Final Report

EMERGY EVALUATION OF ENERGY POLICIES FOR FLORIDA

Report to the Florida Energy Office

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Executive Summary

This is a final report of the findings of EMERGY analysis evaluations of alternatives for energy use and development in Florida. First, evaluations are given of alternative systems for supplying fuels for transportation, including hydrogen, fuel cells, electricity, ethanol from sugar cane, methane, and natural gas. A mass transit alternative, Dade County's Metro Rail, was also evaluated. Second, EMERGY evaluation was made of alternative plans for the redevelopment of areas of south Florida devastated by hurricane Andrew.

EMERGY Evaluation Methods

The best uses of resources and environment in a process can be analyzed by calculating the EMERGY (spelled with an "m") of all the inputs, including those received free from the environment and those supplied by the economy. EMERGY is the sum of all inputs, expressed as one form of energy, required directly and indirectly to make a product or service. Its unit is the emjoule. As a common measure of real wealth, EMERGY measures everything: fuels, materials, services, information, etc. Based on the concept that successful, prevailing systems maximize wealth, production and use of real wealth, alternatives can be chosen for maximum EMERGY flow.

The procedure for evaluating a process has the following steps:

1. Define the boundary and make a systems diagram of sources, components, processes and products, arranged from left to right in order of transformity.

2. Prepare EMERGY evaluation tables with a line item for each item identified in the systems diagram. Determine total EMERGY flows, storages, and yields of line items. Determine emdollar (Em$) equivalents of EMERGY values. An Em$ is the proportion of gross economic product determined from the proportion of the national EMERGY budget. Microcomputer simulation models of the system may be run, which generate trends over time for different assumptions and alternatives. EMERGY, Em$, and transformity graphs may be generated by these simulations.

3. Compare results using EMERGY indices such as net yield ratios, investment ratios, exchange ratios, EMERGY/money ratios, etc. Recommend for policy choice those alternatives which contribute the most real wealth, measured by EMERGY, to the combined system of environment and economy.

4. For primary energy sources, use the net EMERGY yield ratio to select the ones that contribute most. For determining what uses are appropriate for an energy type, use the transformity. For necessary processes that consume the primary sources, use the EMERGY investment ratio to predict which are likely to be economical.

The transformity is defined as the EMERGY per unit, a measure of the position of something in the scale of energy hierarchy. In order of increasing transformities are sunlight, wind, rain, mechanical energy, wood, food, electric power, critical materials, drugs, human service, information sources, and education. Tables of transformities from previous studies simplify evaluations. Data on inputs are multiplied by their transformities to obtain EMERGY flows. For determining which energy processes are most efficient for a desired output, the system with the smallest transformity is used.

Evaluation of Alternative Fuels for Transportation

Alternative systems of supplying energy for transportation were evaluated for their EMERGY flows. Pathways of energy transformation were evaluated. Sources were arranged according to their Net EMERGY yield ratios, measuring their overall ability to contribute to the economy. The efficiencies of various sources and pathways were evaluated using EMERGY per unit energy and EMERGY per unit of transportation. The following are the preferred means of transport, arranged in order of overall efficiency:

Bicycle
Compressed natural gas car
Gasoline car
Methanol fueled car
Metrortail
Hydrogen fueled car
Electric car with nickel-zinc batteries
Ethanol car
Public bus
Fuel cell electric car

The best transportation alternative uses about 1/3rd the resources the worst alternative uses.

Hydrogen

In the short range future, while there are available fossil fuels, hydrogen is not likely to compete with natural gas or motor fuels made from fossil fuels for transport and general industrial sources of concentrated heat, because the net EMERGY yield ratio of hydrogen is lower than that of these other sources. In the long range future, after fossil fuels are scarce and expensive, hydrogen requires too much EMERGY for a general fuel to be competitive, because too much energy is required to make electricity first and then hydrogen. A possible exception is nuclear energy if nuclear fuels are still available after the fossil fuels are gone. These conclusions are based on emergy evaluations of a few cases and should be regarded as tentative until confirmed by evaluation of more examples.

Hurricane Andrew

Emergy analysis of Dade county and the hurricane Andrew impact area for conditions prior to the hurricane were conducted to develop insight into the magnitude of hurricane damage and rebuilding efforts, and to provide the background for growth scenarios for the south Dade region.

As a result of the vast differences in population density and development status, the two regions are quite different. Emergy use per unit area (Empower density) in Dade county, as a whole, is nearly three times that which is characteristic of the hurricane impact area. On the other hand because of the relatively low population density in south Dade, emergy use per capita is nearly 20% greater than the average for the entire county. Low emergy empower density and high per capita emergy use suggest higher than average natural emergy contribution to the economy of south Dade.

Emergy analysis of the damages and costs resulting from hurricane Andrew revealed that the damages to structure were equal to about 3 times the annual emergy flux within the impact region. The clean up and reconstruction emergies (dominated by emergy of human services) were nearly 60% greater than the damage incurred. By far, the greatest damage was to urban, agricultural and social systems (about 86% of the total) while environmental systems comprised about 14% of the total damages.

A macroscopic, simulation model was developed and simulated to test theories of the relationship between order and disorder, and to evaluate the effects of better quality urban structure on hurricane losses. With no hurricane input, total structure in both the urban and natural systems was higher over the 250 year simulation period. Increased frequency of hurricanes, and/or severity decreased total structure and production, and if post hurricane aid was not given, recovery took longer and resulted in lower total structure and productivity.

A key question is related to the costs and benefits of increasing the quality of structure built to withstand hurricanes. Theory would suggest that there should be an optimum quality of structure for given hurricane forces and frequency. If the frequency of hurricanes is longer than the life of the structure, it may not pay to build structure capable of withstanding the hurricane. On the other hand, if the frequency is shorter than the life of structure, it may be beneficial to build less structure of higher quality. Simulations of the model were conducted to test this optimization strategy. Optimization suggested that increases of 4% in the total emergy "invested" in structure yielded positive benefit/cost ratios for most hurricane intensities, 6% increases yielded positive ratios for only the most intense hurricanes and greater increases in emergy invested in structure did not yield positive results.

Emergy Analysis of Rebuilding Options After Hurricane Andrew

Rebuilding of south Dade after Hurricane Andrew has drawn much attention. There are those who believe that it will be many years before the area once again reaches the level of population and economic activity that it had prior to the storm. Others suggest that rebuilding will be relatively quick. The ultimate question, however, is not how long will rebuilding take, but to what level of urban structure and population density should the region be developed? In other words, what is the carrying capacity of south Dade?

