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# RESOURCE AND ENERGY SUBSTITUTION*

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## ABSTRACT

The principal conclusions of this paper are:

(1) The crucial issues regarding resource scarcities concern the rates and prices at which resources will be available and the political constraints to using them in ever increasing amounts.

(2) We need to increase the flexibility of our economic system to respond to sudden resource supply disruptions through broadening our understanding of and technical potential for resource substitution.

(3) Natural resource conservation through substitution is an important response mechanism. It should be viewed as the rational adaptation of producer or consumer to a change in the social costs and benefits associated with the use of a unit of resources, or to better information regarding these costs.

(4) Major substitutions require long times for invention, innovation, information diffusion, commercialization and market penetration. Governmental initiatives can play a positive role in reducing the lag time.

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[†] Work done with support from the U.S. Energy Research and Development Administration.

(5) The substitution of productive factors should be viewed in a unified framework that permits the exploration of the concerted interdependencies of capital, labor, material and energy resources. Little definitive information regarding the substitution of natural resources by capital and labor is available, and even that is conflicting. Prior to instituting policies that affect these substitutions, a much clearer understanding is required.

(6) Two novel modes of substitution are discussed--the tradeoff between the energy needed to drive a process and the time required, and the substitution of materials for energy resources. Assessment methods have been developed for the latter and are being explored in the former case.

(7) International comparisons of energy requirements in industrial production show that there are many opportunities for energy conservation in the U. S. through the introduction of more advanced technologies. Similar opportunities exist in the buildings and transportation sectors. Parallel comparisons of energy use in Sweden and the U. S. indicate that equivalent standards of living can be attained with remarkably different levels of energy use. Therefore, there does not seem to be an immutable direct proportionality between economic growth and growth in energy use.

(8) Consumer substitution occurs at two different levels with possibly differing responses to price. On a technical level, a consumer will seek an identical amenity satisfaction through choosing a different group of goods and services that deliver an identical bundle of characteristics. Alternatively, changes in relative prices may produce

a modification at the personal, subjective level, where a consumer modifies his set of preferred amenities--a behavioral or lifestyle change.

(9) Congressional and governmental action can stimulate enhanced resource substitution capability in our economy through three mechanisms in addition to the collection and dissemination of comprehensive information on appropriate technologies: the funding of both fundamental and applied research directed toward resource-conserving technological change, the assurance of the existence of sufficient economic incentives for adoption and through direct regulatory policy or practice.

(10) The attainable and economically efficient operating points might be usefully evaluated in order to predict the amounts of the resources that could be conserved relative to prevailing practices and constraints--which might include market imperfections, peculiarities of pricing practices, lack of capital or information, or other institutional barriers.

(11) Perhaps the most critical issue facing our society is how to achieve a more just distribution of income under resource constraints that may impair economic growth.

## A. INTRODUCTION

The attitude toward natural resource use in the preceding decade was one of ebullient optimism. Historical experience showed that possible resource scarcities, as evidenced by decreasing ore grades or smaller areas under cultivation, had been mitigated or eclipsed by technological advances or through price-induced substitutions.

This optimism has been replaced in the '70's by a more guarded stance. We now realize that natural resource markets may be buffeted by the actions of international cartels and that national security considerations can dictate policy steps that may not appear economically efficient over the short term. Intensive resource use also may generate unacceptable levels of thermal, air or water pollution, and another constraint is thereby placed on the actions of private economic agents. Finally, we have become increasingly concerned with our obligations to future generations, who may cast their votes in economic decisions only through us. This barrage of new complexities suggests that intelligent decisions, either market-based or policy-oriented, require a much broader understanding of the technology and sociology of resource use than heretofore achieved.

Available evidence regarding resource scarcity is mixed. Barnett and Morse in their classic exposition of the economic evidence of scarcity[1] showed that, with the possible exception of forest products, the real inputs of capital and labor to the extractive sectors (including minerals, agriculture and fishing) had decreased over the period 1870-1957. Thus, they concluded that there was no economic basis for presuming the existence of either Malthusian scarcity or Ricardian scarcity, the latter arising from the use of increasingly lower-grade ores. Similarly, Goeller and Weinberg[2] argue that total world resources of the most extensively used elements are so large (one million to one billion times current yearly consumption) that a transition to a society that uses only these materials will result in an age of "infinite substitutability." There is the implicit assumption that some resources are in foreseeably short supply, but that substitution and technological change can ameliorate any physical shortage. They also project that this transition can be accomplished with tolerable costs, although individual sectors could be severely impacted.

A less sanguine view is taken by Skinner,[3] who chaired the prestigious study by the National Academy of Sciences' Committee on Mineral Resources and the Environment. Again emphasizing the need to shift to technologies that use iron and other abundant metals for all our needs, he specifically examines the maximum economically-recoverable tonnages of scarce resources, such as copper, lead, mercury and uranium.* His assessment shows, for example, that society's use of mercury and gold is at a rate that is 110 times faster than iron and that the rate of lead use is 40 times that of iron, when the rates are taken proportional to respective crustal abundances.

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[*] It is interesting to note that, where comparison is possible, the estimates of recoverable resources given in Ref. 3 are 10 to 30 times smaller than those given in the article by Vogely (Ref. 4), and those of Vogely are 10 to 10,000 times smaller than those in Ref. 2, except for phosphorous and manganese. One cannot determine whether the assumptions used in preparing the three sets of estimates are identical. A continuing effort to establish accurate world and nation resource estimates is clearly warranted.

This formation of the supply picture comes closest to identifying the key considerations regarding resource use and the need for new resource substitution options between now and the year 2000. Let us accept for the purposes of the discussion given below that potentially recoverable stocks of resources are sufficiently large to fill society's needs over this period. The crucial issues concern the rates at which they can be used:

(1) Will flows of natural resources be available at the rates needed and at prices that we (and other nations) are willing to pay? Are capacities of current and projected extraction and beneficiation enterprises sufficient to meet projected demand? Keyfitz has recently pointed to the enormous increase in demand for resources that may attend the efforts of a large portion of the world to become middle class.[5] Will it be possible to furnish the resources required for world economic development at an accelerated rate? How effective will resource cartels be in constraining supply and thereby stabilizing prices at much higher levels?

(2) Even if we suppose that resources are available at prices commensurate with our economic vitality, will it be politically feasible to continue to use them in ever-increasing amounts? What are the extra-economic dimensions of the problem of resource use?

(3) What is required for efficient societal response to sudden supply distributions arising from embargoes, crop failures or disaster? Does a smoothly operating price system furnish us with sufficiently rapid signals of these disruptions?

There are many facets to the answers to each of these questions, but a single pervasive one. To ensure the continued health and growth of the U. S. Economy, we must understand the full dimensions of resource substitution and be prepared to set substitution mechanisms in motion. In this paper, we will emphasize how little is known about the technical basis of and potential for substitution and technological change and about the times required for these responses. In parallel, we will examine some recently developed assessment methods that are being used by several active research groups to begin to explore these problems.

The purpose of the substitution mechanisms that we shall discuss is the implementation of resource conservation as a response to possible supply constraints or price increases. The term "conservation" is almost always used emotively and left undefined. We should like to be precise. Natural resource (energy) conservation is the rational adaptation of producer or consumer to a change in the social costs and benefits associated with the use of a unit of resources or to better information regarding these costs and benefits. The change may result in the increased use of a resource, which distinguishes the concept of conservation from that of preservation. A principal function of policy intervention is to effect the rapid dissemination throughout the economy of information about the total social benefits and costs.

The discussion in this essay will often focus on substitutions for energy resources. This should not be taken to indicate that energy resources are necessarily scarcer than some other materials. However, under the stimulus of the oil embargo and subsequent cartel actions, the understanding of the complex economic role of energy resources in our society has been greatly expanded. In the energy market, the prices that consumers and most industrial users pay in the absence of governmental regulation or market imperfections reflect <u>average</u> producers' costs. For the first time in decades, the marginal costs of new supplies of today's energy forms, or of substitutes such as synthetic fuels, lie significantly higher than average costs. Thus, the evidence suggests that energy prices will continue to escalate. Market prices are used by both producers and consumers in calculating their optimal economic behavior. Energy users wishing to maximize their welfare will reoptimize their consumption/production activities by finding substitutes under the new set of prices that obtains. Government initiative may be required to ensure that considerations of national security and the environmental impacts of energy harvesting, conversion and use are reflected in this new set of prices. Insitutional changes may be required to allow desired responses to occur.

## B. MATERIAL-MATERIAL AND ENERGY-ENERGY SUBSTITUTIONS

Above we have stressed the need for society to prepare itself for encroaching shortages of less abundant materials by thoughtfully examining substitution for these by more plentiful resources. There is little to be gained at this point by constructing a material-by-material list of substitution possibilities. Similarly, our technical flexibility in making energy-energy substitutions is substantial and increasing, both in industry, where boilers convertible to various feeds are increasingly prevalent, and in the home, where conventional fuel and electric use is supplemented by wind, wood and other forms of captured solar energy. Of course certain industries may be seriously affected by constraints on supplies of specific fuels because technologies that permit fuel substitution do not exist. For example, sectors as diverse as the baking and foundry industries both are critically dependent on sufficient supplies of natural gas.

Evidence of energy-energy substitutability can be found in the small differentials in prices of fuels on a per btu basis. The full costs per btu of using alternative fuels, which would include the cost of sulfur removal from high sulfur coal, for instance, are approximately equivalent. American industry is more concerned with the perturbations attending potential short-term shortages of specific fuels. Because of this, we may see industrial users convert to electrically-powered technologies, reasoning that a moderate increase in energy factor costs is outweighed by security of supply.

