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A SYSTEMS MODEL OF THE INDIRECT ENERGY
EXPENDED IN FARM MACHINERY PRODUCTION AND USE

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CONTENTS

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Energy research covers a wide range of topics and problems. Ordinarily, we associate the research on farm economic sectors as that dealing with direct use of conventional sources of power -- gasoline, diesel fuel, LP gas, other fossil fuels and electricity. But inputs such as feeds, fertilizers and farm machines require energy in other agricultural or industrial sectors. This energy -- that required to produce and deliver these inputs ready for use by farms (or any other economic sector) -- is sometimes referred to as indirect energy (IE).[1]

A number of studies have concentrated on the direct energy (DE) used in farm production and marketing processes, e.g., see Dvoskin and Heady. These studies, though providing detail on the individual farm processes or sectors, have tended to ignore the flows of IE, thus largely ignoring any supply and price effects of energy on the cost of many inputs purchased by the agricultural sectors. Other studies (e.g., see Steinhart and Steinhart) have been more general and macro in nature as they have included measures of both DE and IE, but by their very general nature have provided little detail on individual economic sectors, especially for specific farm production processes. Accordingly, we encounter two types of measurement problems: (1) how to clearly and accurately specify the portion of energy use which is to be included, hence the portion omitted, (2) how to obtain the necessary empirical data to prepare estimates of indirect energy use.

This paper develops a conceptual framework (a conceptual systems model) to indicate clearly the portions of direct and indirect energy being measured. The application of the framework to previous empirical results illustrates a

methodology that should provide valid and consistent estimates of energy that should provide valid and consistent estimates of energy usage for alternative processes being studied.

The research is concerned with the aggregate adjustments farmers can or should make to changing energy prices.[2] Total energy accounting is neither required nor particularly useful to analyze many of these adjustments (see Edwards or Bullard et al.), particularly in the short run.

If the goal is profit maximization by individual farm firms, major concern would not focus on indirect energy accounting. Increases in energy prices could be assumed to be incorporated promptly into the prices of capital inputs such as machinery, equipment and building materials. Yet some crop and livestock production systems require less energy (direct plus indirect) than others and farm firms will be interested in evaluating these alternatives for profit maximization. But at the aggregate level, energy accounting (direct plus indirect) is of major concern for establishing energy policy. Such accounting provides the basic information on how crop and livestock production systems vary in total energy use, and incentives can then be used to encourage resource allocation consistent with energy policy.

Much of the current energy accounting appears to be inadequate, for national or regional policy decisions and especially for farm firm level adjustment decisions.[3] The framework developed and outlined in the following section is relatively general in that it can be applied to any level or sector(s) of the economy. To be precise, however, the examples are drawn mostly from farm production processes, emphasizing the energy required in farm machinery acquisition and use.

THE SYSTEMS MODEL

The model focuses primarily on expenditure of direct and indirect energy at various stages in the production and use of durable inputs. Figure 1 and a set of linear equations depict the model's general framework which is structured to be consistent with the laws of thermodynamics (Obert and Young, Georgescu-Roegen).[4] Many of the concepts abstracted in figure 1 and illustrated more concretely in figures 2 and 3 (subsequent section) are consistent with the empirical procedures in the study of automobile production, use and discard by Berry and Fels (1972). Hence, the model is amenable to empirical applications, particularly to estimation of the indirect energy required to produce, maintain and use farm machines.

General Framework

Figure 1 pictures an energy using process. The process is denoted as process i to emphasize that the concepts underlying the figure are general and that energy using processes are not isolated in time or space. Rather each process is a dynamic system, usually an open system, existing and changing in time and space.[5] Such changes are manifested in the process outputs which are divided into three categories:

(1) finished products,

(2) recyclable materials, and

(3) wastes.

A finished product is the output for which the process is intended and thus, its exact identification depends upon the particular nature of the system and process under consideration . In a farm production process an example is harvested and dried corn grain ready for sale. In the manu-

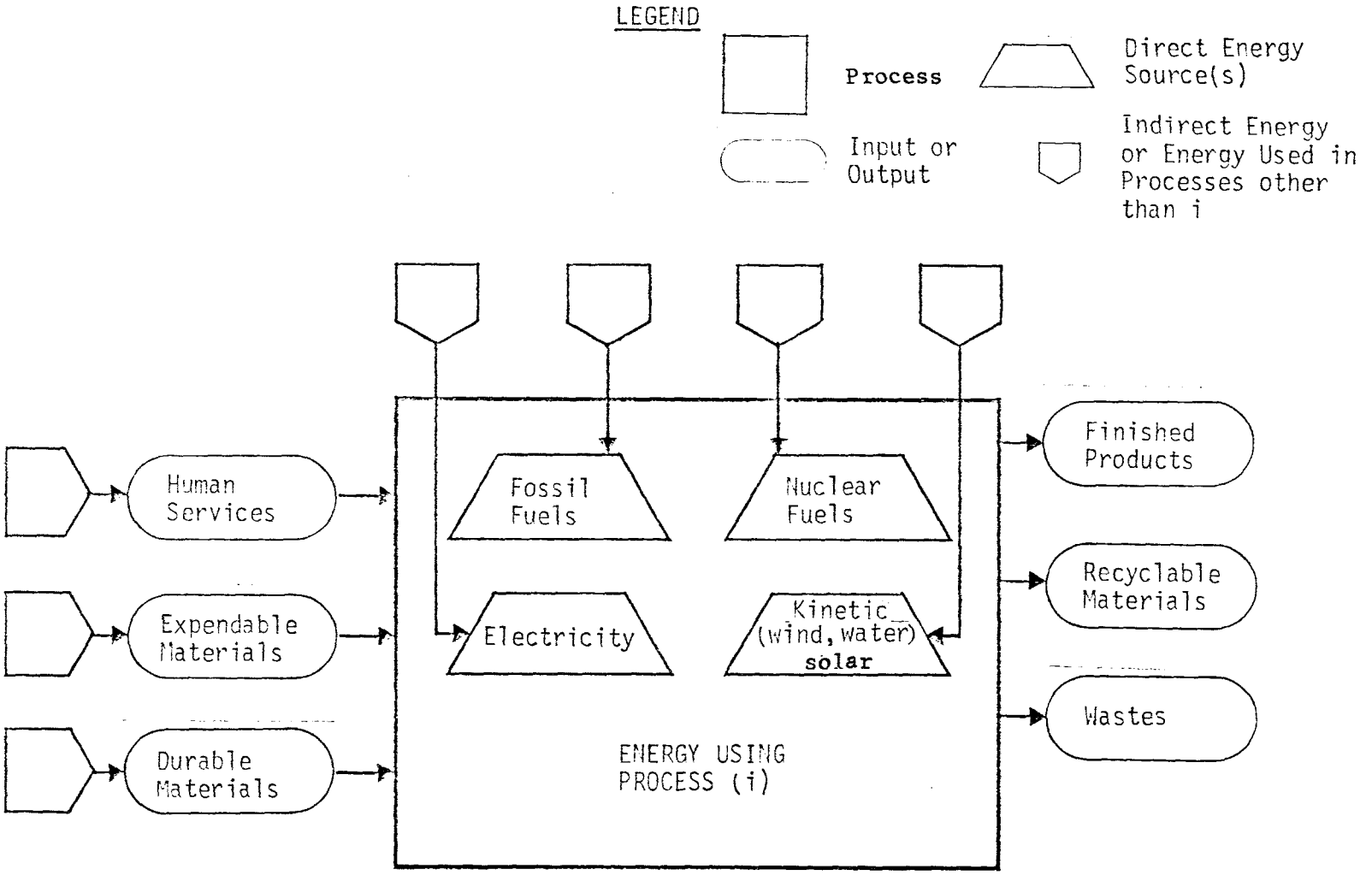

Figure 1. General Scheme of Energy Use for a Hypothetical Production or Consumption Process

facture of a corn combine the finished product is the combine ready for shipment to a sales location. Recyclable materials are products which are coincident in "delivering" output of the finished product(s) from process i; examples are corn stover when producing corn grain or the industrial metal scrap when manufacturing a corn combine. Wastes include: (1) outputs not usable in any other processes because of prevailing market, institutional and economic forces, and (2) other wastes of energy due to mechanical or natural inefficiencies in the process. Corn stover may be recycled or it may be wasted to the extent it is not fully recovered as a feed or an organic material. This sort of waste depends largely upon economic forces. But, even if all the output of process i appears to be used, energy wastes still occur. Friction in the motors of machines, smoke from a factory, imperfect labor, management inefficiency are examples. These wastes are due to the entropic nature of a process which is discussed in a subsequent section (see G.-Roegen, pp. 354-359).

Direct energy (DE) used in any given process (i) for a specified time period (t) is the sum of direct energy from all energy sources:

$$(1) \quad DE_{it} = \sum_{j=1} (DE)_{ijt}$$

for $i = 1, 2, \ldots, p, \ldots n$ processes,

$j = 1, 2, \ldots, m$ sources of direct energy, and

$t = 1, 2, \ldots, T$ time periods.

DE, thus, is the energy consumed only within the process or sector under consideration. Many processes use no more than one or two sources of DE. Only the sources which currently supply practically all of the DE needs of conventional agricultural or industrial processes are shown in figure 1.

For example, corn drying will use a fossil fuel (e.g., LP gas) and electricity; operating a tractor requires either gasoline or diesel fuel. But it is always necessary to use some DE in order to power a process ($DE_{it}>0$). Even for labor-intensive processes some quantity of DE, most likely solar energy, is necessary to sustain the process over time.

Indirect energy (IE) required for a particular process (p) is the sum of all direct energy (DE) expended in other simultaneous (t = 0) or previous (t = -1, -2,... -T) processes required to deliver output(s) from process p. It may be expressed as

$$(2)\quad IE_{pt} = \sum_{i=1}^{p-1} \left(DE_{it} + \sum_{t=-1}^{-T} DE_{it}\right) + \sum_{p+1}^{n} \left(DE_{it} + \sum_{t=-1}^{-T} DE_{it}\right) = \sum_{i=1}^{p-1} \sum_{t=o}^{-T} DE_{it} + \sum_{p+1}^{n} \sum_{t=o}^{-T} DE_{it}$$

The first series of terms, 1 through p - 1, symbolize IE for the processes "before p" in place or form. Within each time frame (t) there is a place-form sequence of production, transportation and marketing required to deliver each material and each other non-energy input ready for use by the process, p. Since any process will require several inputs and each input is the finished product of some other process or processes, one could draw numerous figures like figure 1 for the processes occurring "just before p", i.e., processes for levels p-1, p-2, p-3, etc. The potential number of processes to be identified expands geometrically as one delineates the stages and levels preceding the particular process p at time t. This branching phenomenon is recognized by other analysts, especially those engaged in input-output modeling (see Bullard et al.).