In this analysis the population carrying capacity of south Dade was evaluated under several different scenarios. The basic driving premise for carrying capacity evaluations was to develop a sustainable pattern of humanity and nature. To achieve a sustainable level of development, energy resources obtained from outside the region must be matched with resources from within to provide a resource base that is both well balanced and competitive. Carrying capacity was evaluated for three levels of development: (1) a population levels sustainable on resources from within, (2) a population level based on developing to the average level of empower density of the state of Florida, and (3) population levels sustainable for full development at the density of northern Dade county. In each case the resources required to sustain populations are evaluated and a hypothetical spatial distribution of developed and natural lands based on EMergy principles are given.

1. Concepts and Methods of EMERGY Evaluation of Policies

M.T. Brown and H.T. Odum

EMERGY analysis is a method of energy analysis that accounts for the direct and indirect use of energy in producing a commodity, resource, fuel, or service, in energy of one type. The solar EMERGY in a resource, product, or service is the sum of the solar energies required to make it. EMERGY includes both fossil fuel energies and environmental energies (like sunlight, rain, tides, etc.) that are necessary inputs to most processes of energy transformation. Thus, the EMERGY of an alternative fuel, such as alcohol made from sugar cane, includes: (1) the solar energy "embodied" from natural sources in the sugar cane, (2) the EMERGY spent for goods and services to grow the sugar cane and process it into alcohol, (3) the EMERGY of the fuel that was burned by agricultural equipment and alcohol processing, and (4) the EMERGY value of labor. EMERGY can be conceptualized as energy memory (Scienceman 1987, 1989), since it is a measure of all of the energy previously required to produce a given product or process. The term "EMERGY" differs from embodied energy as defined by other schools of thought. For example, environmental inputs and labor are omitted by IFIAS (1974) and Slesser (1978), energies are added without using transformities by Hall et al. (1984), and energies are assigned by input-output data (usually money flows) with different results by Hannon et al. (1976), Herendeen et al. (1975), and Costanza (1978).

EMERGY, Wealth and Economic Vitality

EMERGY is a quantitative measure of the resources required to develop a product (whether a mineral resource that results from bio-geologic processes, a renewable resource such as wood, a fuel source, or an economic product that results from industrial processes) and express the required resources in units of one type of energy (usually solar). We suggest that evaluations using EMERGY may help to clarify policy options, because the use of EMERGY as a measure of value overcomes four important limitations of other methods for evaluating alternative fuels and technologies. These limitations are as follows: (1) mixing units of measure such as weight, volume, heat capacity, or economic market price cannot lead to comparative analysis; (2) evaluations that use the heat value of resources for quantification assume that the only value of a resource is the heat derived from its combustion. In this way, for example, human services are evaluated as the calories expended doing work and, when compared to other inputs to a given process, are several orders of magnitude smaller and often considered irrelevant; (3) unmonied resources and processes (i.e., those outside the monied economy) are often considered externalities and not quantified. Most processes, and all economies, are driven by a combination of renewable and nonrenewable energy; (4) price determines value. The price of a product or service reflects human preferences, often called "willingness-to-pay." It can also reflect the amount of human services "embodied" in a product. A valuing system based on human preference assigns either relatively arbitrary values, or no value to necessary resources or environmental services.

EMERGY is a measure of the ability to cause work (Odum 1984; Odum and Arding 1991). New energy sources are often evaluated based on dollar costs per unit of energy produced, and suggestions are made that if prices rise, a new source may be economical and thus competitive. However, price merely suggests what humans are willing to pay for something; the ability of a resource to cause work--and thus its true value to the public--is determined by the effect it has in stimulating an economy. For instance, a gallon of gasoline will power a car the same distance no matter what its price; but its value to the driver is the number of miles (work) that can be driven. Its price reflects the scarcity of gasoline and how important it is to do the work. Price is often inverse to a resource's contribution to an economy. When a resource is plentiful, its price is low, yet it contributes much to the economy. When a resource is scarce, its total contribution to the economy is small, yet its price is high.

EMERGY may be a measure of the equivalence when one resource is substituted for another. Sunlight and fossil fuels are very different energies; yet when their heat values are used the difference is not elucidated. A joule of sunlight is not equivalent to a joule of fossil fuel in any system other than a heat engine. In the realm of the combined system of humanity and nature, sunlight and fuels are not equally substitutable joule for joule. However, when a given amount of fuel energy is expressed as the amount of solar energy required to make it (solar EMERGY), its equivalence to sunlight energy is defined. Since EMERGY is a measure of the work that goes into a product expressed in units of one type of energy (sunlight), it is also a measure of what the product should contribute in useful work in relation to sunlight.

Other methods of energy analysis do not account for different types of energy, but assume that the heat value of energy is a common denominator by which quantification and comparisons can be made by Slesser (1978, 1987). We believe this to be incorrect. All energy types are not equivalent in their ability to do work and, without accounting for the differences in what has been termed the quality of different types of energy, erroneous conclusions can result. Use of EMERGY to represent all the contributions to any given product or process accounts for differences in resource quality and expresses different resources in equivalent capacity to do work.

Net EMERGY

In this study, various alternative transportation fuels are evaluated using EMERGY analysis to shed some light on their potential to contribute positively to the economy. For an alternatie fuel source to contribute, it must yield more energy than it costs to produce. The higher the ratio of yield to cost the greater its contribution to the economy. Evaluation of net yields of fuel sources has been called net energy analysis and has been done for some time. Most often, however, net energies are determined using only the heat values of energies consumed in the production process. Often not included are the indirect energies--associated with goods and services that are consumed, labor, and nonrenewable resources such as soils-- which are sometimes greater than direct energy consumption. Net EMERGY analysis accounts for all energy used, including the so-called "free" renewable energies like sunlight, wind, or rain, and those associated with goods and services. Net EMERGY ratios (the ratio of yield to costs) of primary fuels have been found to be on the order of 10/1, while the ratio for secondary sources is lower, about 3/1 (Odum, 1995). If a potential fuel source has a ratio much below current primary sources, it is not economical, and will not complete. Under such conditions, fuels are often subsidized through government intervention in the market or through tax incentives.

We believe that conservation strategies can be evaluated in the same manner, since they should yield more than they cost. True conservation strategies should have net yield ratios that are greater than 1/1; the higher the ratio the better the conservation. We estimate that for a conservation strategy to be economical, it should have a net EMERGY yield ratio of at least 3/1.

Previous studies using EMERGY evaluation of choices include: alternative fuels, alternative sites for power plants, alternative agriculture, mitigation of wetlands, aquaculture compared with environmental production, national characteristics, benefits of foreign trade, impact of wars, allocation of waters, waste disposal alternatives, and importance of historic events.

Definitions

Before presenting detailed descriptions of each step in the methodology, definitions are given for several key words and concepts.