There are two points that should be emphasized. First, substitutions that are effected through technological change take time, and, historically, major substitutions have required very long times. Second, a discussion that divides substitution possibilities into categories such as material-material, energy-material, labor-energy, etc, is clearly artificial. Almost all two-factor substitutions involve significant interdependencies with other factors. For example, replacement of productive labor by fuels and electricity can usually be accomplished only with the installation of new capital facilities. Let us examine these points more fully.

Large-scale substitutions of one resource for another have most often occurred over periods of time that extend beyond the perspective of this study series and of accurate economic projections. Time-consuming technique for technology development must be followed by an adjustment phase in which the new method penetrates the market. An example of a successful substitution for a dwindling resource that is cited by those who are optimistic about the ability of the market to self-regulate is that of coal for increasingly scarce wood in eighteenth century Britain. It is rarely mentioned that a half century (ca. 1730-1780) of effort and expense by British ironmakers was required before a successful method of using the mineral fuel (which contained inpurities that gave iron undesirable properties) rather than the renewable timber resource in steelmaking was developed.[6] Coal-dependent growth of the industry was such that production rose from 68,300 long tons in 1788 to 2,701,000 long tons in 1852.*

Certainly, technological responses to resource constraints should be more rapid today, but how fast can we expect them to be? The lag between the beginning of fundamental research on commercial polymers by DuPont and the first commercial production of nylon was 11 years.[7] Other examples are given in Table 1. A study by Lynn[8] found that in the post-World-War-II period (1945-64), the average lag from basic discovery to the beginning of commercial development extended for an additional 5 years, a total of 14 years. His investigation also indicated that government support significantly reduced the time required for the initial "incubation" phase, positive evidence that governmental

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*Landes also points out[6] that British iron manufacture avoided economic suicide in the pre-1789 period by cultivating timber specifically for that industry. Domestic iron output actually increased slightly, but imports from Sweden and Russia doubled in the period ca. 1710-1755 even in the face of import duties.

activity in technological research and development is beneficial.

Equally important in determining the total time to implement a feasible substitution is the interval required for diffusion of a process throughout an industry. A recent internationally-based review of this question[9] selected ten new technologies, including numerically-controlled machine tools, tunnel kilns, basic oxygen steel, continuous casting, special presses, float glass, the use of gibberellic acid in malting, shuttleless looms, plate cutting methods, and automatic transfer lines. As a rough generalization, market penetration to achieve a diffusion of 50% (as a percent of national output of the product) occurs in a period equal in length but additional to that needed for incubation and development combined.

Consequently, the total time required for effective substitution via technological change rather than price induction--following identification of a potential scarcity and invention of an appropriate substitution technology -- is on the order of 25 to 30 years. Certainly cost incentives can play a role in this process. Through thoughtful analysis and preparation, society can and will mitigate serious economic perturbations that could arise from increased rates of resource use and concomitant supply constraints. Support by governmental agencies is absolutely necessary in stimulating the basic research that is vital to the slow, creative process of invention itself, and it is also effective in speeding up the incubation process between invention and the commercial development decision.

Let us return to the interdependencies among factors in the resource substitution process. Consider two steel making processes, one utilizing an older blast furnace that requires 16 × $10^6$ btu of heat per ton of raw steel produced and the other using only 10 × $10^6$ btu/ton (these numbers are not exact, only illustrative). From what could this difference arise? The lower energy consumption of the second furnace could be due to the following factors:

1. the walls are thicker, of new materials, and furnish better insulation;
2. maintenance of the fuel combustion unit is carried out more frequently;
3. the heating up of the furnace is timed to more carefully match the time that the charge of iron moves into place;

and

4. the hot gases emerging from the furnace are used to generate electricity, and the waste heat from the generation process is then piped to another area to heat offices (or, alternatively, to preheat the next charge).

In this description of "energy conserving" factors we recognize that the substitutions have been in the form of capital (thicker walls, innovative materials), labor (maintenance), information (timing), and thermodynamic optimization (the use of high-temperature heat as an input to another process) for energy. While differences 1 and 2 are straightforward substitutions of energy by a single factor, the last two are not. Both require new capital items and an increased labor input, at least in a process-control capacity.

Recycling activities substitute used for virgin materials, but the second-order subsequences of the material-material substitution are often more important. For example, aluminum is an abundant material, and the benefits of recycling lie in a 90% reduction in the energy required to produce a new aluminum product, as well as reductions in capital and labor inputs.

Thus, resource substitution should be considered in a unified framework that permits a consideration of complementarities among substituting factors as well. Two recent econometric examinations[10,11] explore this question at the macroeconomic level for American industry. Both studies employ translog production or cost functions, and this functional form is somewhat controversial. The Berndt-Wood formulation[10] relates the flow of gross output to the services of four factors of production; capital, labor, energy and materials. The specification used by Humphrey and Moroney[11] is somewhat different, treating the dependence of new output in specific industrial sectors on inputs of natural resources, capital and labor. Both investigations utilize time-series data, but different aggregate indices. The studies are not entirely in agreement regarding the relation between capital and resource inputs, although the differences in specification preclude direct comparison of the results. Humphrey and Moroney[11] find that there is limited substitution between capital and natural resource products, while the results of Berndt and Wood indicate substantial complementarity between capital and energy, although some substitutability between capital and material inputs is evident.[10]

These two publications are important because they reflect a clear break with the value-added motif, which subtracts out natural resource costs and considers only capital and labor, that has dominated econometric evaluations of the production process. Continued probing of the relation of the productive services of natural resource inputs to total output will enhance our understanding of the resiliance of our economy to sudden constraints on the supplies of these resources. Of particular interest would be disequilibrium analyses and cross-sectional studies, perhaps based on international comparisons.

## C. SUBSTITUTION OF MATERIALS AND ENERGY

There are three levels at which materials and energy substitute for one another. Above, we have called attention to the possibility of using recycled aluminum rather than virgin ore, with an effective substitution from energy. Additionally, we should recognize that intermediate materials carry with them into subsequent fabrication steps the energy that has been embodied in material extraction, beneficiation and other previous manufacturing processes. Consequently, loss of the material through slippage is equivalent to a waste of the embodied energy. (Here, the term "embodied" is used in the same sense "embodied labor" has been used by economists). Any modification in a process that changes the relative proportions of materials that embody different amounts of energy also changes the energy required for the process.

Finally, materials contain real amounts of energy that can be released in the same way that it is released from fuels--through a chemical reaction. For example, sulfur reacts with oxygen in a combustion process that yields two-thirds as much energy as the combustion of coal, for chemically equivalent weights of sulfur and coal. Likewise, aluminum combines with oxygen, releasing four times the energy of coal-burning, and a reaction of barium oxide with another chemical, sulfur trioxide, gives off 1.5 times the combustion energy of coal. Almost every chemical can react with another so as to furnish energy under the proper conditions. In real industrial processes, material use may substitute for fuel and electric use. The Hall-Heroult electrolysis of alumina to produce aluminum metal utilizes a carbon electrode. For every ton of aluminum that is produced, a ton of electrode is chewed up, and carbon dioxide is produced. The carbon substitutes partially for electricity in the reduction of the alumina, and the heat released in the effective combustion of the carbon in part reduces the fuel requirement in maintaining the melt. As a related point we note that the paper industry provides a portion of its own steam and electric power by burning pulping wastes and licquors.

Obviously, the determination of the most <u>physically</u> efficient production process is complicated by the need to consider all three types of substitutions in concert. Here, physical efficiency connotes physical output of product per unit of energy input. One response to this has been the birth of a new discipline, called resource analysis (or, in a more restricted sense, energy analysis when applied to analyses of fuel and electricity consumption).[12] The goal of research in this area is an accurate quantitative assessment of the productive flows of resources in economic processes. As a familiar example of such an analysis, consider the production, use and eventual discard of an automobile.[13] In order to answer the question of how much energy is required in production, we must go not only to the automaker to find out the energy requirements for fabrication, but we must start back with the fuels and electricity needed for the extraction and beneficiation of iron ore and trace through the energy inputs to the blast furnace and to steel making. A refined analysis would investigate these steps for several types of carbon steels, for ferroalloys, stainless steel, automotive sheet, iron and steel castings, as well as copper, aluminum, zinc, plastic, and glass components. Fuel consumption in normal driving must be totaled in, as well as the energy required for replacement parts. And the possible energy savings introduced by recycling the scrapped auto through shredding or compacting must also be evaluated. This sounds like a tall order--and it is--but has been done.[14]

But why have such analyses focused on the energy requirements for processes, rather than the water needed or the inputs of iron ore? Certainly, these are increasingly important resources, and the analytical procedures that have been developed to evaluate all material resource flows as an initial step. Energy requirements are emphasized for two reasons. First, the physical scientist recognizes that in order to make a process "go," energy must be used. In this use, the ability of a given quantity of energy to do work is partially lost. A conservation law tells us that the elements in material resources are never destroyed. Given a sufficient quantity of energy that can be utilized to do work, we can reaggregate and reconstitute any form of matter. If an automobile is left to rust in a field and the rust is then dispersed by the wind, it may still be conceivably possible to sweep up the rust using a giant electromagnet. All that would be required is enough energy to power the magnet. While the energy used in a process is also completely conserved, it is inevitably degraded, finally, to heat at ambient temperature. In the near term, before solar radiation can furnish a substantial fraction of our energy supply, we must rely on existing and finite quantities of usable energy in the form of low-entropy fossil and uranium fuels. We must husband these supplies wisely.

