the century, declining wood supplies and the development of large-scale coal burning technology brought about a transition to dependence on the coal industry. In the '40s, the seemingly endless supply of cheap and easy-to-process oil and gas provided the impetus for the second transition, and petroleum is still the dominant form of energy. The behavior of the economy today might lead us to believe we are in the middle of a transition now.

In the '70s, the the U.S. economy began to feel the first pains of a third transition approaching. The OPEC oil embargo created the first energy shortages ever experienced on such a grand scale. Gas lines formed, energy prices climbed, and funding for research in alternate forms of energy increased. The purpose of this paper is to examine the forces behind the transition which is now upon us.

Transition Charcteristics.

Historical data indicate that the previous two transitions were smooth and relatively unstressful; the price of energy gradually decreased from the level dictated by the old source to the limit imposed by the new source. The ongoing transition does not seem to be following this characteristic pattern. Energy prices in many cases have doubled while we still remain heavily dependent upon domestic and foreign petroleum. This response indicates the lack of an efficient energy alternative. Solar, nuclear, wind, geothermal, and others all represent viable sources of energy. Yet their productivities remain too low to create large investments in their development. Instead of a smooth transition, the current situation could lead to a rough transition, characterized by inflated energy prices, reduced growth in GNP, and prolonged dependence on a depleting energy source such as petroleum.

This introduction may be concluded by stating explicitly some of the major assumptions that have been made to simplify and permit aggregation of the economic structure:

1. We assume the economy operates with perfectly competitive markets.
2. We assume that the elasticity of substitution for factors of production is constant.
3. We assume that short-term lags in supply lines or inventories are not significant within our time horizon and can be accounted for with a delay time to adjust capital.

MODEL DESCRIPTION.

We have developed a simple system dynamics model of the economy that is specifically designed to simulate a transition in energy dependence. The simple model is based on larger model developed in 1981*. The model consists of an aggregate production sector, two parallel sectors representing the new and old forms of energy, and a household sector. Figure 2 shows an overview of the model and its three sectors. The only exogenous variables are an exponentially growing labor supply and an exponentially growing technology base. The model simulates the disequilibrium adjustment of investment in capital to the needs of a growing economy. The model is simple and contains the minimum structure necessary to illustrate the dynamics of the transition process.

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* See Sterman (1981)

The production function of the model combines three inputs: capital, labor, and energy. The first half of the production equation is a constant-elasticity-of-substitution (CES) function blending capital and energy into an effective capital term. The elasticity of substitution of energy for capital (ESE) is set to 0.9. Technology is indirectly included by positively affecting the relative productivity of labor. Thus, labor and technology together form an effective labor supply. Effective capital and effective labor are then combined in a Cobb-Douglas production function to formulate the potential production of the economy. The structure of this function inherently holds constant at unity the elasticity of substitution between these two factors. In summary, capital and energy are combined, and this result is combined with labor and technology to yield potential production.

This production is distributed to the three sectors in the economy according to their demands for investment. The desired consumption of the household sector and the desired investments in energy and nonenergy capital comprise the total demand of the economy. These desired rates of investment in energy and nonenergy capital are determined by the sum of two separate terms, each representing a different part of the investment decision process. The first term attempts to replace the capital which has depreciated or been discarded and thus attempts to hold the stock of capital constant. The second term attempts to correct the discrepancy between the desired stock of capital and the actual level. The desired level of capital is that level which would meet all demand for production. Desired consumption simply demands what production is left over after supplying the other two sectors. The actual investment levels are then determined by splitting production according to the proportion each demand comprises of the toal demand of the economy.

The decision concerning the split of investment in energy capital between the two energy sources is based on the relative productiveness of the two energy sources. Initially, the desired levels of investment in each source are decided in exactly the same way as the desired investment in nonenergy capital is determined. These initial desired investments are multiplied by the effect of profitability to obtain the actual desired investments utilized in the allocation decision. Profitability is determined by the productivity of a single source relative to the aggregate productivity of all energy sources. The price of energy is the same for both sources and is formulated as the sum of the production costs weighted by the amount produced in each sector, modified by the effects of a competitive market. An energy source with low productivity would not appear profitable compared to the market price and would therefore receive a decreased amount of investment.

Capital, labor, and energy are combined in a production function to produce GNP. This, in turn, is allocated to the three sectors of the economy and is either consumed or invested to further increase the levels of capital associated with these factors of production. The description above includes only those portions of the model critically involved with the dynamic behavior of an energy transition. A more rigorous description of model equations can be found in an appendix yet to be written.

THE NONENERGY SECTOR

Nonenergy Capital

```
L NEK.K=NEK.J+(DT)(INEK.JK-DNEK.JK)                    '72$
R INEK.KL=MAX(GNP.K*(DINEK.K/TD.K,0)                   '72$/YR.
R DNEK.KL=MAX(NEK.K/APLNEK,0)                          '72$/YR.
C APLNEK=25                                            YR.
```

The nonenergy sector of our model reproduces the behavior of four basic elements of the aggregate economy. The first, the accumulation of nonenergy capital, is represented as a level variable with a single inflow, investment, and a single outflow, depreciation. This level, in combination with inputs from the energy sector, produces GNP through a Cobb-Douglas production function. This is the second element. The third element is then the distribution of this wealth to the three areas of demand in our simple economy; consumption, investment in nonenergy capital, and investment in energy capital. Finally, the level of the energy requirements of capital is represented in a first-order delay structure which combines with the level of nonenergy capital to produce the demand for energy. These four elements are the basic components necessary to reproduce the behavior of a simplified economy during a period of energy transition.

The level of nonenergy capital, NEK, is fed by the investment in nonenergy capital, INEK, and decreased by the depreciation of nonenergy capital, DNEK. The investment in nonenergy capital is a function of GNP, the desired investment in nonenergy capital, and the total demand for GNP. This formulation will be discussed further in the consumption sector. The depreciation of nonenergy capital is represented as a first-order feedback mechanism determined by dividing the level of NEK by the average productive life of nonenergy capital, APLNEK. This life expectancy of capital is assumed to be a constant to twenty-five years in our simple economy.