The second series of terms, p+1 through n, symbolize IE for the processes "after p" in place or form. Some of these processes provide

materials or other inputs which are recycled to process p, that is, looping throughout the entire multistate system is possible. In most production, however, few of the processes "after p" affect IE use by process p. If process p, for example, is a tractor assembly line and tractors are the products of primary concern (the "target products"), one must conceive of the metals being fabricated and prior to being mined. But process p could be mining, utilizing tractors and other mining machinery that requires energy to be produced. Thus, in general, the particular ordering of processes is a function of the finished or target product(s) being studied.

Figure 1 shows three categories of inputs that require indirect energy to be available and usable by any process i: human services, expendable materials, and durable materials. Human services (HS) include labor, management and other professional services. The investment in human services and their sustenance requires DE from other processes in current or previous time periods as expressed in relation (2) -- energy for food, clothing, shelter, transportation, training, etc. Expendable materials (EM) include nondurable inputs, such as fertilizers and other chemicals, which are completely utilized during period t. The energy required to produce and transport these materials from other processes is also indirect, and could also be expressed by equation (2). Durable materials (DM) include capital items such as land improvements, buildings and machinery. The investment in these items requires energy (DE) from other processes in simultaneous or previous time periods.

The amount of energy required in acquisition and/or maintenance of durable materials is sometimes called "embodied energy", something of a

misnomer because insofar as a particular process (p) is concerned the energy has already been expended. Hence there is no "energy value locked in the metal" as has been asserted in some previous studies. However, recycling the metal when the asset is worn out or discarded may require less energy than producing metal from newly mined ores. This possibility for saving energy is discussed in a subsequent section.

The question of how much IE to charge to a given process, i, depends upon the time horizon (t) and upon whether energy flows or average energy requirements are to be measured. Generally there is little doubt regarding allocation of expendable materials (EM). Since these items are procured and entirely used by the process during time period t, all IE associated with their production, procurement and use is attributable to the particular process, p. Essentially the same argument can be made for human services. If a particular process, p, requires more labor or other human services, more indirect energy (IE) must be expended to furnish and maintain these services for the process.

But suppose certain machines and other durable materials (DM) are newly acquired for the process during period t. For a measurement of energy flows, all energy required to produce and deliver these machines or materials can be charge to the process during the period. If the process is sustained by maintaining and repairing existing units of DM, again some IE must be expended. In short, from an energy-inflow standpoint, the allocation of IE for durable materials takes place at the time of delivery to the process and, thus, from a strictly physical standpoint is proportionate to the sometimes lumpy requirements of the process. But if we are interested in estimating the average amount of energy required per unit of output

(analogous to estimating the average cost per unit of output in economies of size studies) then the energy required to produce the durable materials can be allocated or amortized among periods t = 0, 1, 2, etc. The question of allocation across time and across processes is dealt with in more detail in a subsequent section.

Energy Sources and Forms

As figure 1 indicates there are various sources and forms of energy.[6] Fossil fuels (crude oil derivatives, natural gas and coal) are the primary sources of chemical energy and are still currently a large component in the production of electrical energy. Kinetic energy (the energy of motion) is commonly associated with the motion of wind or water. Nuclear energy is the energy of atomic processes. Finally, solar energy is a flow from the sun which presently, other than photosynthesis by plants, can be collected and used only to a very limited extent. Solar energy is absolutely necessary for any biological process and, of course, is the original source of chemical energy of the fossil fuels.

Each energy source may possess some energy which is available and a certain amount which is unavailable. Available (free) energy can be transformed into work, whereas unavailable (bound) energy cannot. The output of wastes (figure 1) is bound energy in that some of the input energy has been dissipated into unavailable forms such as smoke from burned coal. The existence of friction in a mechanical process (e.g., a farm tractor's engine) is another common example of thermodynamic waste.

Accessible energy is defined as the available energy that can be extracted (from the earth or from other sources) and converted to use if the direct energy to extract and convert it is less than the energy extracted. This is essentially the definition employed by Georgescu-Roegen (pp. 354-56), although his discussion of the concept does not distinguish between direct and indirect energy (he does not use the terms direct and indirect). Presumably he, as we do, means only direct energy since he concludes (p. 354): "Economic efficiency implies energetic efficiency, but the converse is not true." Including both direct and indirect energy in the definition leads to a need to account for time-place-form qualities, in which case the alternative which is the most energetically efficient may or may not be the most economically efficient.

The economic qualities of time-form-place utility ultimately determine if and when accessible energy sources will be brought into production. Geologists and oil company engineers, for example, have geographically delineated three areas of oil reserves lying under Atlantic ocean waters relatively nearby the eastern U.S. shoreline. In effect, they argue that this oil is accessible and that the prospective net economic payoff is high enough to warrant investment in drilling rigs, etc. Environmentalists contend that the costs to society outweigh the benefits as they cite certain probable deleterious effects of eventual extraction. But virtually no one contends the oil is not accessible. Most prospective deep water oil deposits, in contrast, possess energy which is available but not accessible. Liquified natural gas from coal may provide accessible energy but technological and economic qualities of time-form-place (combined) still run strongly in favor of using natural gas reserves.

Relative measures of efficiency, energy and economic, provide a means for combining and thus comparing alternative changes in time-form-place qualities of energy sources or more broadly for combining and comparing alternative changes in all inputs for one process or for several energy using processes (figure 1). Energy efficiency and economic efficiency are defined as input-output ratios: [7]

(3) Energy efficiency $(EE_1) = \frac{\text{DE (amount) + IE (amount)}}{\text{energy value of output(s)}}$

where

DE is direct energy, defined in relation to each process (i) -- expression (1), above,

IE is indirect energy, defined in relation to each particular process (p) -- expression (2), above.

(4) Economic efficiency $(EE_2) = \frac{\text{\$Value of DE + IE}}{\text{\$Value of output(s)}}$.

The latter ratio, of course, is (in form at least) identical to the usual input-output measure of economic efficiency defined and used in economic literature. It can be calculated simply by converting the BTU's or Kcals of expression (3) by a single dollar value. But this simple method of conversion grosses over the complexities of changing economic value of energy (DE and IE) as energy using processes change the form of products and change the utility of products across time and space.[8] Using either coal or LP gas for space heating, for example, is more energy efficient than using electricity, but electricity currently is more economical for many households in specific geographic areas. Another example is that of recyclable materials (seemingly accessible) which continue to go unused. Worn-out farm machinery may constitute a large source of recyclable metals.

But it is widely dispersed geographically. Prevailing industrial market forces apparently still make fabrication of metal parts from newly mined ores more economical.

Processes and Thermodynamic Laws

The laws of thermodynamics, historically, have been used by physicists and engineers (starting with Sadi Carnot in 1824) to explain the flow and efficiency of heat when work is performed through engines. Now, in a broader sense, these laws are used by economists to analyze materials processes, focusing on the finite stock of the earth's natural resources.[9] A brief summary and explanation of each law follows:

> Law 1: Conservation of matter and energy (kinetic and potential) -- a mechanical law which, in effect, states that all mechanical energy which enters a process must come out in exactly the same quantity. Energy can neither be created nor destroyed but only converted from one form to another. The process can either be real or reversible.

Law 1, considered alone, is often referred to as the law of conservation of matter and energy (the word matter is added to accomodate atomic processes). In terms of figure 1, Law 1 dictates that the sum of input energy to any process must equal the sum of the energy for all outputs of the process, including wastes. The logic of this law allows for reversibility of a process; that is, any process could proceed backwards and not violate Law 1. For example, try to visualize several versions of figure 1 as the frames of a movie reel running backwards so that one could see the untransformation of coke into coal; or, try to visualize "unproduction" of a beef animal, moving backwards in time. Indeed some writers (G'-Roegen pp. 350-352) contend that the economic myth surrounding equilibrium analysis is the subtle implication that

economic processes are reversible, which obviously is unrealistic. The first law, thus, does not deal with whether a process is ideal or with the direction of a process.

The heretofore distinction between available and unavailable energy and most of the other concepts of energy systems analysis depend upon understanding Law 2 (the entropy law).

> Law 2: In the pure physical sense this law states "heat flows by itself only from the hotter to the colder body, never in reverse." In general --"... entropy of a closed system continuously and irrevocably increases toward a maximum...", where entropy is an index of the amount of unavailable energy in a given thermodynamic system at a given moment in its evolution (Georgescu-Roegen, pp. 351-54). Entropy may also be viewed as a measure of disorder of a system. As entropy increases the thermodynamic potential of a system decreases.

Just as Law 1 is a theorem on the conversation of energy, Law 2 is a theorem on the degradation of energy. The second law recognizes that the available energy of the system and all its surroundings (i.e., the total solar system -- virtually a closed system) can never remain the same. It can only decrease. Reversibility of technical or economic processes, in the light of Law 2, becomes totally unrealistic.

In applying the concepts of figure 1 the entropy law is always of consequence. If one considers all resources (of the solar system, or usually those of the earth), the entropy law tells us that any process, i, must always lead to an increase in entropy. Thus, the roots of economic scarcity and value are ultimately governed by entropic processes. When, for example, a steel sheet is produced from iron ore the entropy (the disorder) of the ore is decreased, but at the cost of a much greater increase in entropy of the earth's total resources. In any type of process the ultimate result for all resources is always an increase in entropy.