The second reason for concentrating our attention on energy resources is somewhat more complex, but it also comes from that branch of science known as thermodynamics. Utilizing a precise description of technologies based on an energy parameter, it is possible to evaluate their physical efficiencies. This knowledge is only one piece of the data set that is needed to assess economic efficiency, along with a knowledge of the minimum requirements of other scarce resources such as capital and labor, but it is a very important piece.

What have such analyses yielded?

(1) The detailed descriptions of processes provide a much clearer picture of how society uses resources than had been available. This is information that both free-market advocates and those oriented to governmental intervention always assumed was incorporated in economic decisions, but rarely was. The importance of this sort of knowledge

is underlined by the fact that one of the largest and most profitable U. S. chemical companies keeps energy accounts side-by-side with financial books and uses them daily in a line management system.

(2) They show that there is no easy path in resource conservation. In energy conservation, a program that can promise a saving equivalent to 0.5% of the nation's energy budget is a major one. This means that conservation programs will be broad, affecting many resource-use decisions. Planning must utilize a growing and accurate information base.

(3) Aside from fuel used for home heating and transportation, the demand for energy and other natural resources is a derived one, depending on the levels of their incorporation in the production of other commodities. Because natural resources are such a small component of input costs, compared to capital and labor, significant increases in resource prices may be required before there is significant industrial response. Given this, it is the individual consumer who will be the target of increased hikes in fuel and electricity prices. Because space-heat and transportation are deemed necessities, much more attention must be given to the distributive questions associated with energy and other resource-conservation policies. Our most pressing national problem is how we will achieve a more just distribution of income under resource constraints that may impair continued economic growth.

(4) Opportunities for resource conservation in individual processes have been probed. For instance, we now know that production of a 3250 lb automobile requires a total of 37,250 kwh, from ore extraction through fabrication.[13] This is equal to the energy content of the fuel burned in its first year of operation (by way of comparison, an average family home uses around 700 kwh/month in electricity[14a]), and one-third of this production energy could be saved by recycling the discarded auto hulk.[13] Governmental initiatives to facilitate retrofitting and adoption of resource-conserving technologies should be pursued.

## D. THE SUBSTITUTABILITY OF ENERGY AND EMPLOYMENT IN THE INDUSTRIAL SECTOR

One of the most sensitive issues in the introduction of any new technology is the extent to which it is labor-saving. Historically, wage rates have been high in the U. S., and innovations have been capital-intensive and directed toward reducing labor's share in production costs. The assertion is often made that energy has increasingly been substituted for labor in post-World War II industrial production. The basis for this assertion is not entirely clear. Two recent econometric studies conclude that labor is a substitute for both materials and energy--or for natural resource products--more generally. To our knowledge, there has been no rigorous micro-economic quantitative evaluation of the substitutions between physical inputs of labor and energy per-unit-output over time. Partially, the claim may derive from the position that the principal contribution of productive labor is in furnishing energy to the process and, if labor's input is reduced, it must be replaced by energy. But menial uses of labor have certainly been minor in this century. Alternatively, large capital facilities utilize large quantities of energy, and this gives the impression that a substitution of capital and energy for labor has been effected. Qualitatively, there is apparent substance to this position.

If we look at the energy used in manufacturing we find that over two-thirds goes for process heating at various temperatures and efficiencies, with a much smaller amount being used to power labor-saving devices. Thus, labor and the largest portion of manufacturing energy use are not directly coupled through the replacement of labor by energy.

However, Table 2 shows that the relation between energy use and labor use in industrial production may be more complicated than would initially seem to be the case. For a representative set of energy-intensive industries, we see that energy use per production-worker man-hour has indeed increased, or in a few cases has been stable, over the period 1954-1967. On the other hand, energy input per constant dollar of shipment has decreased for every industry over this time period. Further disaggregation of these industries to examine energy use per unit of physical output may be very revealing. It appears likely that increased capital input has substituted for both energy and labor. Because energy costs are small relative to those of capital and labor, energy use has been the tail of the dog, wagged by the interaction of the larger factor costs. This is in spite of the fact that energy prices have decreased over the period studied. This raises the converse question of how far prices must rise before energy costs enter sensitively into the industry sector's planning.

Economic evidence regarding the substitutabilities or complementarities of labor, capital and energy is sparse and somewhat conflicting. The econometric study by Berndt and Wood[10] concludes that, while capital and labor are quite substitutable, energy and capital are complementary, as noted above, and there is only a slight substitutability between labor and energy. In a similar investigation, Humphrey and Moroney[11] assert that, for most of the resource-intensive sectors, the substitutabilities between capital and resource products and between labor and resource products appear to be equal to that of capital and labor. This latter study tends to support the earlier, more aggregated results of Barnett and Morse.[1]

One other caveat should be offered at this point. The energy intensity of a particular branch of manufacturing is dominated by process heating requirements, at least within the seven sectors that consume most of all manufacturing energy (paper, metals, chemicals, refining, stone/glass/clay, and food). Variations in energy use per employee or per unit of product among different industries or over time can be caused by changes in production processes, changes in output, or changes in the efficiency with which energy is applied. One should, therefore, disaggregate the manufacturing sector carefully so as to separate these factors. In the U. S. this analysis would ideally consider industries at the 3 and 4 digit SIC classification level; greeting cards should not be mixed with pulp production, and so forth.

On the basis of present evidence, one must conclude that the substitutability of energy and labor is slight in our productive structure. However, even this slight effect may reflect the non-separability of capital and energy factors, [10] and policies that are based on the possibility of energy-labor substitution isolated from other changes may be misguided. The subject of labor substitution for energy and materials should be accorded more attention. At the macroeconomic level, different forms for production and cost functions should be explored and new aggregation indices developed, and quantitative microeconomic evaluations of specific technologies are also needed.

## E. SUBSTITUTION OR COMPLEMENTARITY OF CAPITAL AND NATURAL RESOURCES

As previously discussed, the two econometric evaluations of the relation between the productive flows of capital services and natural resources (materials and energy) are not completely compatible. We believe, however, that the issue of greater consequence is not the past relation between these two factors, but that that can be expected to evolve with the introduction of new capital facilities in the U.S. A laboratory for measuring the relation exists in the production facilities in Europe, particularly in the Federal Republic of Germany, Sweden, Holland, and in Japan, where industrial plants were constructed in the 1950's and 1960's that incorporated numerous technological advances over the older U. S. physical capital stock. Although slight variations in the inputs of material resources occur, they are important only in a few cases, such as polymer production using natural gas feedstocks in the U. S. (a rapidly changing situation) as opposed to complete reliance on nephtha cracking for feedstocks elsewhere. Therefore, we will concentrate our attention on possible substitution, through technological change, of capital for energy.

The motivation for making these international comparisons is two-fold. First, as will be explored below, we have found the analyses to be sensitive quantitative indicators of differences in technologies, and process technologies exhibit marked variations internationally. Thus, the possibilities for energy husbandry through international and interindustry technology transfer can be explored. Second, they provide us with information about how elements in economic society can respond to higher prices for energy goods. It is generally agreed that price elasticities of demand for energy goods generated by regression analysis of time-series data for the pre-1973 period of relatively stable fuel prices may not be reliably applied to today's volatile energy market. To the extent that sectors in different countries have faced widely different prices for energy goods, cross-national comparisons may yield superior information regarding elasticity responses. Of course, these will correspond most closely to long run price elasticities of demand.

Our attention was drawn to international comparisons when we were examining data on aluminum production in the U. K., The Netherlands and the U. S.[15] In this industry, the technology for the energy-consuming electrolytic step is the well-known Hall-Heroult process in all three countries, and we anticipated that the total energy requirements would be similar. Our anticipations were borne out by the data for the totals in the three countries: 217 million btu/ton, U. K.; 200 million btu/ton, The Netherlands; and 222 million btu/ton, U. S. A. However, a careful examination of the energy requirements for sub-processes alerted us to some of the pitfalls that one faces in making international comparisons. Referring to Table 3, we see that although the total requirements are approximately the same, the requirements for individual steps are substantially different. The variation in energy use in alumina production can be attributed to different technologies and ore grades. The figures for the smelting step were more surprising. Closer examination showed that the smelting number for the U. K. applies to their most efficient cells only and that the average U. K. value is 194 million btu/ton. Both the Dutch and U. S. figures are national averages, but the facilities in The Netherlands are of later vintage.

Similarly, the energy required for steel production is apparently 50% greater in the U. S. and the U. K. than in the Netherlands.[14] This result has been confirmed by more recent research in international comparisons of industrial energy use carried out under the auspices of the NATO Committee on Challenges of a Modern Society (CCMS), Pilot Study on the Rational Use of Energy.[15] German and Italian steelmaking facilities also are energy-efficient when compared to the U. S. Both of these European countries possess more modern facilities that utilize basic oxygen and electric furnaces, respectively, while open hearth facilities produce a larger proportion of U. S. output. Because they utilize electric furnaces, the Italians are able to inject a larger scrap charge.

A comparison of energy requirements for cement production by process and national averages is given in Table 4. The most important observation from these data is that replacement of the old capital facilities in the U. S. by modern kilns and processes of the types now operating in West Germany and Japan will yield a large saving in the national energy budget. However, transportation costs of the finished product result in this being a geographically-segmented industry, with little possibility of market penetration outside of a 200 mile radius of a plant. Thus, the large scales of the energy-efficient plants operated in Japan may be inappropriate within the U.S. market structure. Nevertheless, there is ample room for improvement in U. S. technology, but this will come slowly because of the substantial capital needs and difficulties in generating cash flow. The speed of substitution will depend, too, on energy price projections over time.