Energy. Sometimes referred to as the ability to do work. Energy is a property of all things which can be turned into heat, and is measured in heat units (BTUs, calories, or joules)

EMERGY. An expression of all the energy used in the work processes that generate a product or service, in units of one type of energy. Solar EMERGY of a product is the EMERGY of the product expressed in equivalent solar energy required to generate it. Sometimes its convenient to think of EMERGY as energy memory.

Emjoule. The unit of measure of EMERGY, or EMERGY joule. It is expressed in the units of energy previously used to generate the product; for instance the solar EMERGY of wood is expressed as joules of solar energy that were required to produce the wood. Solar EMjoules is abbreviated "sej."

Empower. The flow of EMERGY per unit time; expressed as sej/time.

Empower density. Empower per unit area; expressed as sej/time*area.

Macroeconomic dollar (Emdollar or EM$) A measure of the money that circulates in an economy as the result of some process. In practice, to obtain the macroeconomic dollar value of an EMERGY flow or storage, the EMERGY is multiplied by the ratio of total EMERGY to Gross National Product for the national economy.

Nonrenewable Energy. Energy and material storages such as fossil fuels, mineral ores, and soils that are consumed at rates that far exceed the rates at which they are produced by geologic processes.

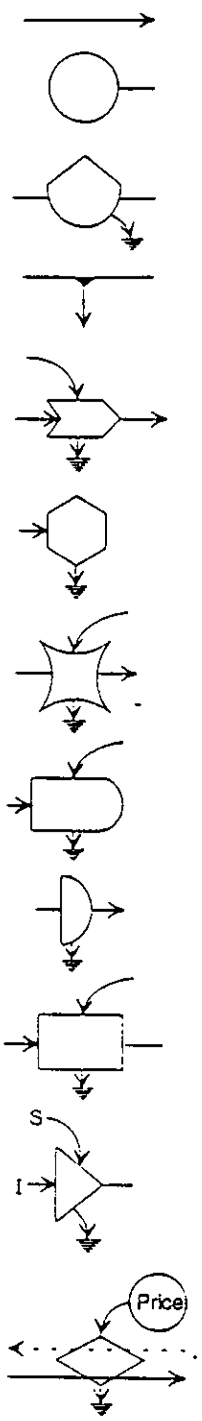
Renewable Energy. Energy flows of the biosphere that are more or less constant and reoccurring, which ultimately drive the biological and chemical processes of the earth and contribute to geologic processes.

Resident Energy. Renewable energies that are characteristic of a region.

Transformity. The ratio obtained by dividing the total EMERGY that was used in a process by the energy yielded by the process. Transformities have the dimensions of EMERGY/energy (sej/J). A transformity for a product is calculated by summing all of the EMERGY inflows to the process and dividing by the energy of the product. Transformities are used to convert energies of different types to EMERGY of the same type.

METHODS

The general methodology for EMERGY analysis is a "top-down" systems approach. The first step is to construct systems diagrams that are a means of organizing thinking and relationships between components and pathways of exchange and resource flow (systems symbols and brief definitions are given in Figure 1.1). The second step is to construct EMERGY analysis tables directly from the diagrams. The final step involves calculating EMERGY indices that summarize and relate EMERGY flows of the economy with those of the environment, and allow the prediction of economic viability and carrying capacity. Given next is further elaboration on the methods used for EMERGY analysis.



Energy circuit. A pathway whose flow is proportional to the quantity in the storage or source upstream.

Source. Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

Tank. A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

Heat sink. Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.

Interaction. Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate.

Consumer. Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.

Switching action. A symbol that indicates one or more switching actions.

Producer. Unit that collects and transforms low-quality energy under control interactions of high-quality flows.

Self-limiting energy receiver. A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within.

Box. Miscellaneous symbol to use for whatever unit or function is labeled.

Constant-gain amplifier. A unit that delivers an output in proportion to the input I but changed by a constant factor as long as the energy source S is sufficient.

Transaction. A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

Figure 1.1. Symbols and definitions of the energy language diagramming used to represent systems (from Odum 1971, 1983).

Step 1: Overview System Diagrams

A system diagram in "overview" is drawn first to put the system of interest in perspective, combine information about the system from various sources, and to organize data-gathering efforts. The process of diagramming the system of interest in overview ensures that all driving energies and interactions are included. Since the diagram includes both the economy and environment of the system, it is like an impact diagram which shows all relevant interactions.

Then a second, simplified (or aggregated) diagram is drawn, retaining the most important essence of the more complex version. This final, aggregated diagram of the system of interest is used to construct a table of data requirements for the EMERGY analysis. Each pathway that crosses the system boundary is evaluated.

Step 2: EMERGY Analysis Tables

EMERGY analysis of a system is usually conducted at two scales. First, the larger system within which the system of interest is embedded is analyzed, and indices necessary for evaluation and comparative purposes are generated. Second, the system of interest is analyzed. Both analyses are conducted using an EMERGY Analysis Table organized with the following headings:

1 Note	2 Item	3 Raw Units	4 Transformity	5 Solar EMERGY	6 Emdollars
Row 1					
Row2					
Row...					

Each row in the table is an inflow or outflow pathway in the aggregated systems diagram; pathways are evaluated as fluxes in units per year. Six columns describe each pathway as follows:

Column 1	(Note) The line number for each pathway, and corresponding footnote number that contains sources and calculations for the item.
Column 2	(Item) The item name that corresponds to the name of the pathway in the aggregated systems diagram.
Column 3	(Raw Units) The actual units of the flow, usually evaluated as flux per year. Most often the units are energy (joules/year), but sometimes are given in grams/year or dollars/year.
Column 4	(Transformity) Transformity of the item, often derived from previous studies.
Column 5	(Solar EMERGY, sej) The product of the raw units in Column 3 and the transformity in Column 4.
Column 6	(Emdollars) The result of dividing solar EMERGY in Column 5 by the EMERGY-to-money ratio (calculated independently) for the

economy of the nation within which the system of interest is embedded.

Step 3: Calculation of EMERGY Indices

The principle used in judging alternative fuel sources is as follows: when alternative fuel sources or transportation systems are compared, the system that contributes the most EMERGY value to the public economy for the least EMERGY invested, in the long run, is most likely to be successful. Several indices which help in gaining perspective about sources and processes are calculated from the data in the EMERGY Analysis Tables. These are:

EMERGY-money ratio (EMprice). The ratio of total EMERGY flow of a source or process to the dollar cost. In addition, a ratio of the total EMERGY in the economy of a region or nation to the GNP of the region or nation is also calculated, as a means of evaluating the EMERGY content of services.

EMERGY yield ratio. The ratio of the EMERGY yield from a process to the EMERGY costs. This ratio is a measure of how much a process will contribute to the economy. Figure 1.2a shows the method of calculating the net EMERGY yield ratio. Sources with the highest net EMERGY yield ratios contribute most to the economy and tend to be used first. This ratio is a useful predictor of the best contributing source.