Farm Machinery Production and Use

Production and utilization of farm machines are the processes of primary interest in this paper. As shown in figure 2, the farm use and maintenance processes are preceded by processes required to produce machine metals -- mining, processing of metals, and manufacturing. They are followed by any processing of the junked machine, with possibly some old parts being used at the farm level and some scrap metal being returned to the manufacturing level. The pattern shown in the figure is a standard one employed in systems design and charting (Chapin, 1970); it is sequential as it is composed of alternating blocks of input (output) identifications and process identifications. The same sort of energy use by each process as depicted in figure 1 is still present but branching details are omitted here in order that linkages between several key processes might be more simply pictured. The basic point is that output from one process serves as the input(s) for other processes.[10] Several open systems of energy-using processes are linked to form an overall multistage system. The entire system always begins with inputs and ends with outputs. In figure 2 the inputs and outputs of primary concern involve farm machinery production, use and disposal.

Any particular process may be subdivided into more specific processes. Figure 3 breaks down the multi-stage system shown in figure 2 into nine processes of farm machinery production and use, consistent with the categories defined by Berry and Fels (1972). Their study was empirical in nature, concentrating on metallic processes to produce an automobile. Mining includes mining of iron, copper and other ores. Berry and Fels also included mining of coal and limestone used for flux in blast and

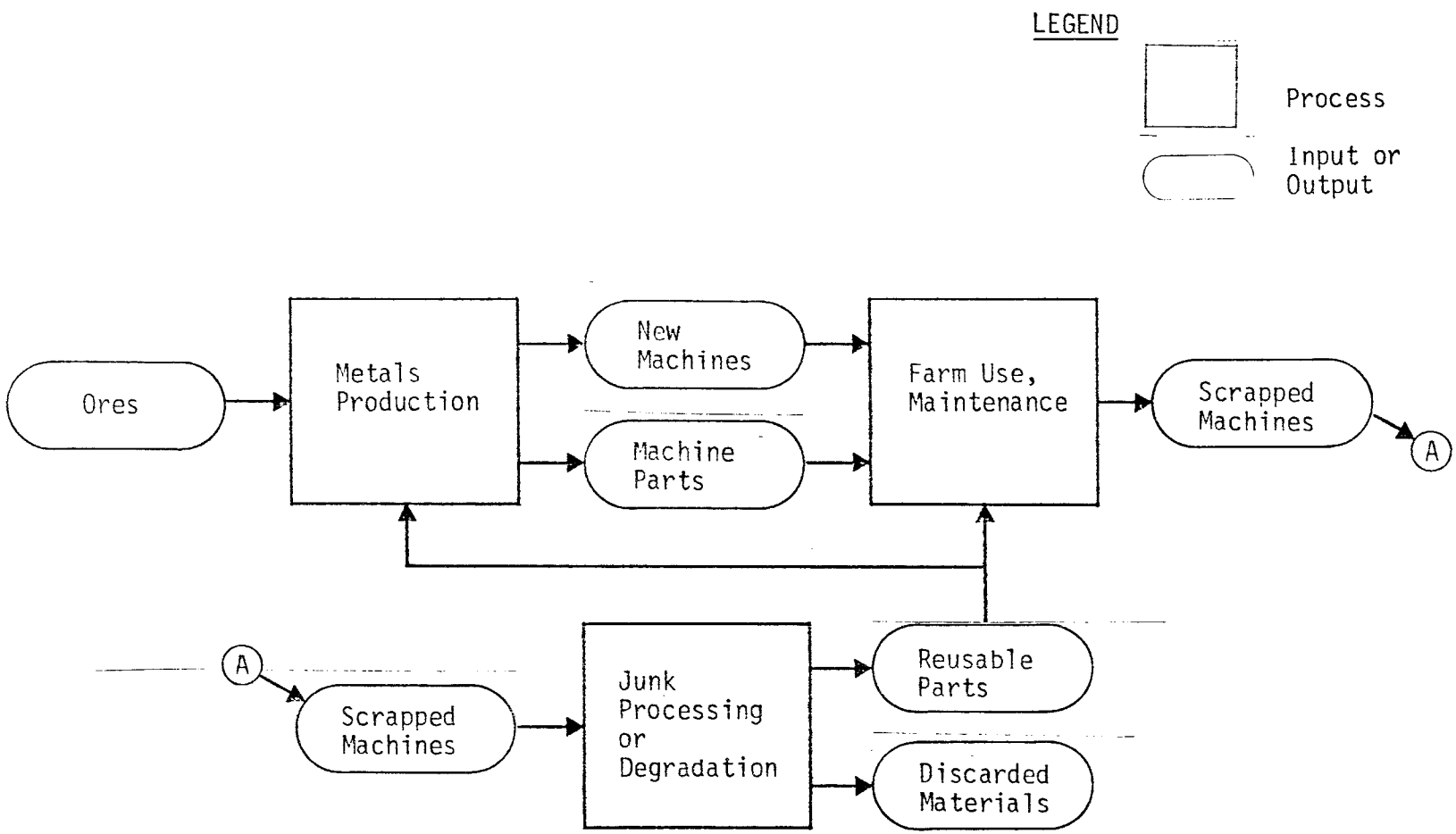

Figure 2. Conceptualized Multi-stage Systems Model for Farm Machinery Production, Utilization and Disposal

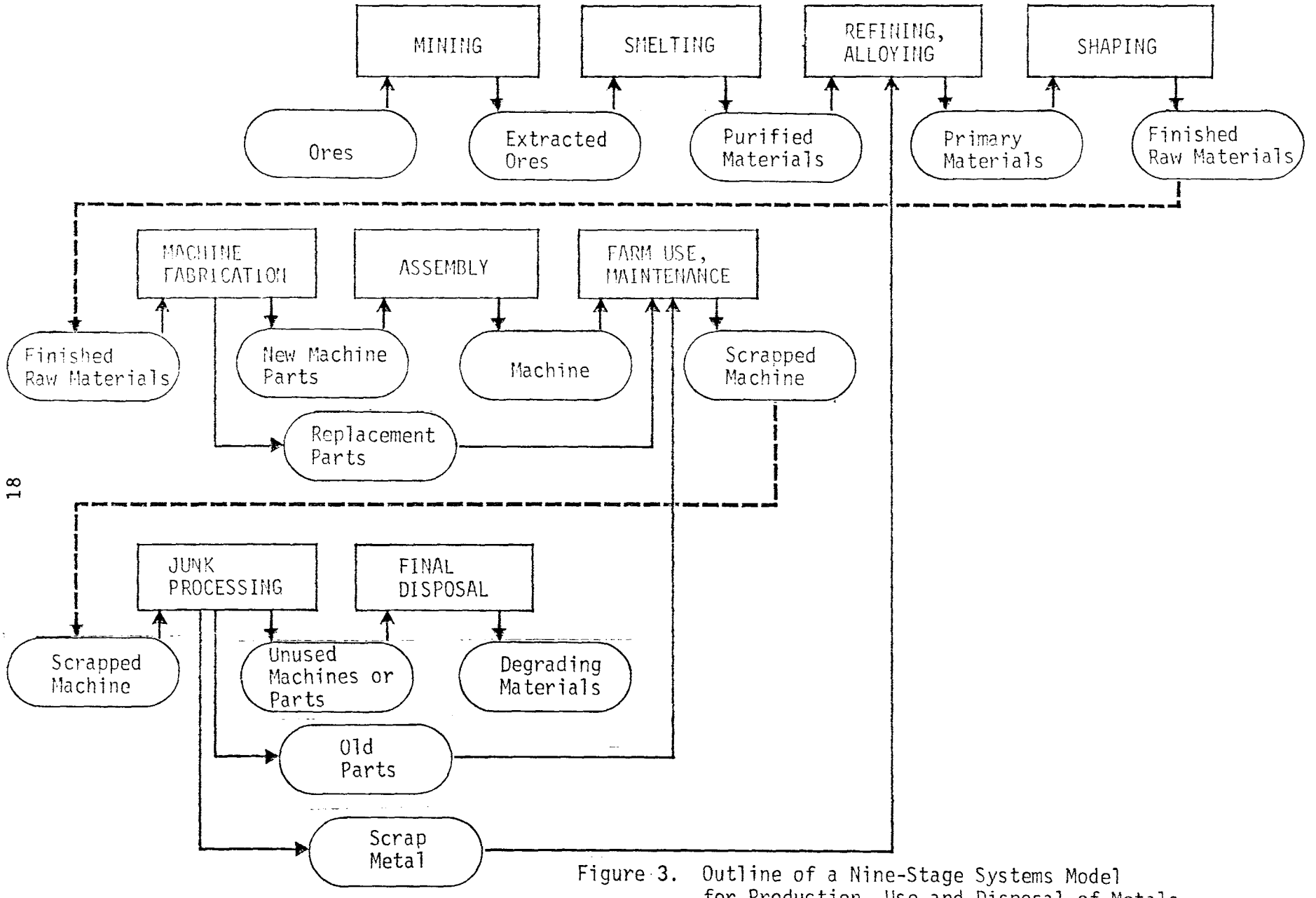

Figure 3. Outline of a Nine-Stage Systems Model for Production, Use and Disposal of Metals in Farm Machines

steel furnaces. Smelting is the reduction of the iron ore in blast furnaces; thus, the conversion of coal to high-carbon coke via a coke oven is implicit for this process. Refining and alloying involve using blast and steel furnaces to make raw steel, ferro/alloys and the other metallic parts. Shaping (as we call it) involves both hot-rolling of the steel and the finishing of steel ingots, sheet, strip, wire, pipe and forging. Somewhat similar processes are followed for the nonferrous metals. Machine fabrication is the manufacture of all finished raw materials (metallic and nonmetallic such as glass, plastics and fabrics) into the various component parts of the machine. Assembly includes combining the machine's body, motor and other parts into a product ready for shipment to users. The farm use and subsequent junking and dispersal processes are self explanatory within the context of figure 3. For each of the nine processes, direct energy sources are required as well as human services and materials (figure 1, above). Also, outputs of any process include wastes and recyclable materials as well as the finished or intermediate product(s).

The emphasis of figures 2 and 3 is on metal parts of machines. Somewhat similar systems models could be structured for tires, glass, electrical and other component parts. Metal parts account for a large portion of the energy requirements to produce most farm machines and are most likely to be recycled since they are most physically durable. The energy requirements for each process (metals and nonmetals) should be additive, but the method of allocating total energy across time and/or processes may vary considerably among parts.