The most recently initiated of the CCMS studies is that investigating the petrochemical industry. Data have been particularly difficult to obtain because of proprietary interests. Polyvinyl chloride (PVC) production was chosen for a pilot study because many basic processes are represented. A preliminary analysis of the data is given in Table 5. Data for The Netherlands will be made available for public release later this year. However, earlier analyses of U. S. and Dutch PVC production energy requirements (Berry, Long and Makino)[14] are in good agreement with CCMS figures, and data from that study are used for The Netherlands. The primary difference between technologies in Europe and the U. S. is the use of crude oil as a feedstock in Europe, while natural gas is used in this country. The latter is clearly a more energy-intensive process, and this fact, coupled with natural gas supply shortages, is stimulating a rapid conversion to the use of crude oil as a feedstock by the American chemical industry.

Note that the synthesis step for vinyl chloride monomer (VCM) formation requires approximately the same energy in all three countries, and that the figures for electrolytic production of chlorine from sodium chloride are also similar. The Transcat process, developed by the Lummus Company (U. S. A.), directly chlorinates ethane using a circulating molten salt mixture, and this technology appears to offer a possible energy saving if natural gas is used as a feedstock. The smaller energy associated with chlorine production in the Transcat process arises purely because of a smaller chlorine mass input to the reactor per ton PVC output. No current production facility utilizes this process, and the data are engineering estimates. The data for The Netherlands and Italy do not include any credit for existing cogeneration of steam and electricity, which would make these countries appear even more energy-efficient in PVC production.

Another excellent illustration of the reduction in per-unit-output energy requirements through the introduction of new technology is in the float glass process for making flat glass, an innovation that already dominates American production. In this method, liquid glass is floated on a surface of molten tin, and heat is applied from above to thermally finish the top surface of the glass. The bottom-surface finish is that of the smooth molten tin support.[9] Energy requirements are somewhat reduced by eliminating a chain of grinding and polishing steps but, more significantly, the breakage that attended these steps, which was on the order of 30%,[9] is avoided. Consequently, a saving of almost a third in energy use is achieved.

There is a clear lesson to be drawn from these observations: the introduction of new capital facilities can and will substitute for energy if it is scarce and this scarcity is reflected in its price. Industry in the European countries and Japan has evolved under higher relative energy prices than were faced when the older facilities in the U. S. were constructed. The American capital structure was not designed to optimize the use of input factors at the prices that exist today. While energy goods were priced so low in the U. S. that they previously did not enter sensitively into management decisions (they effectively had a zero price) they do so today. As a corollary, attempts to measure input price elasticities should consider the change from zero prices to present levels in setting a lower limit for the elasticity.

The U. S. is entering a new cycle of capital investment that will have an energy and resource conserving effect. While some have commented that we should import these technologies intact, it would be to our long-term competitive advantage in international markets to leap-frog existing methods with increased attention to the construction of an economy that is prepared to meet increasing resource prices and constraints on supply flexibility.

## F. THE TRADEOFF BETWEEN ENERGY AND TIME

Scientists and engineers are acutely aware of a substitution that is not usually considered by economists, the tradeoff between the rate at which production proceeds and the energy required. This is a particularly important phenomenon for processes involving chemical transformations. For such reactions, one can ascertain a theoretical minimum energy requirement, which corresponds to the energy needed if the transformation proceeds at an infinitely slow rate. In order to drive the processes at finite rates, commensurate with profitable operation, more energy must be expended. This is illustrated in Fig. 1, which shows the decrease due to technique improvement (in the actual energy required to produce ammonia) toward the theoretical limit of 15.0 million btu/ton of ammonia (based on a second-law-of-thermodynamics efficiency). It appears that an asymptote is being approached that is approximately double the ideal limit for the process. The asterisk indicates a hypothetical lower limit for an energy-conserving technological innovation.

Thus, the kinetically-determined practical limits to the minimum energy use in a process may be more meaningful than the thermodynamic limits for real phenomena. Very little is known about the relation between the rates of finite-time processes and their corresponding minimum energy requirements, although this is a subject of active research by one group.* Some individuals with experience in process

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*Three preliminary manuscripts discussing the theoretical foundations of this relation are available from B. Andresen, P. Salamon and R. S. Berry, Department of Chemistry, University of Chicago, 5735 South Ellis, Chicago, IL 60637.

management have conjectured that the limits to real industrial processes, driven at present rates, are 50 to 100% greater than the ideal limits for the infinitely slow processes. Thus, some potential for energy substitution may exist through driving processes at slower speeds. However, the reduced cost of energy must be balanced against potentially increased costs of capital and labor.

## G. BEYOND SUBSTITUTION IN PRODUCTION: THE CONSUMER'S ROLE

The consumer demands for energy and other natural resources are in the main derived demands, stemming from their incorporation in other goods and services. Only in the case of food items and in the use of fuel for heat and transport are resources directly consumed. In evaluating the opportunities for resource substitution at the consumer's level, it is helpful to recognize that a consumer's demands are not for specific items, but for amenity satisfaction.* For example, we heat our homes in order to be warm, and not for the pleasure of burning fuel--although roaring logs in a fireplace may be an exception. The warmth amenity may equally well be furnished by burning less fuel with greater insulation or by wearing an additional sweater or warmer fabrics. In this case, the level of amenity satisfaction remains the same, but the goods that furnish the amenity are different. If the proposed options could conceivably be available at equal cost to the consumer, increased levels of insulation could, and would, substitute

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*A thorough mathematical formulation of consumer demand from somewhat the perspective we are suggesting has been provided by Lancaster.[16] In his terminology, we refer here to a market basket of product characteristics desired by the consumer, and the possible substitutions in the goods and services that furnish the identical set of characteristics.

for between 25-90% of fuel typically used today.[14a] At this technical level, the emphasis is on the relationship between the amenity--the bundle of desired characteristics--and the alternative bundles of goods and services that furnish that amenity. Thus, there is a consumption technology. An interesting application of this formulation was made by Quandt and Baumol in synthesizing the demand for hypothetical modes of transportation.[17]

In addition to the technical level, one must consider the personal, subjective level at which the relationship is between the individual and the chosen amenities. We will assume that this relationship is identical to that usually assumed between consumers and their preferences for goods, responding identically to market forces. As the cost of providing an amenity rises, consumers of that amenity will, in addition to seeking technical substitution possibilities that ameliorate all or most of the increased cost, seek to maximize their welfare by adjusting their preferences. If the price of a natural resource increases, consumers will forego some of the amenity for which the resource is used, expressing a marginal preference for other consumption, given the new menu of prices.

Changes in the relationship between the consumer and his preference set of amenities are often termed lifestyle or taste changes. Though lifestyle changes occur continuously, policies designed to stimulate such changes must be advanced only with a maximum of caution. The tendency to champion ill-informed technocratic manipulation of society is all too prevalent. For example, one issue that surfaces when "lifestyle" is discussed is that of "waste." Take, for instance, the household that trades a manual defrost refrigerator to a frost-free unit. In return for a reduced level of human effort required to maintain the same amount of cooling, and greater convenience, the household uses more electricity, with subsequent higher electricity bills. This is not, however, a more "wasteful" method of keeping food cold, but a measurable tradeoff of energy and greater cost for valuable time and escape from drudgery. Similarly, substitution of automatic transmissions for manual ones increases driving energy requirements, but saves effort. Yet many drivers preferred automatic transmissions, particularly during the decades when gasoline prices fell and autos got larger.

It is, therefore, unfair to label these more energy-intensive choices as "wasteful." This is because the intensity of energy use alone is not a sufficient yardstick with which to measure optimality. One person's frivolity may be another's necessity and last year's indulgence this year's need. Some forms of resource use may rightly be deemed wasteful, if, when the users are informed of the full social costs, they do not act to optimize that use. Judicious use of thermostats is a good example: setbacks during night hours and attention during the day could reduce heating-fuel use by 33% with little change in comfort.[18]

It is clear that care must be exercised in discussing conservation via substitution of resources along with conservation via taste changes. How the resource use responds to the change in the vector of resource prices depends on both the possibilities for factor substitution and the consumer's own long-run marginal preference for the amenity that the resources make available. Whether or not the consumer reduces energy use for heating depends both on whether she has access to capital and information and whether in the long run she might come to prefer different indoor climates. These two conservation options may have different elasticities with respect to resource prices.

When projecting resource needs on the basis of highly aggregated statistics, we must recognize that some goods and services may be demanded in lower quantities than expected if increases in resource costs, though mitigated by substitutions in production processes, are nevertheless felt in those goods and services. Lifestyle changes might, for example, be expressed as preferences to live closer to work and to be able to walk to services, recreation, and entertainment. Since the demand for most of personal auto use (75% of vehicle miles traveled) is derived from the demand for these services, we might mistake the inelasticity in the short run of vehicle miles traveled for a long-run preference to travel, when in fact consumers express their preferences by moving towards more clustered settlements that enable a high level of services and contact with others with fewer miles driven. Technical price-stimulated changes in the goods that furnish the desired bundle of characteristics will likewise modify demand.

Of course, many of the changed resource-use patterns can evolve from the dissemination of information about simple resource-conserving practices. People may well come to prefer lower indoor thermostats in winter, shifting their demand curves for heat towards lower quantity at a given price. More importantly, they may learn to perform certain tasks that allow for resource savings at little or no cost except for the time involved in carrying out the task. We are referring to practices such as shutting off unused lights, lowering hot-water consumption where possible, putting up or removing storm windows, or combining short automobile trips so as to lower distance travelled all reduce direct energy consumption.