Solar transformity. The ratio of the solar EMERGY that is required to generate a product or service to its energy. The transformity measures the resource contribution per unit of energy in service or product. Solar EMERGY units are solar emjoules per Joule, abbreviated sej/J. Since products that require more resource input are only used if they have more effect, there tends to be a correlation between the transformity of a product and its effects. Figure 1.2b shows the method of calculating a transformity.

Using Transformity to Select Efficient Pathways

Energy sources can be arranged in a series according to their solar transformities (discussed in more detail in Part 2). Fuels with higher transformities represent more previous work, and thus should be used for purposes where the extra inputs are justified. To use a high transformity fuel for a purpose where a low transformity one is sufficient is a waste of the energy used to generate the higher quality fuel. Inappropriate uses of high transformity energy are not usually economical, since they require more inputs for their production and thus cost more for the same effect.

The Principle of Appropriate Transformity

The appropriate uses of energies of different types may provide maximum economic vitality by accomplishing more useful work. The approach is to match transformity of a source with the task for which the energy is intended. Energies of higher transformity can interact and control flows of lower transformity. Control by higher quality energy is shown in systems diagrams as a pathway entering the top of the transformation process (Figure 1.2). An energy source is well used either in small quantity to interact and control a larger source of lower transformity, or in larger quantity to interact and be controlled by a smaller quantity of higher transformity energy. For example, higher transformity electricity is apropriately used to control lower transformity heating systems, but may not be as appropriate to substitute for heating with natural gas or wood.

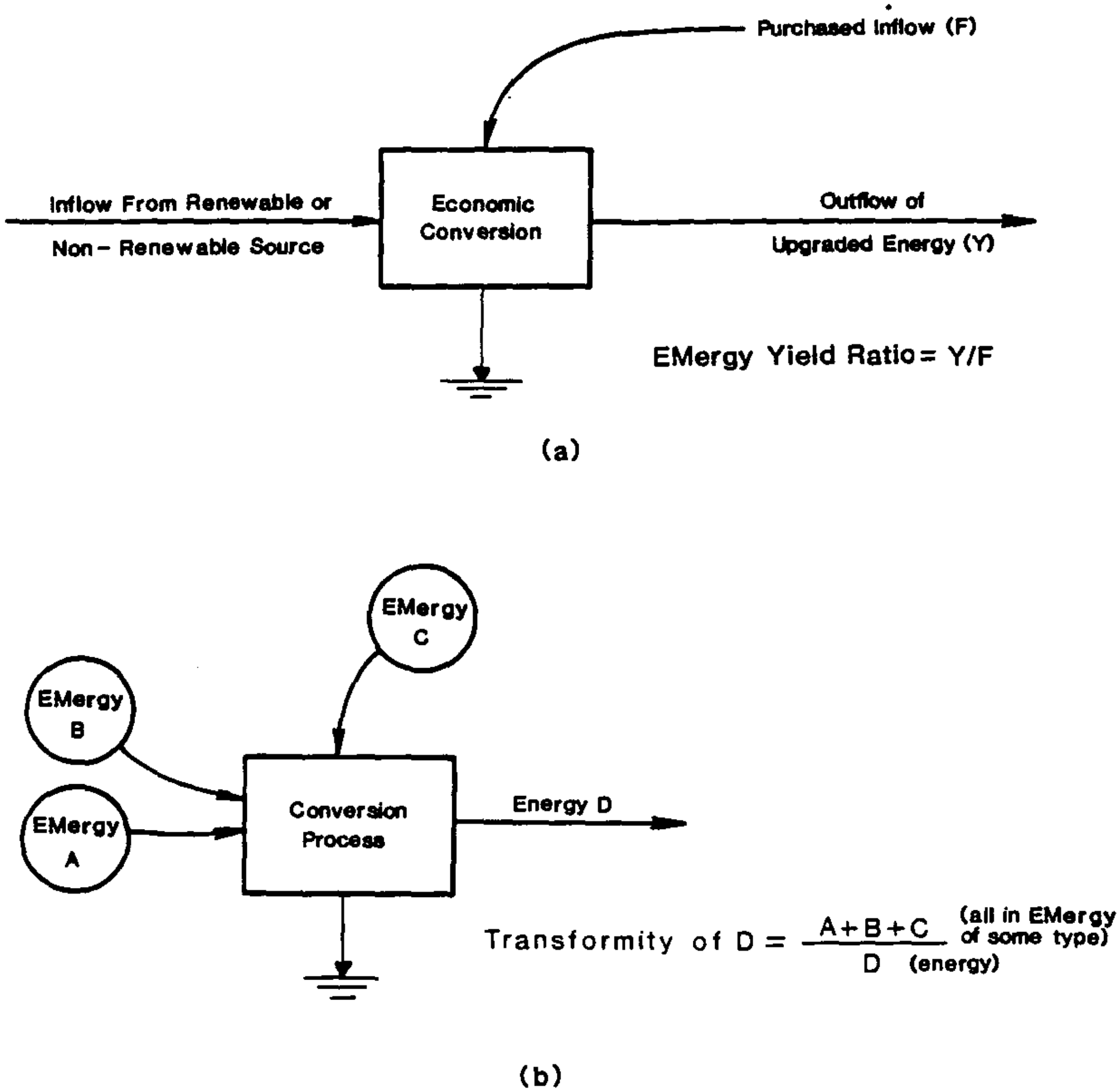


Figure 1.2. Diagram of energy flows in a typical energy transformation process showing method for calculating EMERGY yield ratio (a) and transformity (b).

2. Transformity of Alternative Energy Sources

H.T. Odum and M.T. Brown

The productivity of modern societies depends on sources of energy and their transformation into the products and services of the human economy. Whether it is natural environmental systems or the market economy systems of human managed technology, self-organizing pressures tend to eliminate those networks that are wasteful or contribute less. But procedures are needed to tell in advance what combinations of processes use resources most efficiently. As world supplies of energy become less available, good planning and policy requires evaluation of alternative sources and processes. Which are abundant and efficient enough to operate our systems? What are the best alternatives for such processes as heating, transportation, and electric power?

Evaluating energy sources and processes in the network of environment and economic sectors is difficult because there are so many inputs that contribute. Inputs such as human labor and services may represent as much energy indirectly as the fuels supply directly. A measure that evaluates various kinds of energy on a common basis is the transformity. The larger the transformity of an energy type, the more energy was required in its formation. This chapter explains the transformity measure, its use to evaluate alternative energy sources, and the principle of appropriate transformity for making energy policy.