INDIRECT ENERGY ACCOUNTING PROBLEMS

When a new machine arrives at a farm site, its acquisition is evidence of the demand (a derived demand) by that farm for the indirect energy (IE) required to produce the machine. The aggregate expenditure of energy in machine production processes prior to farming is a function of the type and number of machines and other durable inputs demanded at the farm level. It is not clear how the commonly cited percentage of energy used by U.S. farms -- 3.2% (see CAST, 1977) -- measures this IE. General equilibrium studies using, for example, I/O models (see Penn and Irwin, 1977) do not attempt to separate the IE for farm machines from the other energy demanded by the farm sectors. The economic sectors usually considered in these models are defined too broadly to allow such a separation. Also, the usual I/O model is static in nature, not designed to isolate input demand (energy or non-energy) across time periods. More precise partitioning of total energy requirements among agricultural and other economic sectors and across time depends upon specification of a logical systems model, as outline in figure 1-3, and upon accepted accounting conventions for indirect energy use by individual firms. The accounting problems are discussed in this section.

Indirect energy (IE) required for a farm machine, to reiterate, is the summation of all direct and indirect energy necessary to produce the machine (the metal and other components). But this definition (see expression (2) in the section discussing figure 1) is difficult to achieve through actual measurements. How can one fully measure the energy required to produce each of the energy sources for each and every pre-farm process? Theoretically, a total accounting of all necessary energy might extend over all inputs

throughout all previous time periods. As processes branch out geometrically from process p, at the farm level, the sheer number alone precludes a complete accounting. Also, measures of the energy to transport materials to each metal process site frequently are not complete. Thus, in practice the IE for selected secondary, tertiary and other "previous" processes may not be included in the multi-stage empirical framework. The analyst typically judges that the IE of certain inputs (relative to process p) is negligible. The resulting truncation error is usually unknown, though it can be approximated by comparing the IE estimated via process analysis to the IE estimated via I/O analysis (a subsequent empirical section includes an example of this comparison).

Procedures for allocating IE for a newly acquired farm machine among farm production activities (processes) and across time periods can be handled similarly to allocating the dollar investment in the machine. For purposes of illustration, these procedures and accounting problems are discussed for a farm tractor example. Procedures and problems of across-process allocation are discussed first, followed by procedures and problems of across-time allocation.

Allocation Across Processes

One can contend that IE to produce and deliver the tractor should not be allocated among farm processes because the exercise is analogous to allocating joint fixed costs. Any allocation method will be somewhat arbitrary. Even so, there is merit to estimating how much IE is required by competing farm production processes in order to estimate the flow of energy required by each process over designated time segments (usually over several years).

For example, suppose a tractor has a useful lifetime of 10 years and during these years it will be used for two enterprises -- soybeans and corn. The tractor's purchase reflects the farm's demand for a specific quantity of energy -- say, 154×10^6 Kcal of energy (IE). Usage of this amount of IE before the 10-year period provides "energy services" to the corn and soybean enterprises. Producing soybeans and corn uses some of the services provided by the IE. This IE will not have to be replaced until the tractor is replaced, i.e., the 154×10^6 Kcal will not have to be used by other economic sectors until a replacement tractor is required for the farm's continued production of corn and soybeans. However, there may still be interest in estimating the amount of energy required over time per unit of corn and soybeans produced. Determining relative amounts of the total IE that should be allocated between the corn and soybean enterprises per unit of time is basically an accounting problem.

The accounting can be made by any number of methods. Historically, farm records of the hours of tractor use for each crop, the acres planted to each crop, or each crop's dollar sales can serve as alternative weights for the allocation. During planning periods, the allocation may be made using these same factors as weights in enterprise budgets and in mathematical programming models. The programming models, by quantifying optimal amounts of each crop to be produced, provide for an accounting of the IE services which, under optimal conditions, will be used by each enterprise. For some problems, the original IE services of the tractor may be entered in the model through a discrete, investment activity. The specific allocation scheme, thus, will depend upon the analyst.

Allocation Across Time

Consistent with figure 2 (above), the processes of the tractor's production, farm use and eventual disposal may be blocked into three time frames. This is illustrated in figure 4, where time is measured along the horizontal axis and IE is measured as a cumulative flow along the vertical axes.

Frame I covers the pre-farm processes -- production of the new tractor. The IE value is hypothesized to increase continously for these processes, i.e., increase throughout time periods -T to 0. The total amount of IE at t = 0 is shown to be RQ, the cumulative total of all energy required for the processes of producing the tractor. The exact pattern of change in IE for -T to 0 will, of course, depend upon the precise techniques of energy use for each machine's production.

Frame II covers the farm use processes, the time (t) running from the date the farmer acquires the tractor (t = 0) until it is reduced or removed from productive service (t = y). The length of productive service is, of course, unknown at t = 0, though it may be estimated using, for example, an optimal replacement model. The tractor is not necessarily "worn out" when t = y; it is simply for various reasons, retired from service.[11] The salvage value at t = y is defined from the standpoint of society as the net proportion of original IE which can be recovered by recycling component parts of the tractor. The salvage value is shown in the illustration (figure 4) to be JS. From a strict energy flow standpoint, this value is identical at the beginning of Frame II (when t = 0) as at the end (when t = y). At either time, the energy to produce the tractor (RQ) has already been expended. Even so, it may be desirable in farm firm analysis to calculate

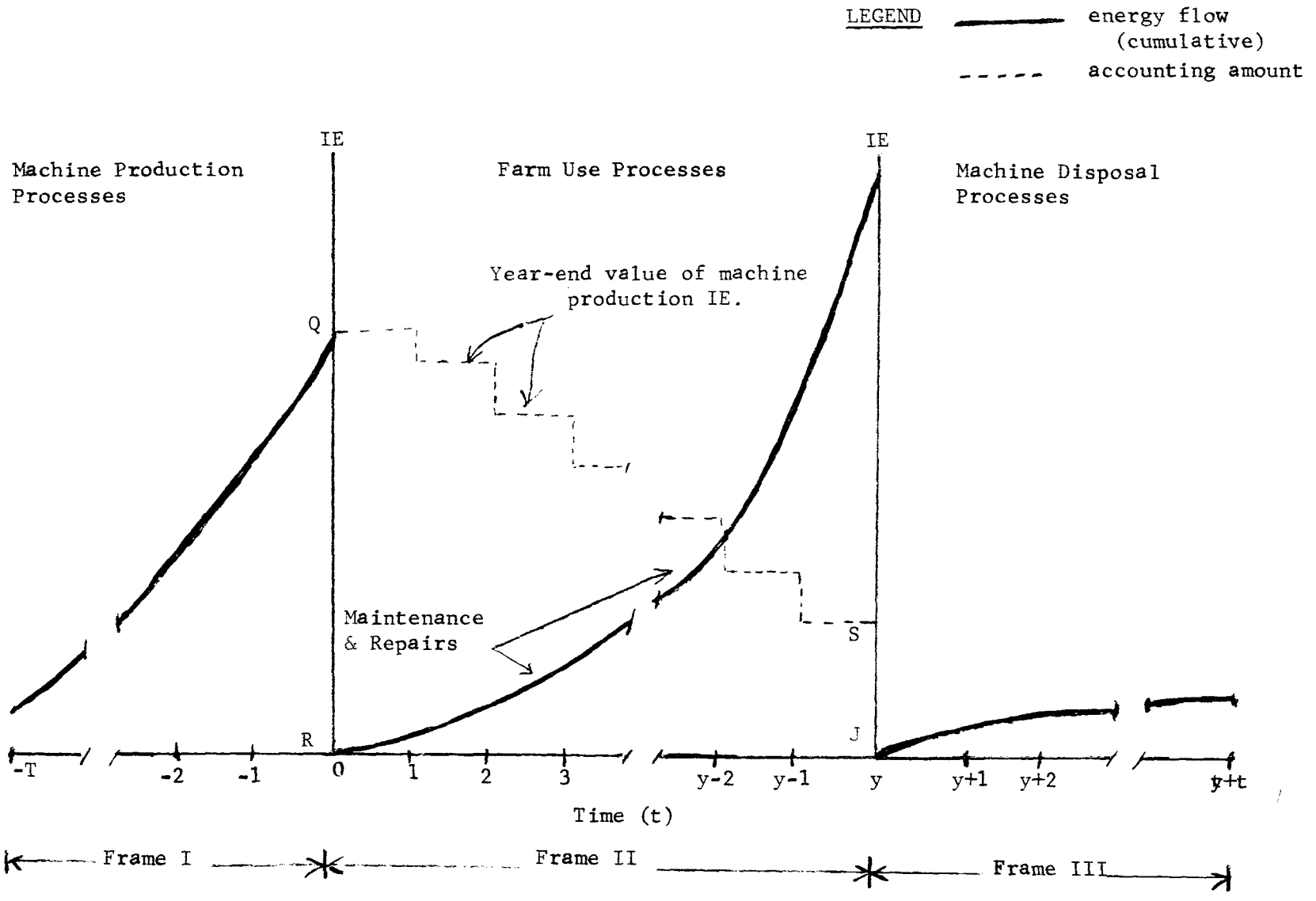

Figure 4. Illustration of Indirect Energy Time Flows

year-end IE values between t = 0 and t = y. It is in this sense that the term "embodied energy" has been used. A year-end IE pattern is illustrated in Frame II as a hashed (---) line, in contrast to the solid lines which illustrate actual energy flows.

As the tractor is used to produce corn, soybeans and in other farm processes, energy is required for maintenance and repairs (M & R) -- parts, housing, transport to repair stations etc.[12] Ordinarily the dollar cost of M & R increases over the time span of a machine's useful life. Energy for M & R may be hypothesized to be closely related to the dollar cost. Accordingly, the cumulative IE for M & R is pictured in Frame II as an increasing curvilinear function of time. The height of this curve at t = y is slightly higher than the IE to produce the tractor; the formula often used (Agricultural Engineers Handbook) shows total M & R dollars to be 120% of a new tractor's cost.

Maintenance and repairs, thus IE flows due to repairs, tend to be very sporadic and unpredictable. Repairs can alter the value of y and the salvage value (as defined above) and consequently alter the flows of IE for the machine production processes -- Frame I in figure 4.