However, there are also more sophisticated preference changes that can have significant impacts, for example, on energy needs for transportation and space-conditioning. These include opening the shades in south- and east-facing windows in the morning and closing them as soon as the sun disappears at night; using movable shades in the summer to cut indoor temperatures; recycling materials; eliminating most auto trips under 1 mile, for which fuel intensity is 4 to 10 times the average for a given car because the engine is not warm. These changes in the way people use energy and materials may be price-motivated but require education for successful implementation. Particularly necessary is the knowledge of how much energy and money can actually be saved by modified practices. We do not yet know the extent or speed with which rising energy prices, education, exhortation, and other non-technical factors might induce the public to adopt these energy-saving habits.

## H. ENERGY AND GROSS NATIONAL PRODUCT

There are vew firm rules that apply to understanding the relationship between energy and gross national product. The proposition that economic growth, as reflected in an increase in GNP, requires increased use of energy is a familiar one. This assertion is based on historical data that shows a direct proportionality between these two quantities, coupled with the knowledge that energy is a necessary (but not sufficient) productive factor. However, the cost share of energy has been small but constant at approximately 5% of total costs[11] and seems unlikely to have entered sensitively into entrepreneurial discussions. The observed linear relationship is perhaps more attributable to the complementarity of energy and capital than to a sensitive direct functional dependence of GNP on energy use.

Manne and Hogan[19] have recently employed two forms of aggregative economic analysis (one, a consumers' surplus calculation; the other, a production-function analysis) to probe the feedback of an energy goods sector onto the rest of the economy. Utilizing a few simpifying assumptions,* they show that the impact of the level of energy use on GNP is a sensitive function of the elasticity of substitution for energy (equivalent within a local approximation, to the long-run price elasticity of an aggregate energy factor). If the elasticity of substitution is as great as 0.5, varying energy consumption by a factor of 3 results in but a 5% change in GNP.** However, if the elasticity of substitution is less than 0.3, constraints on energy supply could significantly reduce aggregate output.

Their analysis again draws our attention to the need for accurate quantitative determinations of the elasticities of substitution, perhaps for specific fuels and electricity in key economic sectors.

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*For example, a constant elasticity of substitution is assumed--a not uncommon approximation in econometric modeling.

**In their static analysis, Manne and Hogan assume a GNP of $4400 billion (in 1975 dollars) in the year 2010, corresponding to an energy consumption of 220 quads ($10^{15}$ btu's).

Only through marshalling such empirical evidence into an aggregative model can we accurately gauge the effect of energy use on economic growth. However, the examples cited in the preceding sections strongly suggest that substitution elasticities of 0.5 or greater are not unreasonable. This is supported by a cross-national analysis of energy use in Sweden and the United States.[20]

This investigation revealed many small effects that have to be accounted for before energy use could be directly compared including differences in natural distances, fuel extraction (almost non-existent in Sweden) and climate.* An additional consideration, often overlooked, turns out to be important. If one counts the energy embodied in the goods and services making up foreign trade, it is found that the U. S. is a slight importer of energy, in an amount equivalent to 1% of the total energy use in 1973. This includes the energy used to refine fuels that are imported and exported, but not the thermal energy of combustion contained in those fuels. Sweden, in contrast, is clearly a net exporter of embodied energy, with the net embodied energy amounting to 8-9% of total internal consumption. On the fuel side, Sweden imports a larger share of her energy, both crude and refined, while the U. S. imports considerably less in relative and absolute terms per capita. The U. S. exports coal and Sweden exports refined oil because of excess refining capacity. Moreover, geography, and trade put certain uses of energy out of reach of the normal accounting

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*Air conditioning is non-existent in Sweden, but there is little need to heat factories in the U. S. and these two uses, by coincidence, nearly compensate.

practices, since a much larger share of Swedish production, consumption and travel passes through foreign countries than is the case for the U. S. Fortunately, the most troublesome discrepancies or difficulties turn out to be relatively small or readily quantifiable.

After allowing for these adjustments, it is found that the greatest differences in energy use appear in the intensities (or efficiencies) of use for process heating, space heating, and transportation. To show the relative effects of both intensity and mix of output, these quantities (for Sweden and the U. S.) are displayed in Table 6. As can be seen in Table 6, space heating in Sweden is remarkably less intensive than in the U. S., when measured in btu/square meter/degree-day. The living space per capita is nearly as large in Sweden as in the U. S., a fact often overlooked in gross international comparisons. The energy intensity of apartment heating in Sweden is nearly as great as that in single-family dwellings (see below). This means that the relative efficiency of space heating in Sweden vis-a-vis the U. S. cannot be ascribed to the greater proportion of apartments there compared with the U. S.

On the other hand, households in Sweden generally have fewer appliances than in the U. S., reflecting a different lifestyle and lower after-tax incomes, and this results in a lower household use of electricity. In the commercial sector, the same lower intensities in thermal integrity appear in Sweden. The indoor temperatures in Sweden are higher than in the U. S. One relative inefficiency in the use of heating and hot water occurs in Sweden because of common metering and unregulated hot-water and heating systems. This leads to a surprisingly large consumption of fuels for heating in Sweden, although the overall use of heating is more efficient in Sweden than in the U. S.

In the industrial sector, the differences in intensity are consistent with the results of the CCMS study[16] (see above). While oil refineries in Sweden produce relatively less gasoline than in the U. S., other product mixes are comparable and the overall Swedish mix in manufacturing is weighted more heavily towards energy-intensive products than is the case in the U. S. The lower energy intensities found in Sweden, however, are generally tied to higher energy prices there, suggesting that prices do affect industrial energy "needs" considerably.[21]

The greatest contrast is found in transportation, dominated in both countries by the auto. Swedes travel 60% as much as Americans and use but 60% as much fuel per passenger mile. Mass transit and intercity rail are less energy intensive and more widely used in Sweden, while air travel is overwhelmingly larger in the U. S. Intra-city trucking in Sweden is considerably less energy-intensive than in the U. S., but long haul trucks in Sweden use slightly <u>more</u> energy/ton-mile than in the U. S. The greater distances in the U. S. mean that ton-mileages (at distances greater than 30 miles) are far greater there. The overall U. S. long haul mix is less intense, but total use is greater because of distance.

Historically, higher energy prices in Sweden than in the U. S. are an important factor that has led to the more efficient energy use in that country. While pre-embargo oil prices in both the U. S. and Sweden were roughly equal, Americans enjoyed natural gas and coal resources that provide heat at a 20-50% lower cost compared to oil. In the case of electricity, the two countries were radically different (up to 1972). Since 75% of all electricity generated in Sweden was produced by hydropower, the ratio of the cost of electricity to the cost of heat from fuel was only *half* as great in Sweden as in the U. S. Industry in Sweden naturally developed a more electric-intensive technology base. However, 30% of thermal electricity generation in Sweden was accomplished through combined production of useful heat and electricity in industries or in communities, the latter systems providing district heat. Consequently, in Sweden only about 7,000 btu of fuel were required (in 1971-72) for the thermal generation of a kilowatt hour of electricity. Increases in the cost of nuclear electricity and oil make the continued expansion of combined generation a certainty.[*]

A final example of the effect of different resource prices helps explain the relative efficiency of Swedish energy use. In Sweden, autos are taxed in proportion to weight both as new cars and through

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[*] The usual procedure of debiting 10,300 btu fuel consumed per electric kilowatt-hour generated is less satisfactory when applied to Sweden or other hydro- (or back-pressure-) intensive countries. This is because the actual hydro-oriented production mix lowers primary fuel requirements relative to the U. S., where thermal generation is more dominant. Since the heat-rate is much lower, electricity is also cheaper in Sweden than in the U. S., when compared to fossil fuel prices, thus stimulating use considerably.

yearly registration. Furthermore, gasoline is taxed heavily, by as much as 70¢/gallon in Sweden vs 12.5¢/gallon in the U. S. Not surprisingly, the average weight of a car in Sweden is 1100 kg (vs 1700 kg in the U. S.). The horsepower/weight ratio is lower in Sweden and the total miles driven at distances less than 50 km (the most energy intensive ones) are less than half of the U. S. figure. Clearly, the higher cost of a vehicle mile in Sweden influences the energy expended.

While the greatest "savings" in energy consumption in Sweden come from price-related conservation, the structure of final demand, which is related to lifestyle, also influences energy use. Institutional factors, such as building codes and bank lending practices, encourage efficient structures. And the "Swedish Example" has by no means achieved all the "conservation" possible in that country. Present policies will allow a 50% reduction in heat per square meter in new structures, more efficient industrial practices, wider use of industrial process-heat, and a stabilization of automobile passenger miles at 80% of all passenger miles (vs 90% in the U. S.). These future savings are being aided by an implementation program providing loans for the installation of energy-conserving technology and roughly a third of the borrowed funds is available as a grant. These funds are available to assist in cost-effective conservation measures. This suggests that there is no "absolute" potential for conservation, only a level of savings to be captured that depends on prices, preferences, and institutional practices.

Although the impression that Sweden is "energy wise" and that the U. S. has been less so is unavoidable, the lesson from the two-country comparison seems not to be related to the microeconomics or technical details of any particular example of energy use or conservation. Instead, the real message from this detailed study is that energy "needs" in the long run may be far more flexible than usually thought given differences in the factors outlined here. This leads substance to our thesis that substitutes for energy do exist and are employed in mature economies. But <u>how</u> flexible are energy needs? That is, how much can the U. S. conserve energy?