The many forms of energy available to do work can be arranged in a series according to the amounts of one kind of energy required to make another. Many joules of environmental energies are required to make a tree, many joules of wood energy are required to make electricity, and many joules of electric energy are required to process information, etc. By expressing all forms of energy in units of one type that was required to make each of the others, a measure is obtained of their position in the scale of energy requirement. This measure is the transformity, the energy of one kind used directly and indirectly to make another kind.

After a century of research, technologies are available to transform most kinds of energy into most other forms of energy. Given a resource of one kind of energy, humans seeking another kind of energy can string together one or more transformation processes to generate the desired product. For example, Figure 2.1 shows strings of energy transformations with various forms of resultant energy, all derived from natural gas. All these arrangements use well established processes, but some involve unnecessary extra steps. Some require more special inputs of energy

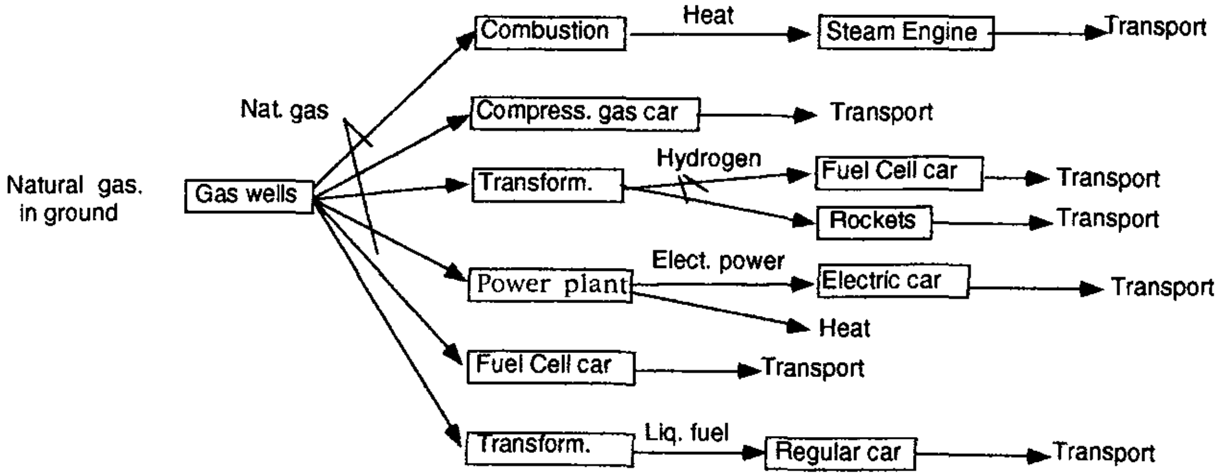


Figure 2.1. Example of the many possible alternative pathways of energy transformation, in this case starting with natural gas.

directly and indirectly than others. First we need to explain energy transformation processes, the EMERGY concept and how the transformity is defined.

Energy Transformation Processes

Energy is normally used in an energy transformation process, as diagrammed in Figure 2.2. The numbers on the pathways in Figure 2.2a are flows of energy per unit of time. In other words, energy is conserved; it is neither increased nor destroyed during the transformation. Normally, there is a large flow of one quality of energy that is required for the transformation, shown inflowing from the left (I) in Figure 2.2a. According to the first energy law, energy inflowing from the left is either stored (if there is a storage indicated with a tank symbol) or passed out of the process. In the transformation this energy flow is normally controlled by one or more higher quality energy flows of lesser quantity, shown flowing in from the right (F in Figure 2.2). The output yield of the transformation process (Y in Figure 2.2) is energy shown leaving to the right.

According to the second energy law, most of the potential of the inflowing energy to do work (energy availability) is used up during the transformation. In energy systems diagrams energy whose "availability" is used up is shown leaving the system through the "heat sink" at the bottom in Figure 2.2. A smaller amount of energy which has been transformed into a new form is shown in Figure 2.2 leaving the process to the right. In classical energy analysis, efficiency of energy transformation is the percent the output flow (Y) is of the input energy flow (I). Sometimes the efficiency is calculated as the percent the output flow is of all energy inflows (the sum of input energy flows I + F) including the feedback flow (F). Since the output energy flow (Y) required more available energy of incoming type (I) to be used up (and dispersed through the heat sink), it can be said to be of higher quality.

It is well known that any energy transformation processes can be operated at different speeds and efficiencies by changing the output loading. You can arrange a process so that it does little work and, as a consequence, rapidly and wastefully dumps energy into heat. Or, you can arrange the process with so much loading that the process, although efficient, stalls or goes so slowly that it is not very useful. Generally, there is an intermediate loading that transforms energy with an optimum efficiency that maximizes the rate of conversion (maximizes the power output). In the following discussions of alternative energy sources and transformations, it is assumed that the processes are loaded to deliver the maximum power output.

The many forms of energy of the biosphere can be arranged in an energy quality series illustrated in Figure 2.3. Energy forms are arranged from left to right in order of the energy