Production

```
A GNP.K=PP.K*EEAP.K                              '72$/YR.
A PP.K=RPP*EKPP.K*ELPP.K                         '72$/YR.
C RPP=0.6E12                                     '72$/YR.
```

300

```
A EKPP.K=EXP(KEX*LOGN(EFFK.K/RNEK))                    DIM'LESS
A ELPP.K=EXP(LEX*LOGN(EFFL.K/RL))                      DIM'LESS
C RL=6.39E7                                            BTU'S/YR.
A EEAP.K=TABHL(EEAPT,EA.K,0,1,0.1)                     DIM'LESS
C EEAPT=.01/.12/.23/.34/.45/.56/.65/.74/.83/.92/1      DIM'LESS
A EA.K=EPROD.K/DCE.K                                   DIM'LESS
A DCE.K=ERK.K*NEK.K                                    BTU'S/YR.
```

The production in our economy is a two-stage process utilized to differentiate between the long- and short-term effects of a depleting energy source. The long-term effects are represented through a Cobb-Douglas production function, which determines the production after a change in the rates of the inputs into this production.

This first stage in output we've named potential production, PP, which is a function of the reference potential production, RPP, the effect of nonenergy capital on potential production, EKPP, and the effect of labor on potential production, ELPP. EKPP is then a function of the level of nonenergy capital, the reference level of nonenergy capital, RNEK, and the exponent of the effect of capital, KEX, which is the equivalent of in the generic formulation. Similarly, ELPP is a function of the rate of energy production; EFFL, which is an input from the energy sector; the reference energy production rate, RL; and the exponent of the effect of energy, LEX. All together this gives

$$PP=RPP*(EEFK/RNEK)^{KEX}*(EFFL/RL)^{LEX}$$

in the generic form of the Cobb-Douglas production function. The values of KEX, LEX, RNEK, RL, and RPP will be discussed at the beginning of the section on the behavior of the model.

The short-term effect of an energy shortage is represented as a multiplier from the effect of energy availability on production, EEAP. this variable multiplied by the potential production level gives the actual output of our economy or GNP. The EEAP is a table function which depends upon the energy availability, EA, of the economy. The energy availability is simply a ratio of the actual energy production rate, EPROD, over the desired level of consumption of energy, DCE. When the energy available for production is below the required level for the available capital stock, then it is clear that production will be decreased.

The desired level of consumption of energy, DCE, used in determining the energy availability is formulated as the level of NEK times the level of the energy requirements of that capital, ERK, a variable which will be discussed in the energy requirements of capital section.

Energy Requirements of Capital

```
L ERK.K=ERK.J+(DT)((DERK.J-ERK.J)/TAERK)              BTU'S/YR.
                                                        '72$
C TAERK=17                                            YR.
A DERK.K=ERK.K*ERPEI.K                                BTU'S/YR.
                                                        '72$
```

The final mechanism represented in the nonenergy sector is the level of the energy requirements of capital, ERK. This level is formulated as a first-order goal-seeking structure dependent upon the desired level of energy requirements, DERK; the previous level of ERK; and the time to adjust ERK of TAERK. This level of energy per unit of capital represents the optimal energy consumption level for already existing capital. The goal which this level attempts to reach is the desired level of ERK

determined by multiplying the level of ERK by the ratio of marginal productivity of energy, MPE, to the marginal cost of energy, which in our model is just the price of energy, PE. This assumes a perfectly competitive market economy. This ratio, the effect of the relative productivity of energy intensity, ERPEI, is the ratio of the expected return of using another unit of energy over the expected cost of using that unit of energy. A value greater than one indicates the profitability of using more energy per unit of capital. A value less than one indicates a loss in revenue due to an excessive use of energy per unit capital. The price of energy is an input from the energy sector, and the MPE is formulated mathematically as follows:

$$\text{MPE=KEX*RVSEK*(PP/EPROD)*(EPROD/REPROD)}^{-\text{ESP}}\text{*(1/EEC)}$$

The time to adjust the ERK is dependent upon two major mechanisms, the turnover of nonenergy capital and the adjustment rate of existing nonenergy capital through retrofits. Neither of these mechanisms is explicitly represented in our model. Instead, we set this adjustment time to a constant with a value less than the average productive life of capital. An adjustment time equal to the average productive lifetime of NEK would approximate the turnover mechanism with no effect of retrofits. The shorter the adjustment time, the greater the ability to utilize retrofits in existing capital.

ENERGY SECTOR

Links Between the Energy Sector and the Nonenergy Sector. The energy sector is responsible for utilizing its capital and resources to produce energy for the rest of the economy. In return for this energy, the nonenergy economy sends a portion of its output back to the energy sector in the form of investment in new capital. Thus, only two material flows cross the boundary of the energy sector. Energy, measured in BTU/yr., is sent out, and capital investment, in '72$/yr., is received.

Three pieces of information are exchanged by the energy sector and the economy; Price of Energy (PE), Desired Consumption of Energy (DCE), and Desired Investment in Energy Capital (DIEK). The price of energy is determined within the energy sector and used by the economy to determine its energy demand, or Desired Consumption of Energy. DCE is, in turn, a market condition that affects the Price of Energy, as will be discussed later. The third piece of information exchanged is Desired Investment in Energy Capital. This variable, DIEK, is determined within the energy sector and used by the economy to make a decision about the actual investment sent back to the energy sector. These three variables (PE, DCE, DIEK) plus the two material flows are the only five linkages that couple the energy sector with the nonenergy economy.

ENERGY SECTOR STRUCTURE

Resources. The energy sector contains Resources and Energy Capital. There are nonrenewable energy resorces (RES_1) and renewable energy resources RES_2) in this model. Both are measured in BTUs. The removal of resources from the stock occurs as a result of energy production. The initial amount of resources can be adjusted to reflect a particular energy base.

L $RES_i.K=RES.J-(DT)(EPROD_i.JK)$ i=1,2   BTU
N RES=ORES   INITIAL=ORIGINAL

Energy Capital.

L $EK_i.K=EK.J+(DT)(IEK_i.JK-DEK_i.JK)$ i=1,2   '72$
R $DEK_i.KL=EK_i.K/ALEK_i$ i=1,2   '72$/YR.
C $ALEK_i=10$ YR.

Energy Capital means the physical machinery, equipment, buildings, and land used to produce energy from raw resources. It is expressed in units of '72$, which is the same unit as the output production of the economy.

The level of Energy Capital is increased by investment in new energy capital and decreased by discards of old, worn-out capital. Investment in Energy Capital is actually determined in the nonenergy economy, as described earlier. Discard of Energy Capital is formulated as Energy Capital divided by the Average Lifetime of Energy Capital. This means that the oldest fraction (1/ALEK) of capital in the total stock wears out each year.

Correction in Capital for Energy Consumption.

A $CEC_i.K=(DESEK_i.K-EK_i.K)/TAEK$ i=1,2   '72$/YR.
C $TAEK_i=3$ i=1,2   YR.