## I. CONSUMER CHOICE AND MARKET PENETRATION

To answer the question of the desirability of natural resource substitution measures we must recall that these are but one class of the economically-valued resources used by society. While there are resource-conserving practices that are essentially costless, unaccompanied by increased outlays for other factors and involving no significant intrusion into living standards or behavior, the majority of our options do involve some modification in the stream of costs and benefits. It is necessary to consider the total dollar-cost implications and not merely the natural resource consequences of changed use practices. It is insufficient, for example, to argue that the second blast furnace described initially is "better" simply because less energy is required. If the extra labor required for maintenance costs more than the energy saved, or could have been more productively employed elsewhere in the plant (or elsewhere in the economy), there is a diminution of total production due to economically inefficient practices. Similarly, an energy-based preference for less energy intensive materials ("natural") rather than petroleum-based synthetics ignores the "scarcities" of land, labor and water needed to produce natural materials that are reflected in greater costs. Also, many such preferences are formed without knowledge of the energy required to furnish the irrigation water and the fertilizers employed to increase the productivity of an acre of cotton. How are we to decide which product or process is preferable?

The answer, again, is to start by considering the total-cost implications of the alternatives, using the prices of inputs as guides to efficient resource use. We readily acknowledge that prices may be distorted for a variety of reasons: monopolies, subsidies, price controls or the failure to include environmental costs. Nevertheless, this cost framework is a useful starting point, provided that we indicate where and when we might depart from decision making based only on the direct costs communicated by the real-world market place, with its imperfections. The private costs are useful for evaluating what substitutions in production are possible that lower or at least maintain cost levels, as well as what changes in final consumption choices might come about as the result of changes in relative prices of different goods. We also acknowledge that in a society the tastes may change over time. These taste-changes, as reflected in patterns of settlement, occupation and personal consumption can have significant energy-use implications beyond those predicted by the economics of substitution in a static framework, particularly in transportation and home-energy use. Therefore, they are important considerations in our discussion even if they are difficult to predict.

Where substitutions are concerned, the economic procedures for evaluating "desirability" are well known. One evaluates the investment and operating costs of alternatives, discounts all future costs and benefits into the present, and chooses the alternative of minimum cost. or maximum present value. Necessary in this evaluation are both the assumed price of natural resources, and assumed trend in the price, and the discount rate. If marginal costs are significantly higher than average costs, this is particularly important.

Given a price for a natural resource, a useful method for evaluating the "desirability" of a conservation strategy is to compare the cost of saving a (marginal) unit of the resource with the cost of producing one. A helpful example is given in Fig. 2, taken from the 2-Zone Program for Retrofit of Single Family Houses, developed at the Lawrence Berkeley Laboratory.

The results of this model show how substitution of key thermal insulation features, each with a certain initial cost, results in successive lowering of the yearly fuel consumption, and more important, the fuel bill, by the calculated amounts. As Table 7 shows, each option pays for itself in a number of years, that number depending on the discount rate, the value of the energy saved, and the initial capital cost. For simplicity, the study escalates fuel prices at the discount rate. For the natural gas price assumed (about \$2.30/MM btu), options I and II pay back relatively quickly, while option III takes more than 10 years. If the homeowner were forced to purchase electric heat (assuming a forced-air system) or synthetic gas (at $4.00/MM btu), then the payback time on the storm windows would be considerably shorter. The option would look more attractive, especially when compared with the cost of nearly any new supply technology. Thus we see that the microeconomics of energy supply and the substitutes for energy play a decisive role in determining which energy-conservation strategies are desirable.

For policy purposes we can calculate the "cost" of saving natural gas via these procedures, and compare that cost with the cost of producing new natural gas or a substitute. In nearly every case, it is considerably cheaper to make a given energy form available via substitution than it is to "produce" that form from a new source or power plant. There is, of course, much variation in the amount of energy "capturable" by conservation from use to use, region to region, and among different classes of consumers, with different discount/interest rates and acceptable payoff times. There is no <u>a priori</u> limit to "conservation," at least not until we approach both thermodynamic limits and the exhaustion of our ingenuity to modify ways of amenity satisfaction. Thus, conservation is not a "one-time" option, but rather a continual reevaluation of the mix of resource use that allows us to minimize total social costs for given benefit levels. For this reason, planners should look to the future and attempt to avoid measures today that will foreclose even more beneficial practices in the future as energy prices and other resource costs change. If, to save heat losses, we restrict the amount of wall area that could be used for windows, we might deprive resourceful home builders or architects of a significant energy source (the incoming rays of sunlight streaming in through large south-facing windows) which, with proper house shading, landscaping, and use of thermal mass in the house, can provide a large percentage of the seasonal heating needs of the house even before active solar collector systems are considered.

At the same time, the 2-Zone Program (Fig. 2 and Table 7) show that significant energy savings result solely from behavioral changes. Options A and E in Table 6 (the first and last options in Fig. 7) employ thermostat setbacks alone. Pilati,[18] using standard modelling techniques, confirmed the 2-Zone results for the U. S. as a whole, finding that changes in winter/summer temperature preferences and operations would reduce space-conditioning needs by 25-33%, representing roughly 3-4% of the 1975 national energy budget. These changes could be carried out before any significant substitutions are considered, and a different set of responses to increases in energy prices would be observed. Technical substitutions that leave amenity level unchanged (but lower or maintain costs while decreasing the resource requirement) and preference changes that lower the amenity level demanded must be examined in concert.* Furthermore, a substitution that significantly lowers the cost of obtaining an amenity might stimulate the demand for that amenity.

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*Manne and Hogan[19] echo this point.

## J. IMPLEMENTATION

That profitable substitutions for energy exist should be beyond dispute, though more information on the micro and macro economics of efficiency timepaths is certainly needed. In particular the problems of implementation must be considered in history, and in practice by governmental and private institutions.

The factors that influence resource-conserving consumer choice are identically important in determining the market penetration of resource-substituting technologies. The decisive elements in determining the rate and extent of the introduction of new methods of production or of the organization of productive structures are: the rate of diffusion of information about processes, their profitability and institutional restrictions, regulatory policies and practices. The ambitious project by six major economic research organizations[22] on the diffusion of new industrial processes did not purposefully select natural-resource-conserving technologies for study, but most are so, as well as more productive (see Section A for comments on these processes). Consequently, we may draw on their results in examining penetration of technologically-based resource substitution.

There are two major conclusions with respect to the rate of diffusion of information about new technologies in an international sphere.[9] First, this is a slow process that requires up to 10 years before first information has been received by the last firm, although the knowledge of the technology has spread to most firms in half that time. Thus, adoption is not a more rapid phenomenon than information dissemination. Second, there is some evidence that diffusion is is faster among large firms than among small. These data covering Sweden, the U. S. and the Federal Republic of Germany, are presented in Table 8, which is taken from Ref. 10. First information about numerical control machine tools appears to have been obtained earlier by a larger proportion of firms having more than 1000 employees than by those having less than 1000. The same holds true for special paper presses in Sweden and the Federal Republic of Germany, but diffusion of this information to large firms in the U. S. took a longer time. The latter observation can perhaps be attributed to the invention of this technology in Sweden or to the possibility that information travels faster in geographically small countries than in larger ones.[9]

A firm incurs real costs in obtaining information and assessing its value in light of the firm's market position and financial status. Consequently, government can have a positive role in stimulating efficient diffusion of new knowledge by finding studies that corral information about important industrial inventions and analyze their technical features. Such studies will be particularly valuable to the small-market participant and, also, to the firm engaged in another industry that would possibly enter a market if it had knowledge of the state-of-the-art technology that is available.

The subjective view of industrial managers is that profitability is the key element in the decision to adopt a new technology, assuming capital availability. However, quantitative confirmation of this relationship is difficult to obtain.[7,9] The explanation for this difficulty lies in the different financial conditions confronting a variety of firms, such as varying costs of capital, and to different perceptions of the uncertainties involved in making investment decisions. The costs of reducing these uncertainties may not be uniform. For example, the information costs discussed above may be much less for a transnational enterprise than for a smaller national concern--or at least of a different character. Also, given identical access to a technology and identical information, market participants in different countries, and even within countries and within industrial sectors, may confront different sets of factor prices, which will modify the profitability calculation. Nevertheless, there is good qualitative evidence that profitability will be a principal determinant of market penetration by resource-substituting technologies. The swift adoption of the float-glass process can undoubtedly be attributed to its obvious potential for a healthy rate of return on invested capital. The reduction in the length of the production line from 1400 ft, in the older Pittsburgh process, to 640 ft carries with it a substantial decrease in investment, and variable costs are also diminished.

How large does the rate of return have to be to achieve facile penetration by a resource-conserving innovation? This is determined by the opportunity cost of the scarce capital, the return that would accrue if it were devoted to an alternate productive use. Conversations with executives of major U. S. firms indicate that the required rate of return may be as great as 30-35%, with payback times not longer than 3 to 4 years. Given energy's low cost share, even with the higher prices that now obtain, one must be pessimistic about the ability of innovations that are purely energy-saving to achieve market penetration in the absence of coupling to enhanced capital and labor productivity. That is, energy-saving technologies must show profitability equal to that obtained from other investments.

Finally, the influence of institutional factors and regulatory policies and practices is substantial and should be meticulously evaluated. Many laws and practices were framed for a world in which relative factor prices were quite different and resource scarcity was not a consideration. We have seen an example of such an adjustment in the legislative actions that resulted in a 55 mph speed limit on highways in order to save gasoline. Examples of anachronistic constraints on the introduction of resource-substituting technologies abound; for example, interpretations of antitrust regulations that prevent interindustry cooperation in joint projects. New regulatory procedures could equally well perform positively in this regard, and the area recommends itself for careful Congressional scrutiny.