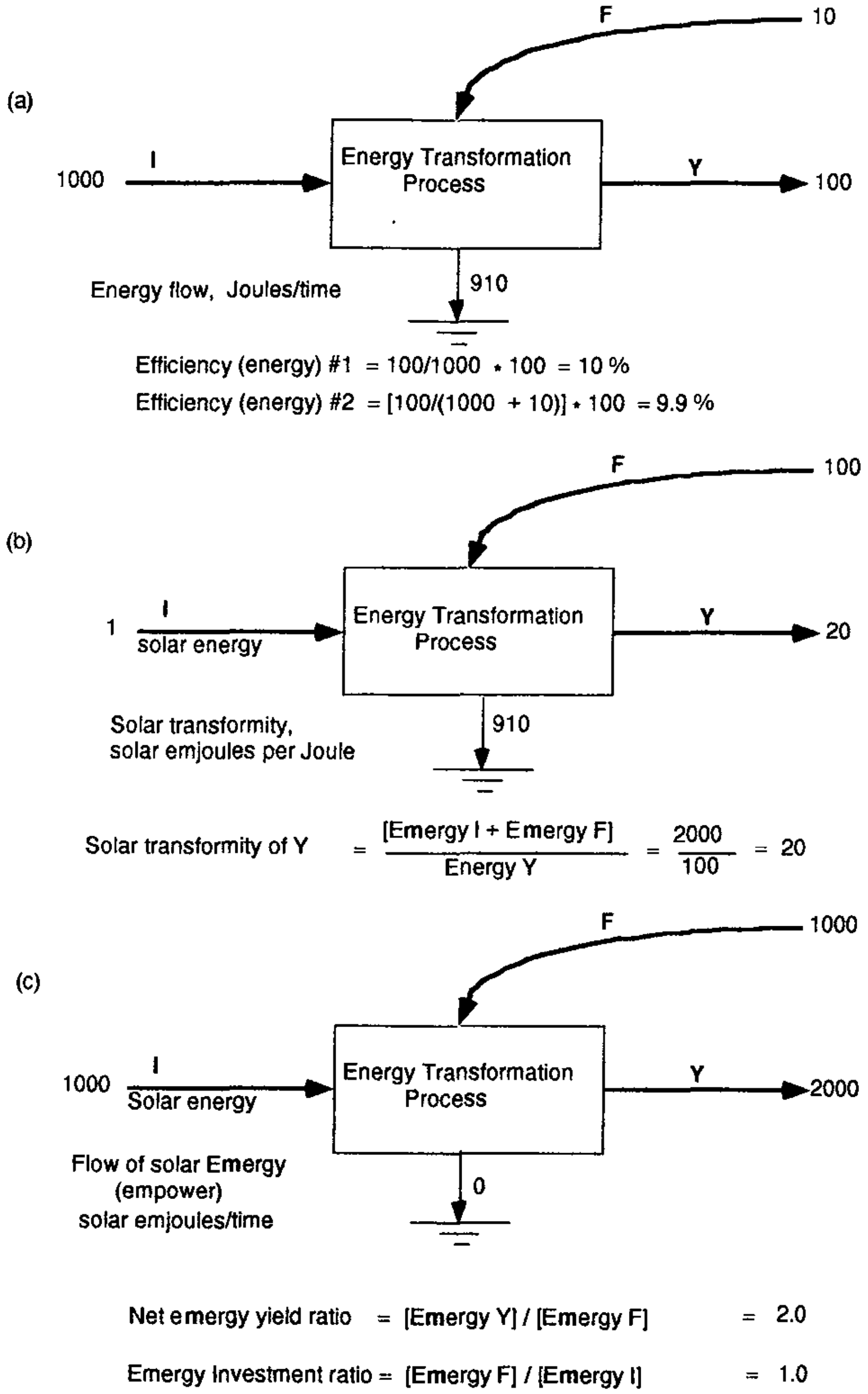


Figure 2.2. Numerical example of energy, transformity, and EMERGY in a transformation process; I, main energy inflow; F, controlling feedback from the larger system; Y, yield from the transformation process. (a) Energy flows and the classical calculation of efficiency of energy conversion; (b) solar transformity given for each energy inflow and the calculation of the transformity of the yield as the quotient of solar EMERGY flow (in c) divided by the energy flow (in a); (c) solar EMERGY of each pathway.

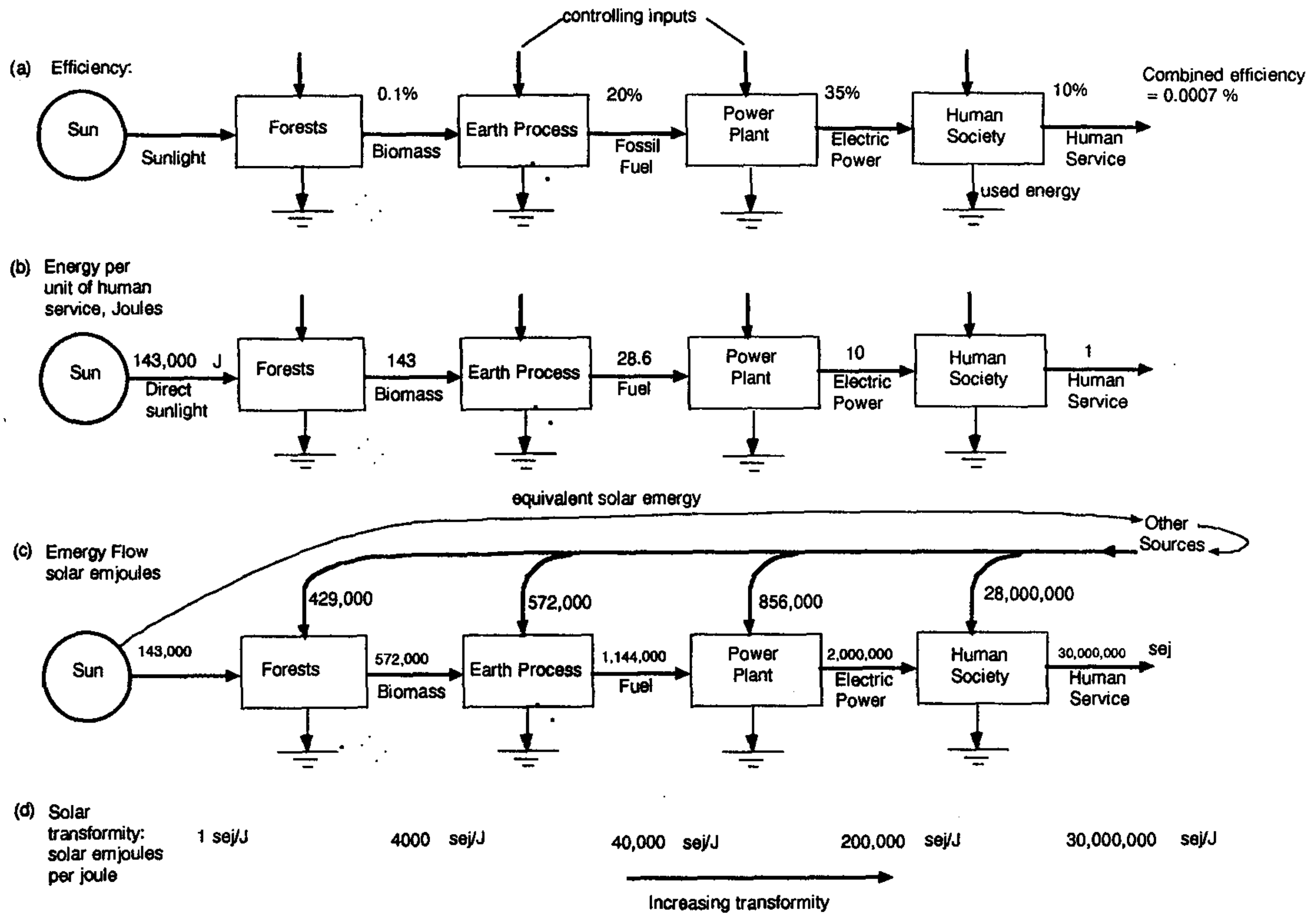


Figure 2.3. Series of energy transformation processes arranged to form an energy hierarchy. Available energy flowing from the left is transformed at each stage to a smaller flow of energy of higher quality. (a) Efficiency of the string of processes calculated by multiplying the efficiencies of each successive transformation together from left to right, ignoring the controlling inputs; (b) energy of the source required for each unit of yield of the last process obtained by back calculating (sucessively dividing from right to left by the efficiencies, ignoring the controlling inputs); (c) solar EMERGY required for the yield of the last process including the controlling inputs; (d) solar transformity of each energy flow calculated as the sum of solar EMERGY inputs divided by the energy yield, as in Figure 2.2.

required for their formation . Many joules of potential energy of one kind on the left are used up in the work of generating fewer joules of a second form of energy to the right. Where many units of one type are required to support a unit of higher type, the word hierarchy is appropriate. All kinds of energy can be located in the energy hierarchy depending on the energy of each kind required to generate another. Since different quantities of energy are required for different forms of energy, it is not correct to use energy units (joules, kilocalories, btu's, etc.) as a measure of work where energies of different forms are compared.