A rise or fall in Desired Capital causes a discrepancy between the desired and actual levels of capital. Since the energy sector's overall goal is to fully meet demand, the desired capital is a goal to which actual capital is adjusted. The correction in capital is the amount of capital to be added or subtracted through increased or decreased investment to help accomplish this adjustment. CEC is not equal to the full difference between desired and actual capital but, instead, incorporates an adjustment time, so that full adjustment does not occur in one year. This reflects the concern of decision makers not to make hasty corrections which may turn out to be unnecessary in the long run. This adjustment time has been estimated to be between two and five years. Three years has been chosen here.

Desired Investment in Energy Capital.

```
A DIEK_i.K=(DEK_i.JK+CEC_i.K)*EKIP_i.K                i=1,2   '72$/YR.
A EKIP=TABLE(TEKIP,PE_i.K/CEP_i.K,0,4,.5)              i=1,2   DIM'LESS
T TEKIP=0/.5/1/1.5/1.8/1.9/1.95/1.97/1.98
```

The correction in Energy Capital is one component of the Desired Investment in Energy Capital. DIEK is the total amount of new capital the energy sector would like to receive from the economy. A second component is discard of capital; investment should make up for depreciation. The third component of desired investment is an effect on investment from the attractiveness of energy as a profit-making investment. The multiplier EKIP is based on the price of energy compared to the cost of energy production. When the price is higher than the cost, a profit is being realized by those producing energy. Speculators looking for a good investment can see the profit potential, and thus the multiplier is greater than one, increasing desired investment. This mechanism also works the other way. When energy prices are lower than production costs, the situation is a disincentive to investment, meaning the multiplier is less than one and investment is depressed.

In summary, the Desired Investment in Energy Capital has three components. Discard capital is replaced, new investment is to meet changing demand, and a positive or negative amount of investment is made due to profit incentives.

Energy Price.

```
A PE_i.K=CEP_i.K*EMPE_i.K                             i=1,2   '72$/BTU
A EMPE_i.K=TABLE(TEMPE,DCE_i.K/PEP_i.K,0,4,.5)        i=1,2   DIM'LESS
T TEMPE=0/.45/1/1.55/2/2.5/3/3.5/4
```

The Price of Energy is the cost of energy production (CEP) modified by market conditions. These supply-and-demand conditions are incorporated into the multiplier from the Effect of the Market on the Price of Energy. This multiplier compares demand (DCE) with supply (PEP). When demand exceeds supply, the multiplier is greater than one and the price is above the cost. The reverse is also true; oversupply causes depressed prices. The Price of Energy is used by the economy to form a decision about its future consumption of and investment in energy.

MODEL BEHAVIOR

The following explanation of the dynamic behavior of the model focuses on three progressive steps, each dealing with a specific mechanism of model behavior. The first step describes the mechanisms behind the behavior of the unburdened economy as it grows at an exponential rate. The second step introduces the limitations of an exhaustible resource base and describes the mechanisms behind the associated collapse of the economy. Third, the second energy sector is introduced, and the base-case smooth and rough transition patterns are discussed. A final section discusses possible policy options and their ability to ease the effects of a rough transition.

Mechanism 1. The unstressed economy, when fed by an exponentially growing source of labor, maintains exponential growth in GNP as long as investment in the other factors of production stays ahead of depreciation. With no depletion of energy resources, growth is unconstrained; this situation corresponds to having a fixed price for some mythical type of energy available in unlimited quantities.

Figure 3 depicts a causal-loop diagram of the main mechanisms responsible for growth. An increase in labor causes an increase in GNP;

when GNP rises, more is available for investment in energy and nonenergy capital. As these factors of production accumulate, productive capacity expands, increasing GNP. This behavior, whereby an initial increase in GNP is amplified, is an illustration of positive feedback. This self-reinforcing process between GNP and its factors underlies the growth of the economy.

Mechanism 2. Petroleum reserves in reality are limited; therefore, the inexhaustible nature of energy assumed in the previous case is unrealistic. In this second step, the effect of a depleting energy source is included in the formulations of the model. Figure 4 shows the behavior of the model with this mechanism active. The economy is initially growing exponentially, but as the resource base declines, this growth is slowed, then reversed until production is driven to zero. It is important to notice the sharp increase in energy capital just prior to the collapse. The price of energy also climbs precipitously during this period. This case of pure depletion, with no replacement source of energy, shows how the energy sector saps the strength of the economy until the resources are so critically depleted that the whole system collapses.

The causal-loop diagram illustrated in Figure 5 shows the mechanism leading to this drastic collapse of the economy. As resources deplete, the productivity of energy capital declines. In order to maintain the same optimal capital-to-energy mix in production, the energy sector must purchase more energy capital to produce the same amount of energy. This creates an increased demand for energy capital and consequently a disproportionate investment in energy capital. This is illustrated by the increase in energy capital in Figure 4. This shift decreases the investment in nonenergy capital, decreasing the growth rate of GNP.

A second characteristic of positive feedback is the negative amplification of a variable due to an initial decrease in value. The effects of a decreasing resource base provide the negative pressure necessary to initialize this negative amplification in the positive loops described in step 1. This pressure is increased as the resource declines even further. The positive force created by the exponentially growing labor supply is weakened and eventually nullified by the negative force of the depleting energy source. An incredibly swift collapse of the economy is caused by the capital depreciation rates overtaking their investment rates. At this point, the combined negative forces of resource depletion and negative amplification drive the economy at an accelerating rate to zero. The behavior of this second step is not intended to be realistic but is necessary to make clear the dynamics of resource depletion.

Mechanism 3. The third step in the analysis involves adding the second energy sector with a new, essentially untapped resource base. Figure 6 shows the behavior of the economy in both a smooth and a rough transition. The smooth transition is characterized by exponential growth in GNP and a constant or slightly decreasing price of energy. The economy gradually and smoothly transfers investment from the first energy sector to the second. A rough transition, however, produces a large overshoot in energy price. Growth in GNP is slowed to near zero for a period of about fifteen years, and the proportion of production invested in energy capital is driven to about twice the value observed in the smooth transition. Notice the significant increase in growth of the economy as the transition comes to a close. The two levels of GNP are practically indistinguishable twenty-five years after the transition begins.

The underlying mechanisms of transition behavior are illustrated in Figure 7. The two positive feedback loops through GNP and each type of capital remain the central mechanisms producing growth in the economy. A transition occurs when the second source becomes more profitable to develop than the original source, but this can happen for two reasons: because the original source becomes less efficient or because the new source gets more efficient. The mechanisms which drive the transition are the same in either cse, but this distinction is an important one, because it determines whether the transition is smooth or rough.