## CONCLUSIONS

Economic considerations are a key element in what happens with respect to conservation, and the response of users to higher resource prices will be a combination of substitution of other resources for those now consumed, as well as an adjustment of preferences within the consumption mix--actions both legitimately termed "conservation." In this meaning, conservation is a normal response to changes in the total social cost of an amenity or to better information about this cost. To hold that the resource intensity of a given activity or the current mix of activities can be maintained as relative resource prices rise sharply is to imply that either economic substitution possibilities do not exist or that consumers will willingly sacrifice a larger share of income towards resources than in the past. This does not mean that market imperfections, peculiarities of pricing practices, lack of capital or information, or other institutional barriers will not inhibit changes of preference or substitutions towards greater economic efficiency. But, in any discussion of resource needs and substitution, the attainable and economically efficient operating points might usefully be evaluated in order to predict the amounts of the resources that could be conserved relative to prevailing practices. For example, one explicit purpose of energy-use guidelines might be to push energy-using capital equipment towards the optimum, based on certain energy price and lifecycle-cost assumptions.

At the same time, we must emphasize the need for careful assessment of the income-distribution impacts of policies that affect resource allocation. Economic efficiency does not guarantee the fairness of the resulting distribution. Distributive aspects should be considered simultaneously with the evaluation of measures whose purpose is to increase economic efficiency. As noted above, a critical issue facing our society is how to achieve a more just distribution of income under resource constraints that may impair continued economic growth.

Congressional and governmental action can stimulate enhanced resource substitution capability in our economy through four mechanisms: the collection and dissemination of comprehensive information on appropriate technologies, the funding of both fundamental and applied research directed toward resource-conserving technological change, the assurance of the existence of sufficient economic incentives for adoption, and through direct regulatory policy or practice. We must be fully cognizant that private- and socially-optimal decisions may diverge. Private returns from socially-desirable actions may be low or the risks unacceptable. Working through the modification of market incentives, government can make private and social goals commensurate while retaining disaggregated decision-making.

These last policy-relevant considerations point to meaningful payoffs to users and to society from soundly conceived conservation approaches. Perhaps the most pressing need for research today is to identify the payoffs, in physical, economic and social terms, taking due note of the direct and indirect costs of different patterns of resource use. As we have defined it here, conservation offers something for everyone. How much can be offered, however, will play a great role in future demands for natural resources.

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Table 1. Lag times between inventions and initial commercialization.[a]

| Invention | Interval (years) |
|---|---|
| Fluorescent lamp | 79 |
| Television | 22 |
| Ball point pen | 6 |
| DDT | 3 |
| Jet engine | 14 |
| Radar | 13 |
| Crease-resistant fabrics | 14 |
| Terylene, Dacron | 12 |

[a] Data from J. Enos, cited in Ref. 8.

Table 2. Energy (Btu×$10^{-3}$) per 1967 $ shipments[a] and energy per unit labor (Btu per production man hour);[b] representative energy-intensive industries (1954-67).

| SIC CODE | INDUSTRY | 1954 | | 1958 | | 1962 | | 1967 | |
|---|---|---|---|---|---|---|---|---|---|
| | | E/$ | E/L | E/$ | E/L | E/$ | E/L | E/$ | E/L |
| 2011 | Meat packing plants | 9.7 | 0.318 | 8.3 | 0.326 | 7.0 | 0.322 | 6.5 | 0.371 |
| 2042 | Prepared feeds | 11.4 | 0.313 | 9.9 | 0.364 | 11.1 | 0.528 | 12.4 | 0.793 |
| 2812 | Alkalies and chlorine | 422.0 | 5.37 | 415.4 | 6.67 | 388.6 | 8.64 | 371.6 | 10.49 |
| 2818 | Industrial organic chemicals N.E.C. | 163.8 | 3.27 | 157.8 | 3.91 | 152.4 | 5.50 | 149.3 | 7.54 |
| 2911 | Petroleum refining | 147.5 | 7.96 | 146.4 | 9.90 | 142.5 | 13.62 | 128.3 | 17.17 |
| 3221 | Glass containers | 118.1 | 1.02 | 114.5 | 1.01 | 108.7 | 1.05 | 100.2 | 1.14 |
| 3241 | Hydraulic cement | 438 | 5.74 | 426 | 6.46 | 431 | 7.97 | 413 | 9.81 |
| 3312 | Blast furnaces and steel mills | 179.9 | 2.96 | 187.6 | 3.31 | 171.1 | 3.52 | 164.4 | 3.81 |
| 3313 | Electrometallurgical products | 214.2 | 4.08 | 300 | 4.66 | 269.6 | 7.00 | 280 | 7.61 |

[a] From: The conference board, Energy Consumption in Manufacturing, Ballinger, Cambridge, Mass. (1974).

[b] From this study.

Table 3. Energy requirements for primary aluminum production (transportation energy is neglected); all units are millions of BTU/ton.

| Process | U.K. | The Netherlands | U.S.A. |
|---|---|---|---|
| Ore extraction | 4 | 4 | 3 |
| Alumina production from ore | 48 | 27 | 11 |
| Aluminum production from alumina | 165 | 169 | 208 |
| Total | 217 | 200 | 222 |

Table 4. Cement kiln energy requirements in millions of Btu/ton clinker.[a]

| | | FRG | Italy | Japan | Netherlands | U.K. | U.S.A. |
|---|---|---|---|---|---|---|---|
| Wet | | 5.43 - 6.14 | 6.40 | 4.93 | 5.34 | 6.35 | 7.03 |
| Semi-dry | | 3.98 - 5.07 | 4.74 | 3.40 | —— | 4.17 | —— |
| Dry | SP[b] | 3.77 - 4.34 | 4.76 | 3.16 | 3.23 | 4.22 | 6.17 |
| | Other | 3.98 - 5.43 | —— | —— | —— | —— | —— |
| Shaft kilns | | 3.81 - 4.70 | 5.22 | 3.59 | —— | —— | —— |
| Average | | 4.62 | 4.77 | 3.89 | 4.64 | 5.99 | 6.68 |

[a] Sources: CCMS, Portland Cement Association report to the Federal Energy Administration, and University of Chicago data.

[b] SP = suspension preheater

Table 5. Energy requirements for PVC in millions of Btu/ton of PVC.[a]

| | The Netherlands | Italy | USA Conventional | Transcat |
|---|---|---|---|---|
| Production of crude oil or natural gas | 0.13 | 0.13 | 0.17 | 0.17 |
| Crude → naphtha | 0.60 | 0.70 | -- | -- |
| Naphtha → ethylene | 11.10 | 4.11 | -- | -- |
| Natural gas → ethane | -- | -- | 7.77 | 8.02 |
| Ethane → ethylene | -- | -- | 3.83 | -- |
| NaCl mining | 2.25 | 2.06 | 1.69 | 1.40 |
| NaCl → $Cl_2$ | 13.70 | 11.68 | 13.72 | 11.87 |
| Ethane + $Cl_2$ → VCM | -- | -- | -- | 14.12 |
| Ethylene + $Cl_2$ → VCM | 11.27 | 13.39 | 12.67 | -- |
| VCM → PVC | 7.83 | 6.77 | 12.08 | 12.08 |
| Subtotal | 46.84 | 38.85 | 51.94 | 47.67 |
| Feedstock | 24.75 | 26.20 | 31.67 | 30.76 |
| Total | 71.59 | 65.05 | 83.61 | 78.43 |

[a] Primary source: CCMS. CCMS data for The Netherlands have been withheld publication to abide by a proprietary request. Data reported are updated values from University of Chicago research. They differ significantly from Dutch CCMS data only for the naphtha cracking step, where our figure is six times larger– perhaps due to different joint product accounting procedures. If this is taken into account, the Dutch and Italian data are nearly identical.

## TABLE 6.

## SWEDEN/U.S. CONTRASTS IN ENERGY USE; RATIOS ARE LISTED

| | | Per capita demand | Intensity | Total energy use | Notes |
|---|---|---|---|---|---|
| Autos | | 0.6 | 0.6 | 0.36 | Swedish 24 M.P.G. driving cycle uses less energy |
| Mass transit trains, bus | | 2.9 | 0.80 | 2.35 | Mass transit takes 40% of passenger miles in trips under 20 km in Sweden |
| Urban truck | | 0.95 | 0.3 | 0.28 | Swedish trucks smaller, more diesels |
| Residential space heat (energy/deg day × area) | | (1.7 ×0.95) | 0.5 | 0.81 | Sweden 9200 deg days vs 5500 U.S. deg days |
| Appliances | | ? | ? | 0.55 | U.S. more, larger appliances |
| Commercial total/sq ft | | 1.3 | 0.6 | 0.78 | Air conditioning important in U.S. only |
| Heavy industry (physical basis) | Paper | 4.2 | 0.6-0.9 | 0.92 | Sweden more electric intensive due to cheap hydroelectric power. Also Swedish cogeneration |
| | Steel | 1.1 | | | |
| | Oil | 0.5 | | | |
| | Cement | 1.35 | | | |
| | Aluminum | 0.5 | | | |
| | Chemicals | 0.6 | | | |
| Light industry ($ V.A.) | | 0.67 | 0.6 | 0.4 | Space heating significant in Sweden |
| Thermal generation of electricity | | 0.3 | 0.75 | 0.23 | Swedish large hydroelectric, cogeneration |

Table 7. Estimated costs, benefits, and payback times for energy-conserving home heating options base case: uninsulated, single-level 1450 sq ft house in Bay Area.[a]

| | Retrofit measure | Initial capital cost ($) | Yearly savings on fuel bill[b] (Nat. Gas) ($) | Payback time on investment[c] |
|---|---|---|---|---|
| I. | Insulate ceiling | 360 | 80 | 4.5 yrs. |
| II. | Insulate ceiling and walls | 910 | 160 | 5.7 yrs. |
| III. | Install storm windows | 490 | 40 | 12.2 yrs. |
| IV. | Lower thermostat setting 70°F - 68°F | no cost | 35 | Immediate |
| V. | Nightly temperature set back 70°F day; 60°F from 11 p.m. to 7 a.m. (clock thermostat) | 100 | 70 | 1.4 yrs. |
| VI. | Measures II, III, IV, and V above | 1500 | 210 | 7.1 yrs. |

[a] From two-zone program for retrofit of single family houses, developed at the Lawrence Berkeley Laboratory.