Short to intermediate-run energy (IE) savings are possible through extension of existing machine life through repairs and maintenance accompanied by postponement of machine purchases. The aggregate IE for repairs and maintenance (Frame II) will increase, leading to the production of fewer tractors (a lowering of aggregate IE in Frame I). One can conceive of cost and/or energy savings similar to the potential savings estimated for the automobile industry by Berry and Fels (1972). Many farm tractors, for example, could possibly be repaired and maintained for 25 to 40 years

rather than the current 10 to 25 years.[13] Total energy consumption over the long run, however, may not necessarily be lowered, as direct energy used due to added repairs and fuel could actually increase by not replacing older obsolete models with more fuel efficient tractors. Estimating the magnitude of such savings, if any, depends upon accurate measures of both indirect and direct energy for current and newly developed farm machines.

An energy expenditure function (IE) for machine disposal processes is illustrated in Frame III (figure 4). General observation suggests that few "retired" farm machines presently are processed through commercial junk yards. Industry and farm economic conditions apparently still favor that retired tractors (or other replaced machines) be retained on farms, either for occasional supplementary use during certain seasonal work peaks or for potential substitutes when active tractors are temporarily out of service. In the language of figure 4, it is difficult to define the dividing line between Frame II and Frame III in many cases, because a "retired" tractor may, at various times, undergo stopgap repairs and be placed into temporary service.

When older tractors reach the point of being permanently retired from farm service they frequently are junked on farms, or they may be moved to commercial junk yards for junk processing and final disposal (see figure 3). The energy (IE) for these final two processes is attributable to the demand by farms for the previous services of the tractor, i.e., had the tractor not been used by farms (Frame II) no energy would be required for these latter two disposal processes. In the aggregate, from society's standpoint, the "net energy cost" of these processes may be very small, however, because the recycling of certain machine parts or the machine's hulk could provide offsetting energy savings. But there is almost no information about these functions. The IE expenditure function (Frame III) is purely illustrative.

Optimal Replacement of Machines

Figure 4 illustrated how the quantity of IE required to produce, use and maintain a farm machine depends on time. The time point dividing Frame II (the use-maintenance processes) and Frame III (the machine disposal processes) was designated as Y -- an unknown age. In reality, of course, Y is purposely selected; a specific replacement age is selected by each machine's owner. The replacement (retirement or trade-in) decision is governed by criteria that likely are multi-faceted, diverse and constantly shifting with the many behaviorial traits of each owner, i.e., his perception and reactions over time to the various economic and noneconomic conditions. Economic theory of decision making behavior abstracts from all this to a much smaller logical subset of decision variables.

The most common decision theory assumes the owner will replace the older machine, the "defender", by a newer machine, the "challenger", in accordance with longer-run profit maximizing criteria. Such criteria underlie practically all present-day capital replacement models, those found in books and articles on operations research (e.g., see Wagner, pp. 353-56) or on marginal analysis (e.g., see Perrin, 1972, pp. 60-67). Perrin states the basic marginal principle at the outset of his article (p. 60): "A machine should be kept another period if the marginal costs of retaining it ... are less than the 'average' periodic costs of a replacement machine." This principle has been employed by Faris (1960), Gaffney (1957) and numerous others in developing previous replacement models. Chisholm (1974), then Kay and Rister (1976) used the same principle, expanding the scope of revenue and cost streams to include income tax savings due to depreciation and repair cost write-offs and investment credits.[14] They assumed that each challenger

and defender are technologically identical, and all challengers are equal in real dollar cost.[15]

We have followed the same approach, using the model stipulated by Kay and Rister (p. 355), in a preliminary investigation to determine how much, if any, the optimal replacement age would change if machines were being replaced in accordance with an energy minimization criterion, as opposed to minimizing dollar costs. This is not to say that machine owners would behave as if they are attempting to minimize the present value of energy flows or, for that matter, attempting to minimize the present value of dollar flows. Rather, the two contrasting criteria are hypothesized as an initial means of assessing the possible effects of a future national energy saving policies which are likely to influence machinery owners' replacement decisions.

Our results with dollar units are quite similar to those of Kay and Rister. To summarize the general directions of the results for several interest rates and several tax brackets: The most important variables affecting the decision are the year-end value of the defender(s) and the incidence, over time, of repair costs. Slowly declining year-end values for defender machines during earlier years of service works toward early optimum replacement. Low repair costs in early years combined with rapidly escalating repairs in later years also lead to much earlier replacement.

Earlier optimal replacement is facilitated by lower tax rates (brackets) or by lower interest rates, whether market rates or opportunity costs, primarily because more funds are available for financing earlier purchases of "challengers." However, neither the present-day investment tax credit policy nor the additional first year depreciation allowances appear to have

much effect toward early replacement. This is probably because the machine(s) must be retained for six (6) years or more in order to claim any additional-first-year-depreciation deductions; seven(s) years or more are required to claim the highest investment credit rate of 10%, under current law.

Results with energy units demonstrate, in general, that the old (defender) machine should be retained for longer periods. Only maintenance and repair (M & R) energy is required by the defender; whereas the challenger, if purchased, necessitates IE for its production plus the energy for M & R. Thus, the optimal replacement age will occur when:

energy to maintain and repair defender one more year (period) > "Average annual" energy to produce (acquire) the challenger plus "average annual" M & R energy.

This assumes that the direct energy for fuel and other operating costs is identical for the two comparable machines. The amount of M & R indirect energy required is difficult to measure since mumerous economic sectors must be involved in producing machine parts and supplying energy for M & R services. Our literature search did not reveal any empirical studies which measure this IE. As a proxy measure, the annual M & R energy was assumed to be commensurate with dollars as estimated by a TAR % (total annual repairs) formula developed by engineers (Agricultural Engineers Handbook, 1976). For example, the IE formula used for tractors becomes:

Cumulative annual repairs (IE units) = .0012 $(X^{1.5})$ (IE amount to produce tractor)

where X is the percentage of accumulated hourly use to total estimated lifetime use.

Specifically during the period year 0 to year i, when 50% of the machine's assumed useful life is over, the result could be

$= .0012\ (50^{1.5})\ \ (154 \times 10^6\ \text{Kcal})$

$= 65.34 \times 10^6$ Kcal.

For this formula, annual repairs increase but at a decreasing rate. Thus, it is doubtful that major overhauls usually required in later years of a tractor's life would be accounted for. But, this same deficiency is present when estimating dollar repairs. We found no empirical studies which quantify repairs for machines in their later years.[16]

There are two basic problems in specifying optimal replacement ages for machines. One is the difficulty of realistically specifying the annual costs of maintenance and repairs, discussed above. The other is that of realistically specifying the remaining values (RV) of defender machines over time. Kay and Rister used the following market value equation for tractors which was developed in a 1970 study by Peacock and Brake:

$$RV = 65.6 - 4.1X$$

Where, RV = the percent of the "original new cost,"

X = age (years), and the coefficients (65.6 and 4.1) are percentages

But, it is doubtful if this relationship represents the used tractor market currently confronted by decision makers.[17] Consequently, the authors are currently obtaining data on used tractor market values and estimating remaining-value relationships for tractors of various makes, horsepower ranges and model-years.

In short, the actual flows of IE energy by machine depend upon a number of variables, but certainly a major variable is the age at which machines are replaced. If decision makers act in accordance with optimal

marginal criteria, earlier replacement likely occurs under existing dollar markets and U.S. tax policies than would occur if, for reasons (good or bad), energy minimization was the overriding criterion.

EMPIRICAL STUDIES

Few studies of farm energy use have measured the amount of indirect energy (IE) required for durable inputs.[18] Our search of previous research on the IE requirements to produce individual durable inputs, particularly individual farm machines, surfaced the study on farm machines by Doering et al. (1977). We compare their results with the Berry-Fels study (1972) on IE measurements due to automobile production, use and disposal. As an aggregate benchmark, we compute the IE for "typical farm machines" using the energy intensity factors developed from I/O macro data by Bullard et al. and by Hannon et al. The review of empirical findings from these studies is made in the context of the systems model as conceptualized in figures 1-4 and the associated discussion.

Doering's Results

Doering et al. made estimates of the energy required to manufacture selected items or categories of farm machines during 1972, 1974 and 1976 (table 1). Data for all three years were obtained from William Burrows at Deere and Co. The explanation given for the considerable reduction in energy in later years (1976 vs. 1974 vs. 1972) is".... improved processes (in manufacture) rather than changes in the scale or type of machinery." The term manufacture includes only the machine fabrication and assembly processes as delineated in figure 3 (above). They describe their measurement procedures (p. 1):

Table 1. Value-added Indirect Energy used to Manufacture Farm Machinery Categories.

Machine category	1972	1974	1976
	(Kcal x 10^6 per ton of metal stock)		
Combines	4.59	3.72	2.82
Hay and forage harvesting	1.87	1.44	1.36
Primary tillage (Planters for large grain, etc.)	3.91	2.55	1.87
Tractors	5.88	4.74	3.17
Secondary tillage (Sprayers, small grain planters, cotton harvestors)	3.18	1.97	1.82

Source: Doering et al. (1977) for 1972 and 1974 data; 1976 data were obtained directly from Doering via an October, 1977 phone conversation.

> "This was done by monitoring all the energy inputs into a plant producing a particular class of machinery. The total energy inputs were then divided by the tons of output. This is a value added concept, as it does not include the energy value of the raw steel or iron entering the plant. This value added concept is particularly suited for determining the machinery energy used in crop production. The piece of machinery can be depreciated on a straight line basis to zero over the useful life of the machine. What is left is the scrap value of the energy embodied in the metal stock as it entered the manufacturing plant.

In defending their value-added approach they state (p. 3):

> "When the machinery is worn out the value added should be exhausted."
>
> "It is important to recognize the critical nature of the distinction that is being made here. As an example; the disc contains 5,600 lbs. of plain carbon steel. According to one estimate (this was a 'total value' estimate found in Auto Products Magazine, November 1974), energy is embodied in this steel from its manufacture at approximately 5,290 Kcal per pound of steel. This means that the 5,600 lb. disc has 29.624×10^6 Kcal of energy embodied in its steel. Yet, we (Doering, et al.) are only counting 8.904×10^6 Kcal... based on the 1972 value added figures in the belief that much of the energy value remains locked in the metal rather than being used up in farming."