The conditions for a smooth transition are that, first, the productivity of the original energy source remains essentially constant, and second that the productivity of the new source increases due to advances in technology. These conditions result in a transition with constant or even accelerated GNP growth. Advances in technology improve the productivity of the new source until it surpasses that of the old source, at which point the new source becomes more profitable to develop. Investment now occurs mostly in the new source, and the capital of the old source declines as fast as depreciation will allow. In the case where the profitability of the new source rises just to or slightly above that of the old, the growth in GNP remains essentially unchanged, and the exchange of energy sources is hardly perceptible to the rest of the economy. On the other hand, if the productivity of the new energy capital rises to a level significantly above the productivity of the old capital, there is a period of accelerated growth. The increasing productivity of energy capital allows the economy to grow even faster than the constant levels of productivity experienced before and after the transition. This behavior could be called an "exaggerated" smooth transition. When the transfer of capital is complete, the economy has adjusted to a new optimal mix of nonenergy and energy capital, and growth has returned to the original exponential rate dictated by the growth of labor.

In a rough transition, the productivity of the original source declines past the constant level of a less efficient new energy source. As the original resource is depleted, the productivity of the old energy capital drops, causing a shift from the optimal mix of energy and capital in production and reduced growth in GNP. This is the behavior created by mechanism two. When the original productivity drops far enough to equal the lower, new energy source productivity, the investment incentives described for a smooth transition take over, the new source becomes more profitable, and investment begins to favor new source capital. However, since it takes a considerable amount of time for capital to accumulate in the new energy sector and decline in the old, the continued use of the old resource base decreases the productivity of old energy capital even further past the level of the new energy capital. Consequently, the cost of energy production, and therefore the price of energy, overshoots the level dictated by the productivity of the new energy capital. It is this overshoot period in which the economy is most damaged by the transition.

As the new energy sector begins to dominate energy production in the economy, an interesting catch-up period ensues. The productivity of energy capital in general is actually increasing as new energy capital replaces old capital, and the economy experiences a period of accelerated growth analogous to the growth experienced in an exaggerated smooth transition. This increased growth is illustrated in figure 7, as the GNP gap between the smooth and rough transitions closes. The final discrepancy betwen the two levels of GNP at the end of the transition is decreased by the pressures of a stressed economy on the energy efficiency of nonenergy capital. As energy becomes more and more expensive, there is an induced pressure to develop more and more energy-efficient capital. Thus, when a rough transition is over, the level of the energy requirements of capital is lower than that experienced in the unpressured smooth transition. This effect on nonenergy capital increases the accelerated growth phase even further. Thus, the lag in the level of GNP is reduced to a practically negligible level twenty-five years after the transition begins. This result is significant in that it implies that the effects of a rough transition are actually quite small in the long run.

The mechanisms described above pertain to the specific cases of a theoretical pure smooth transition with no rough effects and a pure rough transition with no smooth effects. However, in reality, energy transitions contain elements of both mechanisms; the transition is motivated by both the decline in availability of the old resource and the increasing efficiency of the new energy source. This leads to a mixed transition with rough characteristics and decreased GNP growth in the beginning, but then replaced by smooth characteristics and accelerated growth caused by increasing energy-capital productivity towards the end. The more gradual the decrease in old energy-capital efficiency and the sooner the development of the replacement energy source, the smoother the mixed transition becomes.

The two previous transitions were fueled by gradual decreases in resources (this effect was minimal in the case of coal) and gradual increases in the productivity of production of the new sources, coal in the first case and oil and gas in the second. The gradual nature of resource depletion and the availability and high productivity of new forms of energy

allowed these transitions to be quite smooth. Presently, however, the rapidly increasing cost of oil and gas and the lack of a comparably efficient replacement energy source have created the beginnings of a truly rough transition.

Policy Analysis. The purpose of studying these various mechanisms is to determine the effective methods of preventing and relieving the stressful characteristics of a rough transition. Our analysis has pointed to two critical factors: the delay in switching to the new source when it becomes more efficient and the time at which it becomes more efficient compared to the time when the old energy source begins to decline in productivity. In the first case, an effective policy would create an artificial demand for capital of the new source before it actually became more productive. This would hasten the transfer of energy capital to the new source and significantly lessen the prolonged dependence on the original source. A tax incentive program which favored the use of alternate energy sources would be an example of such a policy. In the second case, a policy which accelerated the increase in productivity of the new energy source would be most effective. This would minimize the period of time that the effects of the depleting energy resource were draining the economy and initiate sooner the investment in alternate energy capital. A program which increased the funding of research and development in new forms of energy production would be an example of this type of policy. Any measure that fostered the rapid transfer of capital to the nondepleting source or the increase in capital productivity would help relieve the economic stress of a rough or mixed transition.

CONCLUSION

Our analysis has explored the underlying mechanisms of an energy transition in the economy. These mechanisms produce growth in the economy with increasing consumption of energy, price and supply-demand equilibrium adjustments to compensate for a depleting resource, and the means by which a new resource base gets developed and utilized to return the economy to a growth stage. We have shown that the critical factors affecting the smoothness of the transition are the productivities of the competing energy sources and their associated levels of capital. A rough transition involves the transfer to a less efficient energy source, while a smooth transition is created by the introduction of a highly productive replacement energy source. An excessive requirement for energy-producing capital is the primary source of inefficiency in a rough transition. Prolonged dependence on the old source leads to declining prodoctivity among energy producers until the new source is available. For the transitory period of time during which neither the old or the new type of energy production is efficient, overall economic growth and health suffers. The stressful effects of a rough energy transition can be reduced by switching to a new energy source as soon and as rapidly as possible. This requires a certain amount of anticipation and a willingness to move on to new forms of capital and energy production in the face of economic stress.

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Figure 1 The life cycle of three forms of energy in the U.S.