[b] Calculated for the effect of an individual measure on the base case.

[c] Interest on capital investment cancelled by fuel inflation costs.

Table 8. Size of firm and date of first information (Swedish, Federal Republic of Germany and U.S. firms).[a]

| | First information obtained | | |
|---|---|---|---|
| | Before 1960 | 1960 or later | Total |
| Numerical control machine tools | | | |
| Employing less than 1000 | 22 | 21 | 43 |
| Employing 1000 or more | 30 | 8 | 38 |
| Total | 52 | 29 | 81 |
| Special paper presses | | | |
| Employing less than 1000 | 10 | 69 | 79 |
| Employing 1000 or more | 7 | 28 | 35 |
| Total | 17 | 97 | 114 |
| Special paper presses excluding U.S. firms | | | |
| Employing less than 1000 | 10 | 69 | 79 |
| Employing 1000 or more | 7 | 11 | 18 |
| Total | 17 | 80 | 97 |

[a] From Ref. 10.

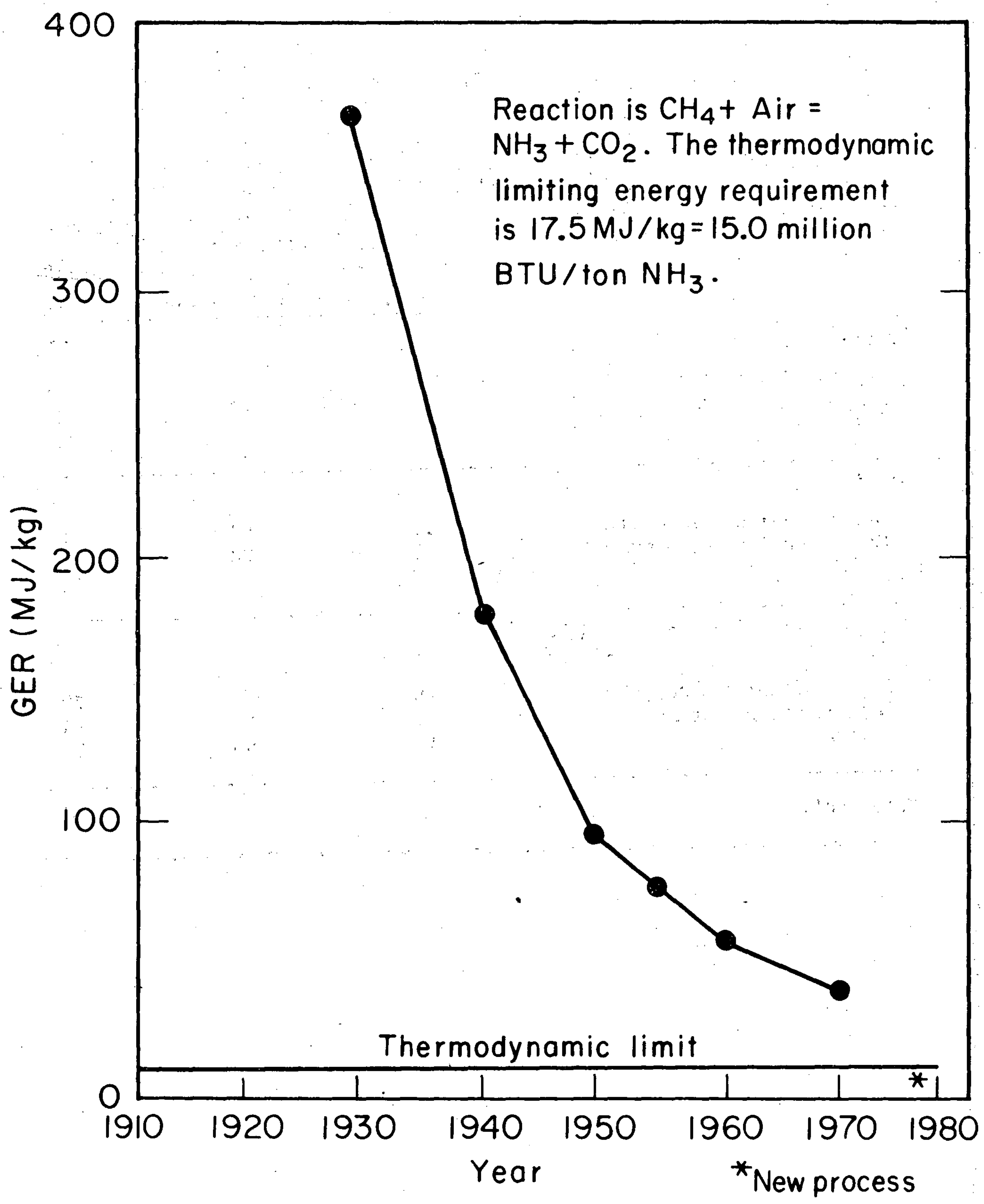

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Fig. 1. Gross energy requirements over time for the production of ammonia. Base reaction: $CH_4$ + AIR = $NH_3 + CO_2$. Thermodynamic limiting energy requirement is 17.5 MJ/kg = 15.0 million btu/ton $HN_3$. Source: Ref. 12, Workshop Report No. 9.

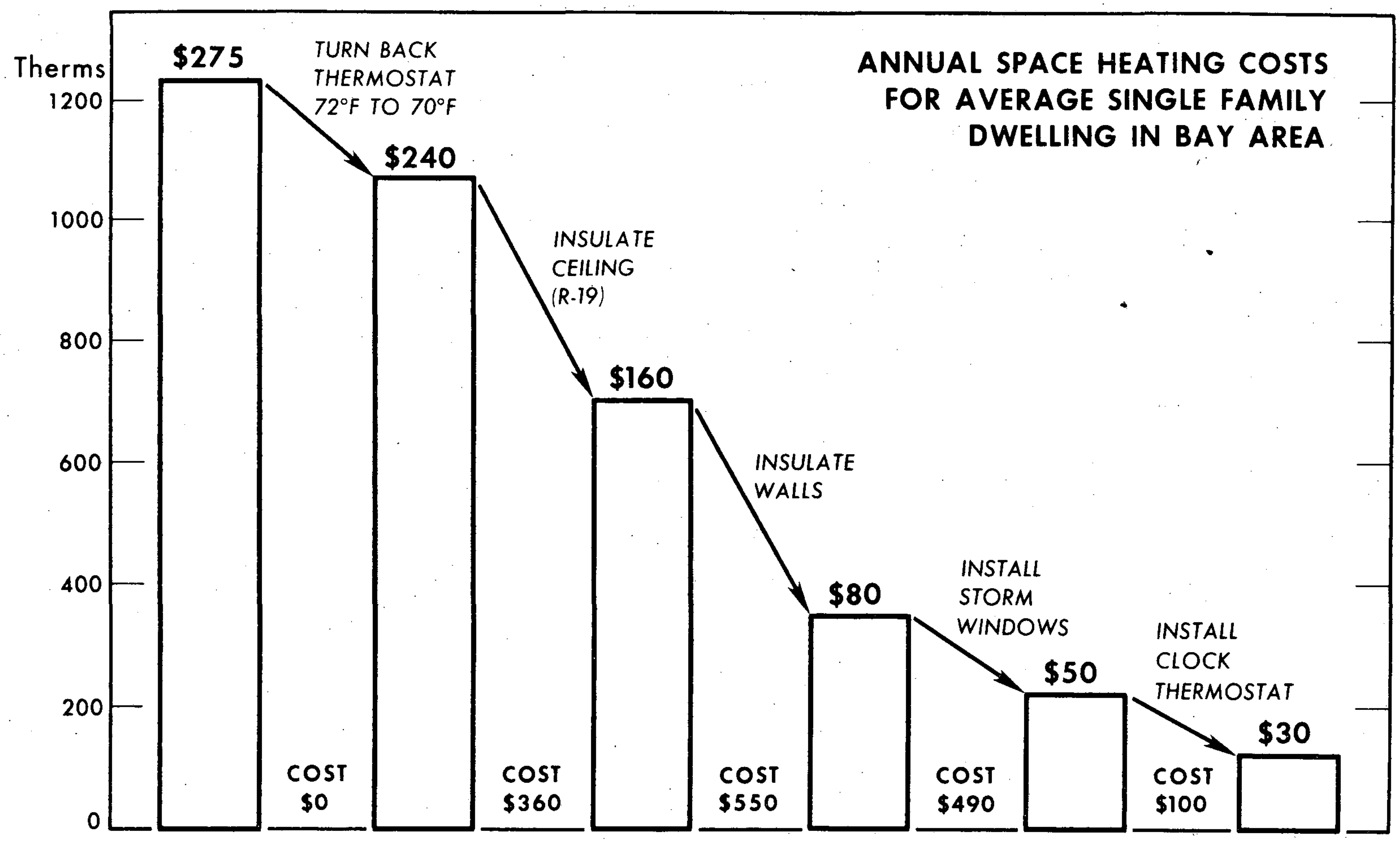

Fig. 2. 2-Zone program for retrofit of single family house, developed at the Lawrence Berkeley Laboratory.

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