However, one may express various energy flows or storages in units of one form of energy that was previously used to develop each. The available energy of one form required directly or indirectly to develop a product or service was defined in Chapter 1 as the EMERGY. To distinguish the energy previously transformed, a new unit was defined, the emjoule. We usually use solar energy reaching the earth's surface as the form of energy used to evaluate other forms. Thus, we evaluate various kinds of available energy in terms of solar EMERGY in units of solar emjoules. A numerical example of Solar EMERGY in an energy transformation is given in Figure 2.2c. The solar EMERGY of the output yield is the sum of the solar EMERGY of the two inputs.

Transformity is defined as the total EMERGY that was used in a process divided by the energy yielded by the process. Transformities have the dimensions of EMERGY/energy (solar emjoules per Joule, abbreviated sej/J). A transformity for a product is calculated by summing all the EMERGY inflows to the process and dividing by the energy of the product. A numerical example is shown for the energy transformation process in Figure 2.2b.

In Figure 2.3 the solar energy on the left, processed through several transformations, produces small amounts of the energy types on the right. The more transformation stages there are, the less energy of the output. The further to the right in the energy hierarchy, the greater the solar transformity to make a joule of that energy type. The solar transformities increase from left to right In Figure 2.3d, marking the position in the energy hierarchy series.

Where there are alternative processes for generating the same power outputs, processes with inputs of lower transformity are the most efficient. Comparing solar transformities of alternative processes is an easy way to select the best choices. The solar transformity of new processes for generating an energy type can be compared with the values in tables of transformity based on previous evaluations (Table 2.1).

Observations suggest that forms of energy with higher transformity have greater effect when they are used, providing they have other forms of energy with which to interact. Efficient systems don't disperse more energy than is necessary (that is, they don't unnecessarily use up the potential for work). Energies are not long transformed to higher transformity unless the product has effects justifying the greater energy use. In other words, the higher the transformity, the greater the effect the energy has in its use. Sometimes the phrase "greater energy quality" is used to describe an energy type that has greater effect per joule. In this sense, it can be said that transformity measures energy quality.

In diagramming a typical energy transformation (Figure 2.2), the lowest transformity is that of the larger, low quality energy from the left (I). The highest transformity is that of the high quality, controlling, (but low energy content) "feedback" (F) from higher levels in the energy hierarchy. The product outflow has intermediate transformity. As shown in Figure 2.2, there is apparently a matching of high and low quality energy flows required for any energy transformation.

By the principle of appropriate transformity, each kind of process has appropriate transformities for its inputs. An energy use is appropriate if it is efficient in supporting useful work of a type needed. An energy use is not appropriate if a higher transformity form is used than is necessary, because this means that more energy was used than necessary. In terms of the series in Figure 2.3, it would be a waste to transform energy into a high quality form on the right and then use it do work that a lower form could do. For example, it is wasteful to convert fuels into electricity and then use that electricity to make heat that the ordinary fuel could generate without the transformation to electricity.

Fuels with higher transformities represent more previous work and thus should be used for purposes where the extra inputs are justified. To use a high transformity fuel for a purpose where a low transformity one is sufficient is a waste of the energy used to generate the higher quality fuel. Inappropriate uses of high transformity energy are not usually economic since they require more inputs for their production and thus cost more for the same effect. High transformity flows with relatively small energy may not have much effect in interactive-control action on energy types with several orders of magnitude lower transformity. In the opposite direction, an energy type may not be controlled by an energy form with a transformity several orders of magnitude higher.

Transformities are evaluated for observed operations as an empirical measure of what a system does. Each EMERGY evaluation of a production system generates additional transformities. Sometimes we use the least transformity known to indicate what the most efficient transformation is (most efficient consistent with maximum power). For other purposes we use the mean of the transformities found from previous studies.

In order to use the appropriate transformity principle to select the best energy alternatives, the lowest solar transformity which is possible for each fuel must be established. Lower transformity means greater efficiency. No doubt there is an ultimate thermodynamic lower limit to the transformity for each kind of energy. Evaluation of many kinds of systems will eventually determine the least transformities (the most efficient conversions) consistent with delivery of maximum power. A national agency may be required to make the hundreds of evaluations needed. Even determining the average transformity will require many duplicate evaluations. In the meantime, we have assembled the available determinations of transformity such as those for electric power in Table 2.1 for evaluating processes and recommending policies.

In the last two centuries of expanded use of rich storages of fossil fuels, these energies were used to interact, control, and stimulate most of the processes of human industry and civilization. For example, fossil fuels were used to process fertilizers and pesticides to improve efficiencies of agriculture. In Figure 2.2 these special inputs are examples of high EMERGY, controlling feedbacks (F). In order to maximize intensive agriculture, these inputs were increased with diminishing returns. The solar transformity that resulted in these over-stimulated processes was larger than the minimum observed. There was not a good matching between the inputs. In other words, the waste of trying to stimulate with too much fuel-based input caused a loss of overall efficiency and thus a higher transformity. In times of rapid economic development and open competition, accelerating power and speed of development displaces efficiency temporarily. Later, when growth is not possible, efficient alternatives may displace the fast, inefficient ones and the observed transformities will be less. In times like the present which are in transition, we often have to consider two transformities: the larger (inefficient) one that is competitive and a smaller (efficient) one that can prevail in non-growth periods. The latter probably has a thermodynamic lower limit consistent with maximizing power in a real system.

Some of the most basic transformities are used in evaluating other transformities. For example, the solar transformity of electric power is estimated from various processes in Table 2.1. The range of values is due to differences in the efficiency of the particular systems evaluated, to variations and errors in the data used, to omissions of some contributions, and errors in the assumptions. Pending a national project to more precisely determine the best and the average transformities, we arbitrarily selected values to use for other evaluations based on studies so far available. Between 1966 and 1990, transformities were revised every few years as more accurate basic transformities were found, which caused many others to change. Many transformities changed when we added geologic energies and tides that had not previously been included in the earth calculations.