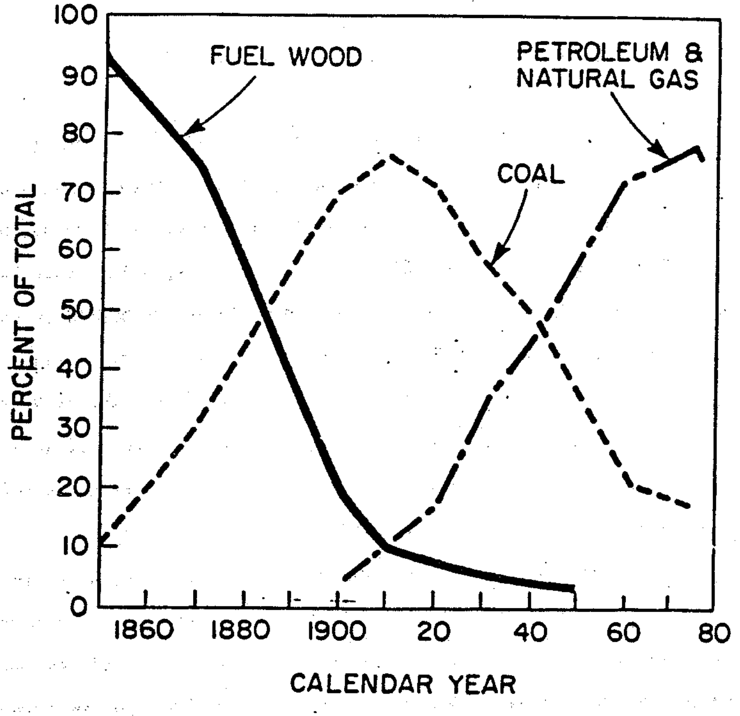


Figure 2 An overview of the model

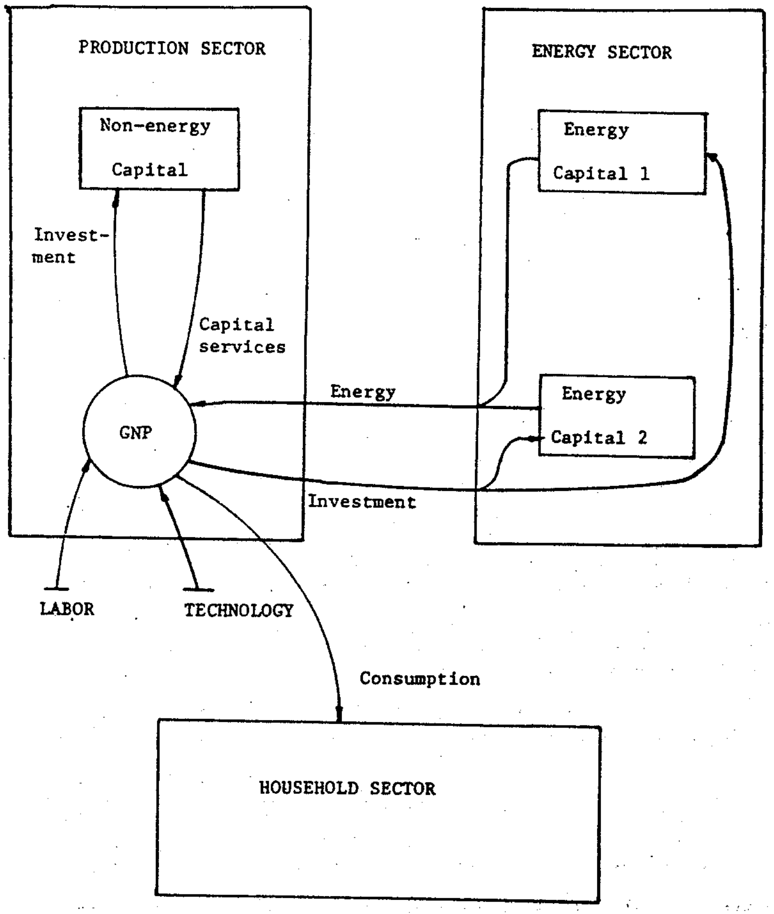


Figure 3 A causal-loop diagram of the main mechanisms

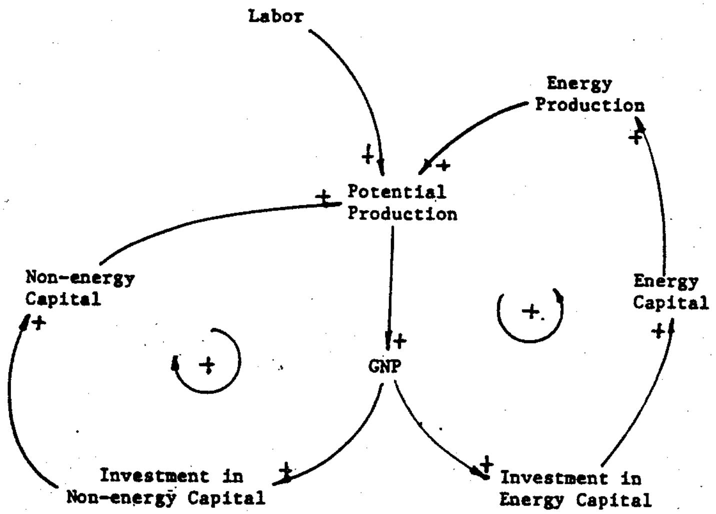


Figure 4 The behavior of mechanism 2

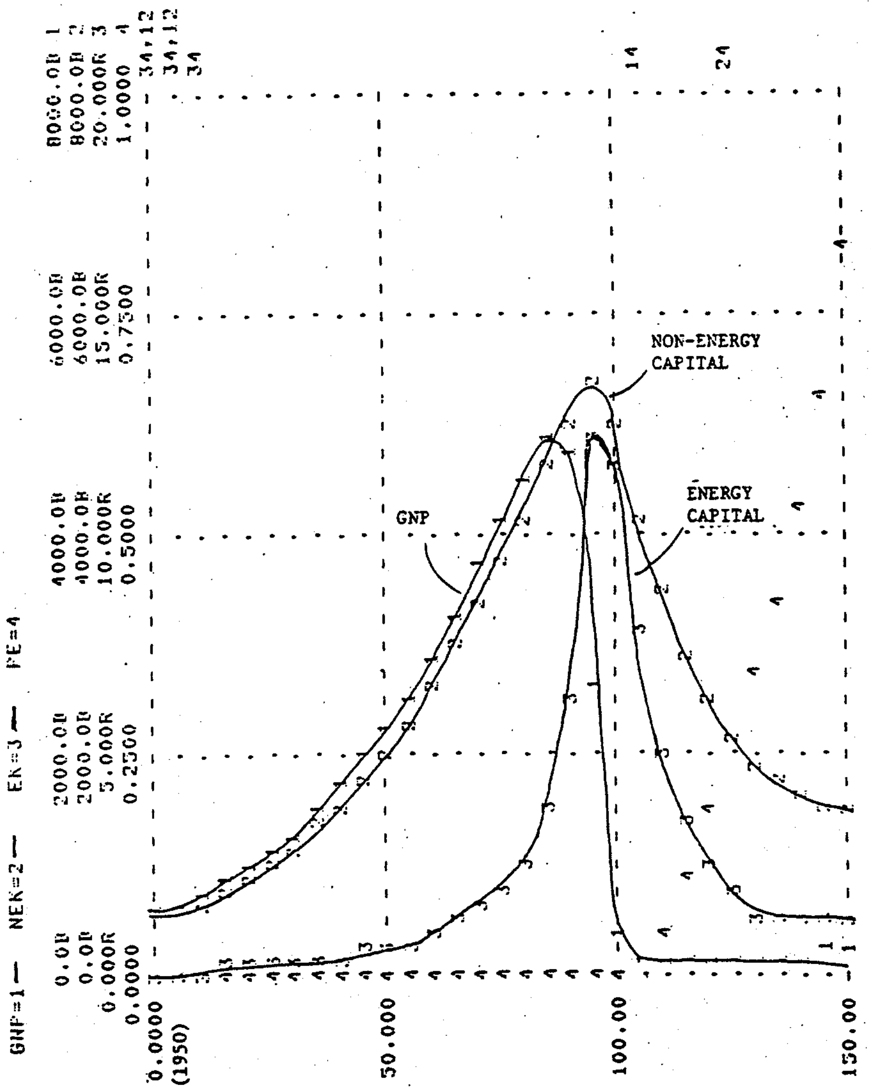


Figure 5 The causal-loop diagram of mechanism leading to the drastic collapse of economy