We will comment on the validity of this approach in the next section.

To the basic data for metal parts manufacture (table 1), Doering et al. added energy estimates for (1) tires and (2) various component parts of motorized equipment (i.e., belts, seats, plastic parts, bearings, rings, generators, diesel fuel pumps, batteries, etc.) which are purchased (by Deere and Co. in this study) fully manufactured. This amounted to:

(1) Energy for tires = 9,299 Kcal/lb.

(2) Energy for purchased component parts = 5% surcharge for motorized equipment of values in table 1

No data source was given for the coefficient for tires. The 5% surcharge estimate for purchased component parts was arbitrary, made in lieu of data.

Energy for repairs for each of the machine categories shown in table 1 was estimated by adapting engineering formulas. The basic formula, commonly called a TAR % where TAR means "total annual repairs," relates total dollar value of repairs over each machine's assumed lifetime to the original list price. Lifetime and annual dollar repair estimates are made. Doering et al. used these percentages as proxies for lifetime energy expended for repairs; total and annual IE for repairs for each machine was assumed to be commensurate with the dollar repairs. Subsequently, they combined IE for lifetime repairs with IE for machine manufacture.

No estimate of IE for housing, insurance and other ownership expenditures are provided in this publication. Presumably this IE amount would be relatively small since the proportion of total ownership cost due to these items is relatively small.

Berry-Fels Results

Berry and Fels (1972) estimated total indirect energy (IE) to produce a "typical-1967 automobile" using detailed process analyses.[19] Their data were derived from numerous sources including the 1967 Census of Manufactures, Mineral Industries, Transportation, and Ward's Automotive Yearbooks (1967 through 1971). Their definitions of energy using systems, states and processes (pp. 3-9) are consistent with those of this paper (see figures 1-3 and discussion). The following numbers provide a summary of their IE estimates:

Item	Energy (IE) (Kcal x 10^6)
Produce metal materials for motor block	1.86
Produce metal materials for auto body and chassis	20.69
Manufacture of glass, plastics fabrics and other component parts	0.74
Fabrication of parts, auto assembly	8.04
Transport of parts, materials (all stages)	0.56
Transport of assembled auto	0.19
Total	32.08

This total (32.08) is for a 3,545 pound (1.773 ton) automobile. Fabrication and assembly of parts, the only machine production processes measured in the Doering study, require only 25% of the total IE. In contrast, as indicated above, the energy required for metal materials production comprises over 70% of the total. It includes the mining of ores through all other pre-fabrication stages, and is further broken down in table 2.

To the extent that such measurements reflect present-day technology (which is open to question), they could be used to estimate energy requirements for individual farm machines.[20] This, of course, is what the Pimentel group did except they made no distinction among farm machines. Total IE for all farm machines was aggregated, the aggregate estimate being directly proportionate to the automobile coefficient (18.1 x 10^6 Kcal per ton of machines). This is a questionable assumption if for no

Table 2. Energy required to produce metals ready for automobile fabrication and assembly.

Metal material[a]	(1) Weight in prototype automobile[b]	(2) Total energy used to produce metal[c]	(3) Energy per ton of metal
	(tons)	(Kcal x 10^6)	
Iron casting, motor block [a]	0.2682	1.69	6.30
Steel casting, motor block	0.0143	0.17	11.89
Total, motor block	0.2825	1.86	6.58
Auto body and chassis:			
Carbon, cold-rolled sheet[a]	0.9514	12.18	12.80
Carbon, steel wire	0.0234	0.36	15.38
Carbon, steel forging	0.0856	1.64	19.16
Other carbon steel	0.1719	2.04	11.87
Raw alloy steel	0.0519	0.65	12.52
Raw stainless steel	0.0067	0.12	17.91
Sub-total, auto body & chassis	1.2909	16.99	13.16
Pig Iron	0.02	0.13	6.50
Aluminum	0.0372	2.16	58.06
Copper	0.0269	0.85	31.60
Zinc	0.0255	0.56	21.96
Total, auto body and chassis	1.4005	20.69	14.99

Source: Berry and Fels (1972), selected tables and figures.

a Iron casting is commonly called gray iron. A more detailed breakdown of types of metal could be constructed from their results.

b Based on a 1967 automobile using data from the 1967 Census of Manufactures, Ward's Automotive Yearbooks and several other sources.

c The free energy of combustion for chemical fuels and the equivalent for electricity, based on 1967 technology; 1 KWH=860.656 Kcal.

other reason than the fact that many farm machines are nonmotorized. To obtain valid estimates one needs to (1) proceed by disaggregated items or categories of machines (classified according to proportions of different metals), (2) multiply total IE requirements by respective component weights in each machine and (3) sum these results to obtain the energy required for each machine or machine category. This approach was followed by the Doering group, except their value-added results represent the energy required only to fabricate and assemble selected farm machines. As noted above, Berry-Fels estimates show these processes to account for only 25% of total IE for automobiles. There is no reason to suspect this percentage would vary much for most motorized farm machines.

Center for Advanced Computation Results

Bullard et al. (1976) of the Center for Advanced Computation at Urbana, Illinois developed procedures for estimating the total quantity of energy (DE and IE) required to produce selected major products in the U.S. economy. The products are classified by industries (Standard Industrial Classification-SIC), and more broadly by the 368 Input-Output (I-O) sectors delineated for the 1967 U.S. economy. The total energy requirement for any given "target product" is called the "energy cost" or on a per unit basis the "energy intensity", viz., the amount of energy measured by BTU's required to produce $1 (in 1967 units) of the product. Their procedure involves combining I-O analysis and process analysis (the term process analysis is identical in meaning to that of this paper). This procedure is relatively straightforward for the I-O sectors which produce only one major product. But for sectors which produce several major products the accounting of processes becomes complex. They develop a method, called "hybrid analysis"

to isolate an estimate of the energy intensity factor for each product of each BEA sector.

Using their procedure we obtained an estimate of 31.06 x 10^6 Kcal per ton of a "typical 1974 farm machine" as described by the Bureau of Economic Analysis. Details of calculating this estimate are outlined in the following two paragraphs.

Their hybrid analysis was not needed since farm machines are designed by the Bureau of Economic Analysis (BEA) to be the only major product for the farm machinery (44.00) I-O sector.[21] Their 1967 farm machinery energy intensity factor for producing farm machines was 79,183 BTU's (p. 52). This basic estimate was adjusted for transportation to farm machinery dealers and for wholesale and retail trade margins in order to reflect the energy cost at the farm gate. Specific adjustment procedures, consistent with those suggested by Bullard et al. (pp. 15-19), are shown as follows for a 4-ton tractor costing a farmer $10,000 in 1974:

Sector (BEA No.)	Percent of purchase price (%)	Allocated share of total cost (1974)	Price deflation[a] (Index)	Energy intensity[b]	Energy "costs"[c]
Farm Machinery (44.00)	75	$7,500	1.41	79,183	421.18
Rail Transport (65.01)	1	100	1.517	97,685	6.44
Truck Transport (65.03)	1	100	2.101	58,149	2.77
Wholesale Trade (69.01)	10	1,000	1.502	39,636	27.21
Retail Trade (69.02)	13	1,300	1.477	39,372	35.37
	Total	$10,000			492.97

a 1974 $ divided by 1967 $ (=1.0) for each sector.

b BTU per $1 in 1967 units

c BTU x 10^6

Numbers in Colums 2 and 3 (allocated share of total cost) are obtained from their publication. These shares are divided by the price deflators, and the result is multiplied by the energy intensity factor to obtain the energy cost of the tractor allocated to each above sector. The total of results in the energy "cost" column is 492.97 x 10^6, as stated above.

The same procedure can be followed for other farm machines. However, the result is always scaled exactly to the machine's dollar value. For example, the energy cost for a 2-ton forage harvester costing $2,410, in 1974, is 118.81 x 10^6 BTU, precisely 24.1% [($2,410 ÷ $10,000) x 100] of the tractor estimate. On a per ton basis, the energy cost of the forage harvester is 59.40 x 10^6 BTU = 14.97 x 10^6 Kcal. Hence, as Bullard et al. (p. 16) stress: "to the extent that the target product is typical of the sector's output, the sector energy intensity is a relatively accurate measure of its energy cost." They list and discuss several other limitations of their approach (pp. 15-19), among them being the assumption that physical energy flows are proportional to dollar values. As they suggest, this assumption can be relaxed by using a more disaggregate model.

Hannon et al. (1976), also of the Center for Advanced Computation (CAC), employed an expanded 1967 I-O model of the U.S. economy to estimate a number of IE coefficients for "building materials." In a series of tables (pp. 41-67) they provide energy intensity coefficients for several types of wood materials, paper materials, paints, asphalts, glass, stone and clay materials, iron and steel materials, primary nonferrous materials, fabricated metal products, nuts, bolts and rivets. These results are shown as

BTU's per common weight units for each material or product. A coefficient is given for each material (by SIC title) for "before delivery to jobsite" and a "delivery and trade" coefficient -- the two coefficients combined give a total IE for the material when used at the jobsite. Thus, these coefficients could be used to estimate total IE for particular buildings or machines, provided (1) materials could be identified in the same manner as identified in their document and (2) the weight of each material is known. These two data problems will be discussed further in the next section in light of the system model of this article and the IE coefficients obtained from previous studies.

ESTIMATES OF INDIRECT ENERGY: SELECTED FARM MACHINES

Coefficients from the studies reviewed in the preceding section can be used to calculate the indirect energy (IE) required to produce selected farm machines. However, since the coefficients vary widely among the studies, depending greatly upon the measurement technique and processes for which energy requirements were measured, criteria are outlined for comparing and selecting the "best" coefficients for application. Coefficients by Doering et al., Berry and Fels, and from the I-O studies are modified in accordance with these criteria, and modified estimates are made of the energy required to produce selected farm machines. Finally, input-output coefficients from Hannon et al. are applied to component weights for a hog crate, providing an example of disaggregate estimation of IE required for a farm equipment item.