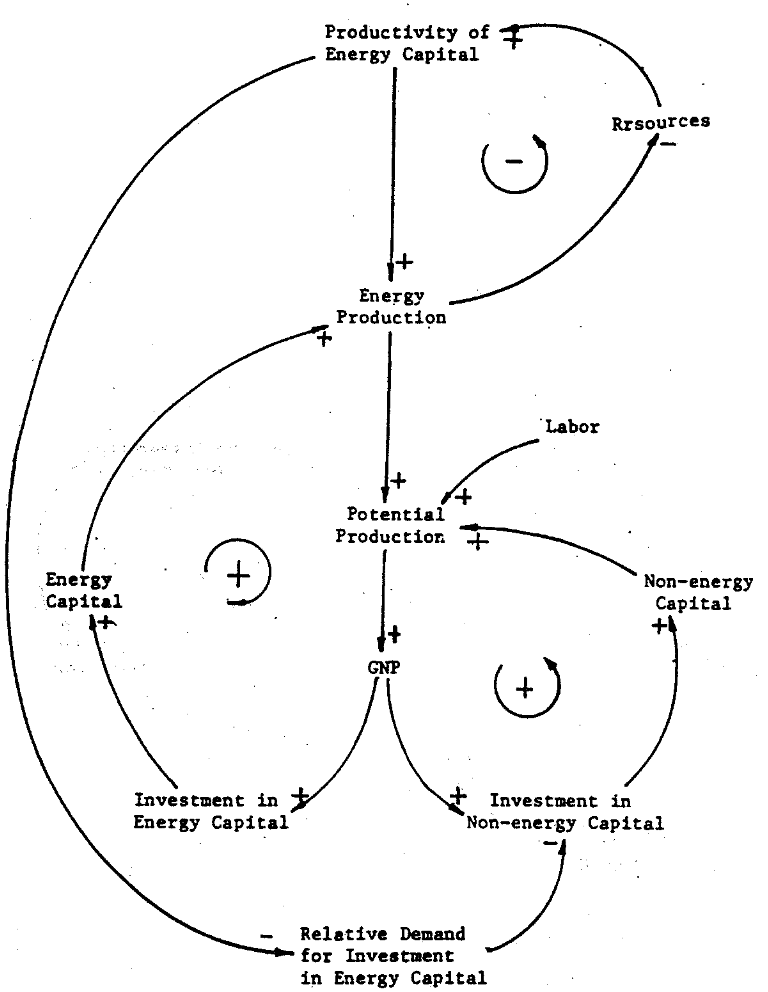


Figure 6 The behavior of the economy in both smooth and a rough transition

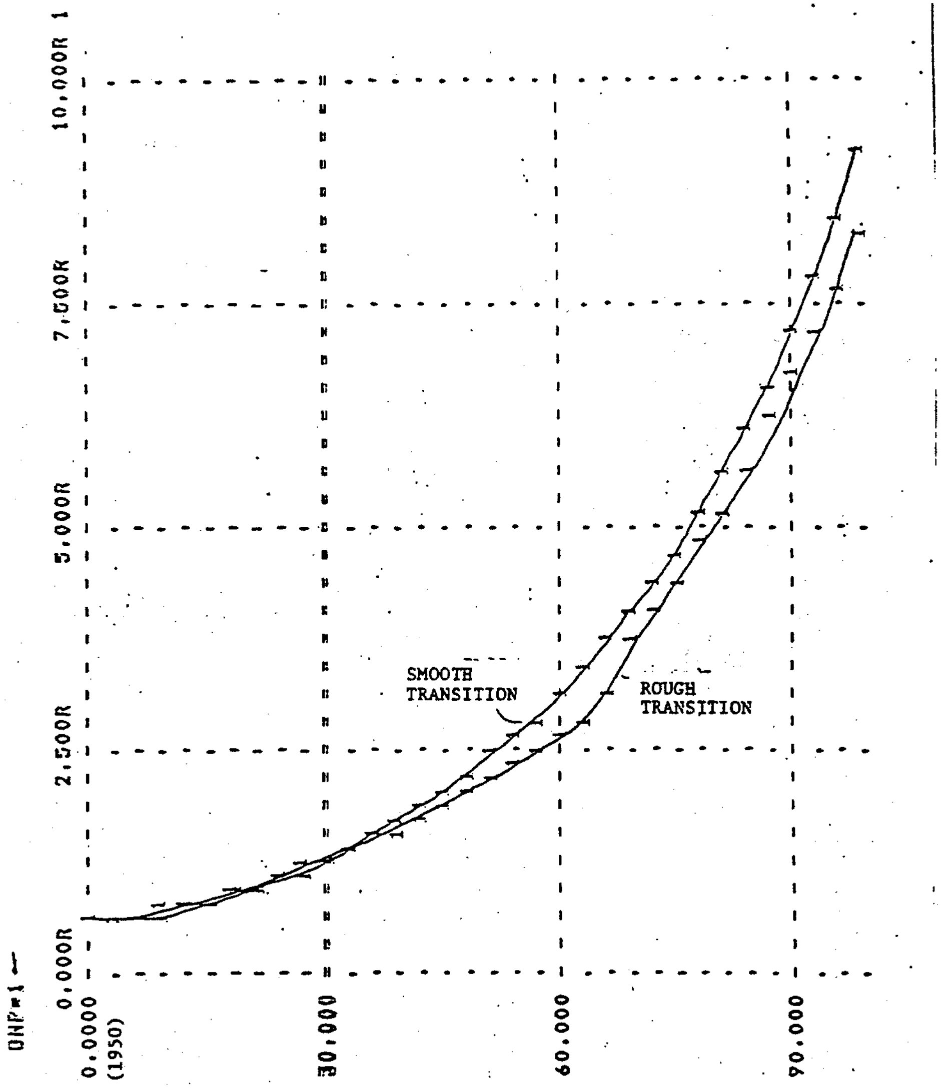
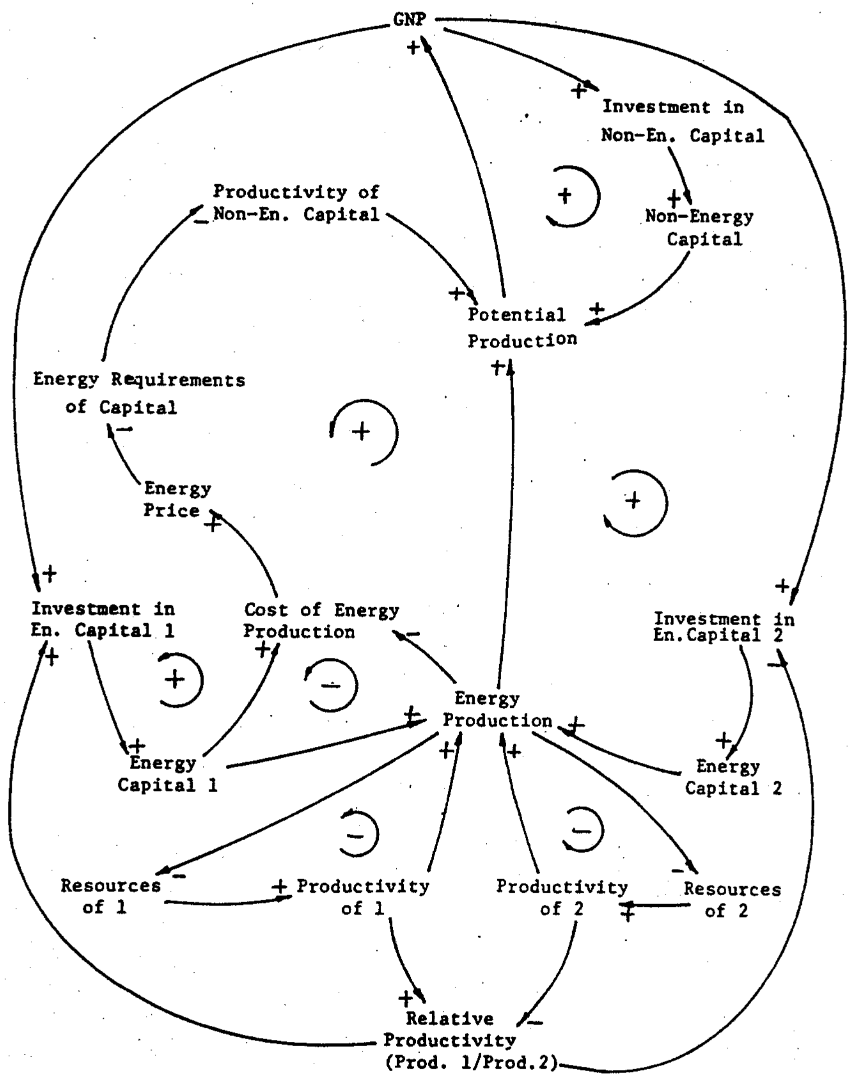


Figure 7 The causal-loop diagram of mechanism 3



APPENDIX List of equations

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* ENERGY TRANSITION MODEL
NOTE
NOTE  ECONOMIC DYNAMICS PROJECT
NOTE
NOTE  AUTORS: Qifan Wang, Brian McKeller and Randy Schweickart. May, 1983
NOTE
NOTE  CAPITAL SECTOR
NOTE
L     NEK.K=NEK.J+(DT)(INEK.JK-DNEK.JK)
N     NEK=KEX*(1-RVSEK)*RPP/CDR
R     INEK.KL=MAX(GNP.K*(DINEK.K/TD.K),0)
R     DNEK.KL=MAX(NEK.K/APLNEK,0)
C     APLNEK=25
NOTE
NOTE  INVESTMENT SECTOR
NOTE
A     TD.K=DCONS.K+DINEK.K+DIEK.K
A     DINEK.K=DNEK.JK+CNEK.K