The following four empirical criteria are based upon the systems model of the study (figure 1-4):

1) Techniques of measurement and modification should be consistent with thermodynamic laws and other logic of the systems model.
2) Resultant estimates of IE could, if needed, be dissagregated into estimates from the basic component metals (various standard forms of refined steel, aluminum, copper, zinc and the commonly used metal alloys) and other materials such as tires, glass, plastics and fabrics.
3) The estimates should be amenable to comparisons among machines, and the relative accuracy should be assessable.

4) Either the estimates should remain relatively constant over time, or the procedure for obtaining them should be possible to repeat.

The criteria are intended to serve as subjective norms which can be used in a general manner. They provide guidelines for developing procedures for modifying presently available estimates or for making future estimates. To illustrate how they may be applicable, consider the wide divergence in results obtained by Doering et al. compared to Berry-Fels or Bullard et al. This may be seen in IE estimates for a tractor, automobile and a forage harvester:

Machine	Doering et al.	Berry-Fels	Bullard et al.
	(kcal x 10^6 per ton weight)		
Tractor (1974, 2 wheel drive, 4-ton size)	11.60	—	31.06
Automobile	—	18.59 (1967 prototype)	22.68 (1963 prototype)
Forage harvester	2.11	—	14.97

Numbers shown in the column for Doering et al. combine the results shown in table 1 (above) with their estimate of the energy to produce tires and a surcharge estimate for machine parts purchased fully manufactured. The tractor and forage harvester results shown in the column for Bullard were calculated in the previous sections, while the automobile results are based on the energy intensity I-O work by Herendeen and Bullard (1974).

A sizable portion of the differences in these numbers is due to

energy required for the pre-assembly processes which were not considered by Doering et al.[22] Thus, in the language of Bullard et al., the Doering estimates are subject to "truncation error". If one assumes that the 31.06 estimate by Bullard et al., is essentially correct for a tractor, the error is 63% below the actual. This percentage magnitude is consistent with the thinking of Berry who offered the opinion (in a December 1977 phone conversation) that approximately 2/3 of the energy required to produce a motorized vehicle is due to the pre-fabrication and assembly processes. This opinion was independent of any knowledge of the results by Bullard et al. To further corroborate his opinion, note that the automobile results by Bullard are very close to those of Berry-Fels. The difference of 4.09×10^6 Kcal can be attributed to the Berry-Fels stated error limit of 10%, use of two different years, and inaccuracies in the Bullard results. Differences in the forage harvester numbers also can be partially explained by the truncation error in Doering's results, but the degree of difference is much larger -- 86% compared to 63% -- than for the tractor. Presumably this can be explained by the relatively lower quantity of energy required to fabricate and assemble non-motorized machines.

Modified Estimates for Farm Machines

Table 3 ahows modified estimates of the IE required to produce selected farm machines. These estimates were calculated by the following three procedures:

(1) Multiply the I-O energy intensity factor, from Bullard et al., of 492.97×10^6 BTU's per $10,000 (1974 dollars) of the farm machine by the machine's 1974 total dollar cost.

Table 3. Modified Estimates of the Energy Required to Produce Selected 1974 Farm Machines

Machine specification[a]	I-O Energy Intensity Method	Modified Doering Results	Berry-Fels plus Doering Results
	(Kcal x 10^6)		
Tractor, John Deere 4430 diesel, 2-wheel drive; 9,926 lbs; $11,490	142.74	93.96	101.64
Combine, New Holland 13-ft. 1400 self-propelled; 13,367 lbs.; $17,438	216.63	102.91	127.40
Forage harvester, Allis-Chalmers model 782,PTO; Base unit, 3,390 lbs.; $2,913	35.66	22.14	26.77
Corn planter, 400 cycle IH, 6-row narrow with strip tillers and dry fertilizer applicators; 3,521 lbs; $4,328	53.76	43.92	29.72
Disc harrow, 18 ft. tandem; 3,800 lbs.; $3,264	40.55	31.71	30.99

a Prices shown are for the Spring of 1974.

Data sources: National Farm Power and Equipment Dealers Association. Official Guide -- Tractors and Farm Equipment Fall 1977, St. Louis, Missouri. International Harvester Agency, St. Paul, Minnesota for corn planter and disc harrow.

2) Multiply the estimates from Doering et al. by 3.0 if motorized and by 7.0 if not motorized. Let us refer to these as modified Doering results, modified in accordance with the hypotheses advanced by Professor Berry.

3) Add the Berry-Fels estimates for prefabrication-assembly processes to the original disaggregats estimates by Doering et al.

The estimates may or may not satisfy the above criteria. They are presented primarily to illustrate empirical results currently available and as a possible basis for comparison of estimates obtained via other procedures.

Estimates from the first column (table 3) may be viewed as the benchmark for a "typical farm machine". This I-O procedure avoids error due to truncation of processes, so the magnitude of IE estimates may be considered to be accurage on-the-average. However, this method will produce relative accuracy among machinery items only to the extent that the IE is perfectly correlated with the machine's dollar value. Pimental et al. (1973) made the assumption that IE requirements are constant per ton of machine when using the automobile estimate from Berry-Fels -- viz., a fixed 18.8×10^6 Kcal per ton.

The "Modified Doering results" are consistently lower than the I-O results. Multiplication of his results by 3.0 or 7.0 is somewhat arbitrary, as this modification is based on the hypothesis (by Professor Berry) that the fabrication-assembly processes account for around 1/3 (1/7 is used for nonmotorized items) of total IE. Perhaps the results in this column still underestimate the true IE, because the basic estimates by Doering et al. (see table 2) were adjusted upwards by only 5% for energy used to produce parts purchased fully manufactured. Doering et al. (p.2) express the belief

that the 5% adjustment is adequate. However, our conversations with Deere & Co. officials suggests this percentage should be higher.

The Berry-Fels estimate, 18.59 x 10^6 Kcal total IE per ton of automobile, is divisible into 4.66 for fabrication-assembly processes and 13.93 for the pre-fabrication processes. This latter coefficient is multiplied by gross weight of each machine (table 3) and the result is added to the estimates for fabrication-assembly (including tires and the purchased parts surcharge) by Doering et al. The results are shown in the third column of table 3. Again these estimates are consistenly below the I-O results, presumably due to the truncation error by Berry-Fels and to undermeasurement by Doering's group. However, judged by the empirical criteria (above) these estimates are preferable to either of the other two columns. First, the Berry-Fels coefficients for pre-fabrication processes could be further disaggregated into various metal parts production processes. Second, estimates to fabricate and assemble farm machines apparently can be updated rather easily, since farm machinery companies are required to provide such data in reports to the U.S. Department of Energy.

Disaggregate Example

The estimates shown in table 3 were calculated using the total weight (or total value) of each machine. Ideally, estimates should be based on component weights of the equipment item, thus allowing for easier updating over time and for comparison with different types and sizes of similar equipment. Most importantly, the total IE for individual machines can be more easily updated making it useful for capital budgeting, linear programming models and other management decision aids.

Table 4 shows an example of computation of the energy required to produce a 214-pound hog crate. The total -- 6.5 million BTU's -- includes energy for all metal processes, mining through fabrication and assembly. Coefficients for pre-fabrication energy -- 6.2 million BTU's -- were taken from Hannon et al. Weights of materials and the fabrication energy data were provided by Clay Equipment Co. Fabrication and assembly energy includes natural gas, LP gas and electricity measured by Clay on a periodic basis. Labor requirements for each product provide, in the judgment of Clay, their most reasonable way of allocating this energy.

The estimate of 30,593 BTU's per pound compares favorably with the estimates for farm field machines (table 3). It compares with the I-O energy intensity estimate of 64,627 BTU's per pound for a diesel tractor. This is as expected; motorized items probably require 100 to 200% more IE.

This example illustrates the essential logic of disaggregate calculations. For items with considerably more components, such as tractors or combines, the calculations could prove somewhat arduous, though details could be overcome by aggregation of similar materials and by standardizing the arithmetic (if needed) via computer algorithms.

Table 4. Energy Required to Produce a Hog Crate

Item	Unit (Pounds)	Energy per unit (BTU's)	Total (BTU's)
Purchased materials:			
Hot rolled flats	51.56	18,736	996,028
Hot rolled sheets	1.96	80,816	158,399
Galvanized	100.29	27,836	3,070,032
Stainless steel slots	3.85	35,533	136,802
Tubing	71.64	25,813	1,849,243
Sub-total	239.30		6,210,504
Fabrication, assembly energy:			
2.17 hours direct labor @ 155,000 BTU's =			336,350
		Total	6,546,854

Note Finished crate weighs 214 pounds. Thus,
total energy per pound of product = 6,546,854/214 = 30,593 BTU's

Date Sources: Weights in purchased materials and energy required for fabrication and assembly obtained from Clay Equipment Co. Energy per unit required to produce materials taken from Hannon et al. (pp. 52-56).

SUMMARY

1. Energy demands by U.S. farms are due to the use of direct energy (DE) -- primarily the energy from fossil fuels and electricity consumed directly in on-farm processes -- and the use of indirect energy (IE) which is the energy expended in non-farm processes necessary to produce and deliver materials (such as fertilizer and machines) and human services ready for use by farm processes.
2. Few studies of farm energy use have dealt directly with the IE of durable inputs, presumably because it is difficult to specify and to measure.
3. The systems model conceptualized in this paper allows clear specification of the procedures for measuring IE and clearly specifies the amounts of IE being measured, thus the amounts not being measured.
4. The model is depicted in a general diagrammatic framework as a multistage, open, thermodynamic system.
   a. The output of each process in the system is divided into three categories:
      1) The finished product -- output for which the process is intended or sometimes called the target product,
      2) recyclable materials -- outputs which are coincident in producing (or consuming) the finished product, and
      3) wastes -- outputs unusable in any future processes because of technical or market conditions or the energy wastes due to thermodynamic inefficiencies in the process.

b. Sources and forms of DE (thus IE) are delineated in a time-place-form context and linked to the laws of thermodynamics.

c. Three categories of inputs require IE in order to be available and usable by a given process, viz., (1) human services, (2) expendable materials and (3) durable materials.

5. Major sources of available DE are the fossil fuels, nuclear fuels, solar and kinetic energy, and electricity.

a. Available energy can be transformed into work through a process. But, a large portion of each energy source is not available for use by production or consumption processes because of physical barriers or because previous processes have converted the energy from a state of low entropy to high entropy.

b. Accessible energy is that portion of the available energy reserve which can economically be extracted and converted to use by processes.

c. Several examples of available and accessible energy sources are presented.

6. Thermodynamic laws describe the flow and availability of energy for processes.

a. The law of conservation (law 1), in summary, states that the amount of energy entering a process equals the amount of energy in the process outputs. A system, thus, can be viewed as being reversible, but the energy is always converted in form.

b. The entropy law (law 2), in summary, states that the amount of available energy for a system and all its surroundings, i.e., the total solar system, must always decrease. The process of a system is not reversible; entropy is always being increased.

7. Special emphasis is devoted to a particular systems framework for the production, use and disposal of farm machinery. This framework, as shown by systems charts, is contrasted with the thermodynamic-economic concepts developed by Georgescu-Roegen and with the framework developed in the study of automobile production by Berry and Fels.

8. Production of a durable material demanded by the farm firm (e.g., a tractor) can be viewed as a series of energy using processes, each producing some part(s) of the finished product, each adding utility through the dimensions of time, form, or place.

9. Procedures for allocating the IE for a newly acquired farm machine across time periods and among farm production activities are diagrammed and discussed using logic similar to that of allocating the dollar investment in the machine.

   Specifically, total IE may be allocated among farm activities either 1) entirely at the time of acquisition or 2) prorated (depreciated) over time in accordance with the changing amounts of energy which could be saved (if any) by continuing to use the machine rather than replacing it.

10. The total amount of IE required to produce, maintain and use a machine depends upon the replacement policy followed by the owner.

An optimal replacement model developed by Kay and Rister shows the replacement age to be earlier for dollar units as opposed to energy units.

11. Results from three types of previous empirical studies of IE measurement are summarized and contrasted in light of the systems model, the purposes being to illustrate the methodology of this study and to establish initial estimates of the IE in farm machines and buildings.

    a. Doering et al. estimated the IE value added due to fabrication-assembly processes for selected farm machines.

    b. Estimates by Berry and Fels of the total IE required to produce metals and other parts of an automobile are presented in disaggregated units. Their aggregate estimate (18.8×10^6 Kcal per ton of auto weight) was used by Pimentel et al. (1973) and in other studies to estimate the IE for all U.S. farm machinery.

    c. Bullard et al. combined input-output (I-O) with process analysis to estimate the energy cost (IE) for target products of the U.S. I-O sectors. Their 1967 estimate for a typical 1974 farm machine -- modified for inflation and for price margins due to transportation, wholesale and retail sales -- was shown to be 31.06×10^6 Kcal per each 1974 dollar. Using the same logic, Hannon et al. employed an expanded I-O model to estimate energy coefficients for numerous building materials, including several metals and other components used in machinery production.

12. IE requirements from previous studies were modified and jointly used to provide illustrative estimates for a tractor, combine, forage harvester, corn planter, disc harrow and a hog crate.
    a. Comparable estimates can be made for numerous farm machines, buildings and other durable materials purchased by farmers.
    b. The general accounting procedure which appears most reasonable is similar to that used in the hog crate example. The procedure is valid (as judged by criteria developed from thermodynamic laws and a general systems model as developed in this paper) and the procedure's relative accuracy should be assessable.
    c. Any comprehensive empirical study using data on IE will require data on relative weights of metals and other components in each durable input -- machine or building. These data have not yet been obtained, though we are continuing efforts to secure such data.
13. Estimates of the IE for particular durable materials can serve a useful function in the form of coefficients for the capital investment portions of models designed to measure resource adjustments by farm firms (local areas, regional or national) as real prices of energy sources change relative to prices for other inputs. At the aggregate level, energy price effects on aggregate supplies of grains, livestock and other farm products could be more completely and accurately determined if the energy requirements for capital inputs were measured and attributed to the economic sector using the inputs.

FOOTNOTES

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1. The term indirect energy has been used in several previous studies (see, e.g., Hirst) in the same sense as defined and used here.

2. By "adjustments" we mean any number of changes by farm firms, particularly alterations in product and resource mixes and the accompanying financial changes made to help achieve specified goals, such as maximizing the growth in net worth for specific periods.

3. For example, in June, 1977 the U.S.D.A. and F.E.A. (combined) published a series of booklets containing "guidelines" for energy savings by farmers. These reports stress piecemeal adjustments, budgeting only direct energy to illustrate how energy might be saved. Acquisition and use of materials, labor and other inputs requiring indirect energy are classified as "nonenergy costs" -- a possible misleading implication being that savings in direct energy translate into total energy savings.

4. The laws of thermodynamics commonly are perceived as being of interest only in the realm of physics and mechanical engineering. However, as subsequently explained, understanding the economics of energy-using processes is enhanced by understanding of thermodynamic laws.

5. Obert and Young (pp. 22-24) define and illustrate open versus closed systems. A closed system is a region of constant mass (material and output of figure 1). Only direct energy is allowed to cross its boundaries. An open system, in contrast, can have transfers of mass and energy across its boundaries.

6. Energy does not lend itself to a simple formal definition. Even so, many writers find it desirable to render a definition. Obert and Young (1962, p. 15) define energy as "the capacity, either latent or apparent, to exert a force through distance." Georgescu-Roegen (1975, p. 351) notes that "energy is capacity in a system for work to be performed".

7. This formulation of energy efficiency is often called "first-law efficiency" in recognition of Law 1 of Thermodynamics (see the next subsection). Bullard et al. (p. 3) refer to EE_1 as "energy cost" or more frequently as "energy intensity". They compute and list an energy intensity for each U.S. Bureau of Economic Analysis (BEA) input-output sector (pp. 48-54). For the five energy sectors they express the reciprocal of the intensity as a percentage (p. 39), including 98.6% for coal, 86.2% for natural gas and 25.7% for electricity. Each of these percentages is expected to be less than 100% in order to be consistent with thermodynamic laws, particularly Law 2. (See the forthcoming subsection for logic of this conclusion).

8. Such complexities of energy budgeting are discussed at length by Turvey and Nobay (1965) and by Edwards (1976).

9. In a current (unpublished) paper by Berry, Heal and Salamon (Berry and Salamon are chemists, University of Chicago; Heal is an economist, University of Sussex, England) the rationale for pursuing their joint thermodynamic-economics theoretical inquiry is given as:

> "Creating such a bridge has been an elusive but tantalizing goal for a long time. We refer to the physical content of thermodynamics, not to its mathematics, which has been well integrated into economics (here they cite Samuelson's Foundations text, 1947) or to its relational structure as a basis for models, which has also been used occasionally in economics (here they cite Samuelson and the 1971 text, The Entropy Law and The Economic Process, by Georgescu-Roegen).

10. In this regard, systems process analysis possesses many of the features of input-output (I-O) analysis (see Bullard et al.). Similarities and differences of the two methods will be discussed further in empirical and concluding sections.

11. The optimal replacement age (Y), as discussed subsequently, may or may not be identical with the actual replacement age.

12. The IE required to maintain insurance and pay property taxes and the direct energy (DE) for powering the tractor might also be shown in Frame II. Since insurance and taxes usually account for only a small portion ot total ownership costs, their IE requirements should be small relative to maintenance and repairs.

13. Doering et al. and the study by Heredeen and Bullard (p. 40) estimated the lifetime total for repairs and then added the total to the IE to produce each farm machine. Thus, they implicitly assumed the discount rate for M & R flows to be zero. But, energy technology changes across time and dollar costs of energy in period i are not directly comparable to dollar costs in period j ($j > i$ for all i and j). Accordingly, the discount rate should be positive, exactly how large being a complex question about future realities.

14. The marginal criterion, as stated here, was shown by Perrin (pp. 61 and 64) to be identical conceptually with an expression for the present value of a perpetual annuity -- an infinite series of challenger machines. Kay and Rister adapted the present value formulation by adding terms for tax savings due to repairs, depreciation and investment credit.

15. A model which accounts for technological improvements and/or real price changes for identical machines certainly would be much more realistic. However, even the static, certainty model is complex to handle and difficult to empirically characterize. Perrin (pp. 62-63) briefly discusses a possible procedure for introducing technical change into the static, certainty model.

16. Hunt (pp. 69-71) summarizes the TAR % formulation and, taking note of this problem, he briefly presents study results for two alternative repair formulas. However, neither of these covers machine use beyond accumulated use limits of 5,000 hours (equals about 6 to 7 years life) for tractors and comparable lives for other machines.

17. It may be that the remaining value which is relevant to each decision maker is not the market value but, instead, the value of the machine in use. The value of the marginal product (VMP) of a machine's services could exceed the market resale (or salvage) value of that machine but be less than the replacement cost of an identical machine. Thus, the asset is said to be fixed -- a problem which received theoretical attention over twenty years ago by Glenn Johnson.

    The use value, of course, depends upon each farm machine owner's production function which is constantly shifting over time. Hence, the empirical problem of estimating market remaining values, complex as it it, pales in comparison to the problem of estimating the use value over time.

18. Several farm management studies have either estimated or used other estimates of the IE for fertilizers and other nondurable inputs (e.g., Burton and Kline, Commoner et al., Davis and Corrigan, Eidman et al.). The few studies which have measured durable input requirements in energy units (BTU's or the like) have adopted the results by Berry and Fels (1973). For example, Pimentel et al. (1973) used the Berry-Fels estimate of 18.1×10^6 Kcal as a measure of the IE to produce each ton of farm machinery.

19. Total weight of the automobile = 1.773 tons.

20. Professor Berry offered the opinion (in a December 9, 1977 phone conversation) that these coefficients have not undergone much change.

21. The BEA list of items for this sector includes around eighty categories of machines, implements and equipment.

22. Doering et al. do not purport to estimate total indirect energy requirements for each machine though they do (as quoted above) argue for the applicability of value-added estimates. Indeed, their results are very useful, especially in view of the fact that no other studies have provided IE estimates on a strict disaggregate basis for specific farm machines. In a forthcoming Experiment Station (Purdue University) publication, they do estimate total IE for a tractor, combine and other farm machines.

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