A     CNEK.K=(DESNEK.K-NEK.K)/TANEK
A     DESNEK.K=NEK.K*(DP.K/PP.K)*ERPKI.K
A     DP.K=AD.K*(1+EGI.K*TAD)
L     AD.K=AD.J+(DT/TAD)(TD.J-AD.J)
N     AD=PP/(1+EGI.K*TAD)
C     TAD=2
A     ERPKI.K=MPK.K/CDR
C     TANEK=3
R     IEK.KL=GNP.K*(DIEK.K/TD.K)
NOTE
NOTE  HOUSEHOLD SECTOR
NOTE
A     DCONS.K=EINC.K-DSR.K
A     EINC.K=GNP.K
A     DSR.K=TDEP.K+CSAV.K+EGI.K*SAV.K
A     EGI.K=TREND(LOGN(EINC.K),TPT,TET,IGI)
C     TPT=4
C     TET=4
C     IGI=.03
A     CSAV.K=(DSAV.K-SAV.K)/TASAV
A     DSAV.K=DISC*EINC.K
N     DISC=(EK+NEK)/RPP
A     SAV.K=NEK.K+EK.K
A     TDEP.K=DNEK.JK+DEK.JK
N     TASAV=25
R     CONS.KL=GNP.K*(DCONS.K/TD.K)
NOTE
NOTE  PRODUCTION SECTOR
NOTE
A     GNP.K=PP.K*EEAP.K
A     PP.K=RPP*ELPP.K*EKPP.K
A     ELPP.K=EXP(LEX*LOGN(EFFL.K/RL))
C     RL=6.39E7
C     LEX=.75
```

```
A       EFFL.K=L.K*TECH.K
A       L.K=IL*EXP(LGR*TIME.K)
C       LGR=.015
N       IL=RL
A       TECH.K=IT*EXP(TGR*TIME.K)
C       TGR=.015
C       IT=1
A       EKPP.K=EXP(KEX*LOGN(EFFK.K/RNEK))
C       KEX=.25
A       EFFK.K=RNEK*EXP((-1/ESP)*LOGN(EEC.K))
N       ESP=(1-ESE)/ESE
C       ESE=.9
A       EEC.K=((1-RVSEK)*TRM1.K)+(RVSEK*TRM2.K)
C       RVSEK=.2
A       TRM1.K=EXP(-ESP*LOGN(NEK.K/RNEK))
A       TRM2.K=EXP(-ESP*LOGN(ERK.K/RERK))
N       RERK=ERK
A       MPK.K=(KEX*(1-RVSEK)*PP.K/NEK.K)*
X       (EXP(-ESP*LOGN(NEK.K/RNEK)))/EEC.K
A       MPE.K=(KEX*RVSEK*PP.K/EPROD.K)*
X       (EXP(-ESP*LOGN(EPROD.K/REPROD)))/EEC.K
C       RPP=.6E12
N       RNEK=NEK
C       REPROD=32.5E15
A       EEAP.K=TABHL(EEAPT,EA.K,0,1,.1)
T       EEAPT=0.01/0.12/0.23/0.34/0.45/0.56/0.65/0.74/0.83/0.92/1.0
A       EA.K=EPROD.K/DCE.K
A       DCE.K=ERK.K*NEK.K
NOTE
NOTE    ENERGY REQUIREMENTS OF CAPITAL SECTOR
NOTE
L       ERK.K=ERK.J+(DT)((DERK.J-ERK.J)/TAERK)
N       ERK=REPROD/NEK
C       TAERK=17
A       DERK.K=ERK.K*ERPEI.K
A       ERPEI.K=MPE.K/PE.K
NOTE
NOTE    ENERGY SECTOR
NOTE                 ENERGY CAPITAL
L       EK1.K=EK1.J+DT*(IEK1.JK-DEK1.JK)
L       EK2.K=EK2.J+DT*(IEK2.JK-DEK2.JK)
N       EK1=PEI*RPROD1/CDR
N       EK2=(PEI*RPROD2/CDR)/RPF
A       EK.K=EK1.K+EK2.K
N       EK=EK1+EK2
C       RPF=0.5
C       PEI=0.58E-6
N       RPROD1=REPROD-RPROD2
N       RPROD2=0.01*REPROD
R       IEK1.KL=IEK.JK*(DIEK1.K/DIEK.K)
R       IEK2.KL=IEK.JK*(DIEK2.K/DIEK.K)
R       DEK1.KL=EK1.K/ALEK1
R       DEK2.KL=EK2.K/ALEK2
R       DEK.KL=DEK1.JK+DEK2.JK
```

```
A       DIEK1.K=(DEK1.JK+CEC1.K)*EKIP1.K
A       DIEK2.K=(DEK2.JK+CEC2.K)*EKIP2.K
A       DIEK.K=DIEK1.K+DIEK2.K
A       CEC1.K=(DESEK1.K-EK1.K)/TAEK1
A       CEC2.K=(DESEK2.K-EK2.K)/TAEK2
A       DESEK1.K=DCE1.K/PEK1.K
A       DESEK2.K=DCE2.K/PEK2.K
A       EKIP1.K=TABLE(TEKIP1,PE.K/CEP1.K,0,4,.5)
A       EKIP2.K=TABLE(TEKIP2,PE.K/CEP2.K,0,4,.5)
T       TEKIP1=.001/.5/1/1.5/1.8/1.9/1.95/1.97/1.98
T       TEKIP2=.001/.5/1/1.5/1.8/1.9/1.95/1.97/1.98
C       TAEK1=3
C       TAEK2=3
C       ALEK1=10
C       ALEK2=10
NOTE             ENERGY PRODUCTION
L       RES1.K=RES1.J-DT*EPROD1.JK
L       RES2.K=RES2.J-DT*EPROD2.JK
N       RES1=ORES1
N       RES2=ORES2
R       EPROD1.KL=PEP1.K*CU1.K
R       EPROD2.KL=PEP2.K*CU2.K
A       PEP1.K=EK1.K*PEK1.K
A       PEP2.K=EK2.K*PEK2.K
A       PEK1.K=NPEK1*ERPEK1.K
A       PEK2.K=NPEK2*ERPEK2.K
A       ERPEK1.K=TABLE(TRPEK1,RES1.K/ORES1,0,1,.1)
A       ERPEK2.K=TABLE(TRPEK2,RES2.K/ORES2,0,1,.1)
T       TRPEK1=1/1/1/1/1/1/1/1/1/1/1
T       TRPEK2=1/1/1/1/1/1/1/1/1/1/1
A       CU1.K=MIN(DCE1.K/PEP1.K,1)
A       CU2.K=MIN(DCE2.K/PEP2.K,1)
N       NPEK1=RPROD1/EK1
N       NPEK2=RPROD2/EK2
C       ORES1=5E18
C       ORES2=5E18
NOTE             ENERGY PRICE
A       PE.K=CEP.K*EMPE.K
A       EMPE.K=TABLE(TEMPE,DCE.K/PEP.K,0,4,.5)
T       TEMPE=0/.45/1/1.55/2/2.5/3/3.5/4
A       PEP.K=PEP1.K+PEP2.K
A       CEP.K=(EPROD1.JK*CEP1.K+EPROD2.JK*CEP2.K)/EPROD.K
A       CEP1.K=EK1.K*CDR/PEP1.K
A       CEP2.K=EK2.K*CDR/PEP2.K
A       EPROD.K=EPROD1.JK+EPROD2.JK
C       CDR=.2
A       DCE1.K=FED1.K*DCE.K
A       DCE2.K=FED2.K*DCE.K
A       FED1.K=PEP1.K/PEP.K
A       FED2.K=PEP2.K/PEP.K
NOTE
NOTE    CONTROL CARDS
NOTE
C       DT=1
```

```
C      LENGTH=20
C      PRTPER=0
C      PLTPER=1
PLOT GNP/NEK/EK/TD/PP
PLOT IEK1/EK1/IEK2/EK2
PRINT GNP,INEK,IEK,DCE,ERK,NEK,EK
PRINT DINEK,TD,CNEK,DESNEK
PRINT DP,PP,ERPKI,MPK,DINEK,DIEK
BOTTOM
E>C>
```