For any study, one set of transformities is used for most purposes so that all evaluations are comparable. However, small differences in transformities of the main energy sources don't

Table 2.1. Solar Transformities of Electric Power

Note	System	Solar Empower sej/yr *	Electric Power J/yr	Solar Transformity sej/J
1	Coal power plant	160,000	1	160,000
2	World stream geopotential	9.44 E24	1.0 E20	94,400
3	Hydroelectric power,Sweden	1.95 E24	2.43 E17	80,246
4	Wood power plant, Jari Brazil	2.38 E20	1.17 E15	203,418
5	Solar voltaic grid,Austin, Tx	7.5 E17	1.8 E12	416,666
6	Hydroelectric,Tucurui, Brazil	1.65 E22	1.0 E17	165,000
7	Wood power plant, Thailand	2.42 E14	3.6 E9	67,222
8	Oil power plant, Thailand	7.14 E14	3.6 E9	197,777
9	Coal power plant, Thailand	6.10 E14	3.6 E9	169,444
10	Lignite power plant, Thai.	5.47 E14	3.6 E9	151,944
11	Lignite Power plant, Texas	5.4 E21	2.65 E16	204,384
12	Geothermal Electric, Calif.	2.13 E20	2.5 E15	84,800
			Mean	166,274

*18% added to those EMERGY evaluations that were made before tide was added to global solar EMERGY budget (items 6 and 11)

1 Assuming 4 coal emjoules per Joule electric power and 40,000 sej/J coal

2 Global calculation made with assumptions about the empower required for the mountain uplift, the carving of basins, and the construction of dams.

Global solar empower, 9.44 E24 sej/yr, generates average stream flow over land 39.6 E3 km^3 runoff (Todd 1970) and maintains an average land elevation, 875 m (Ryabchikov, 1975). Average land and average streams were taken as by-products of shared empower.

Stream geopotential: (39.6 E12 m^3/yr)(875 m)(1000 kg/m^3)(9.8 m/sec^2) = 3.39 E20 J/yr.

Electric power potential = stream geopotential times efficiency of hydroelectric conversion taken as 80%.

(3.39 E20)(0.8) = 2.7 E20 J/yr electrical.

For a 25% feedback of empower from the economy for dam and operation, the net yield of electricity could be 3/4 of 2.7 E20 J/yr = 2.0 E20 J/yr.

If stream energy in the long run has to carve a basin half the time to allow generation of electricity the other half, then the electric output is half or 1 E20 J/yr.

3 Realized electric power 1988:72 Terawatt-hours page 17 in Energy in Sweden, National Energy Administration 1990 S117 82 Stockholm Sweden. 30 pp.
(72 E9 kilowatt-hrs/yr)(860 kcal/kwhs)(4186 J/kcal) = 2.60 E17 J/yr;

For 80% efficiency, input geopotential is 2.6 E17/0.8 = 3.25 E17 J/yr.

Time for erosion to make a basin may be assumed to be similar to the time for filling with sediment.Thus the dam in the long run operates for half the time as it fills with sediment, eroding for half using the same stream energy. Either consider the long range electrical yield as half or consider the short term operation as receiving the prorated EMERGY of the carved basin as equivalent to the input geopotential (2 times geopotential in use). (2)*(3.25 E17 J/yr) = 6.5 E17 J/yr input geopotential. For 3rd order streams, solar transformity from Fig. 4.11 on the Mississippi River is 3 E4 sej/J and therefore the input solar EMERGY is (3 E4 sej/J)*(6.5 E17 J/yr) = 1.95 E22 sej/yr

Using 1/4 of empower feedback for dam and operation, net electrical yield is
(3.25 E17)*0.75 = 2.43 E17 J/yr.

4 Rainforest logs supplied in a steady state from a 100 year rotation requiring 2.324 E9 m2; Solar EMERGY from main use of rain by trees and 3 mm transpiration, 4.94 J Gibbs free energy per gram of rain water and solar transformity of rain, 1.82 E4 sej/J :
(3mm/d)(365 d/yr)(1 E-3 m^3/mm)(1E6 g/m^3)(4.94 J /g water)(2.3 E9 m^2)(1.82 E4 sej/J)
= 2.27 E20 sej/yr; plus solar EMERGY from fuels use 0.085 E20 sej/yr and services used 0.025 E20 sej/yr.
Electricity produced, 1.67 E15 J/yr minus electricity used in the processing: 0.032 J/yr debarking & chipping and 0.46 E15 J/yr in plant operations.

5 Power grid evaluated by R. King (1991). See Table 22.5

6 Modified from Brown(1986) Energy analysis of the hydroelectric dam near Tucurui, Brazil, pp. 82-91 in Energy Systems O overview of the Amazon Basin, H.T.Odum, M. T. Brown, and R.A. Christianson.
Electricity produced: 1.0 E17 J/yr based on 0.8 capacity factor and 4000 megawatts.
Contribution to dam and operation from economy: = 4.25 E21 sej/yrContribution of geopotential of inflowing water and also the prorated contribution of the basin that was developed by the same streamflows earlier. See note #3.
(2.06 E17 J/yr)(2.36 E4 sej/J) = 4.87 E21 sej/yr
Total input includes this factor twice (present inflow + prorated basin EMERGY). In a full cycle of damming and allowing reerosion of basin, there is no net sediment diversion.
(4.87 + 4.87 + 4.25) E 21 sej/yr = 13.95 E21 sej/yr
(13.95 E21 sej/yr)(1.18 tidal correction) =

7 Wood power plant (25 megawatt generating 173.5 E3 kwh/yr)using eucalyptus plantation wood (S.Doherty and Bo Hector, 1991). Values estimated per megawatthour electrical
(1 mwh)* (1000 kwh/mwh)* (860 kcal)/kwh*(4186 J/kcal) = 3.59 E9 J/yr
Solar EMERGY inputs in sej per mwh:
Rain, 44 E12; Fertilizer, 6 E12; Labor, 7 E12; plantation capital, 29 E12; plant operational service, 96 E12; power plant capital, 55 E12; transmission, 6 E12; total, 242 E12 sej/mwh

8 Oil fired power plant (S.Doherty and Bo Hector, 1991).
Values estimated per megawatthour electrical
(1 mwh)* (1000 kwh/mwh)* (860 kcal)/kwh*(4186 J/kcal) = 3.59 E9 J/yr
Solar EMERGY inputs in sej per mwh:

Oil, 402 E12; Oil services, 100 E12; plant operational services, 131 E 12; capital, 40 E 12; transmission, 41 E12;total, 714 E12 sej/mwh,

9 Coal Powered plant (S. Dohery and Bo Hector, 1991)
Values estimated per megawatthour electrical
(1 mwh)* (1000 kwh/mwh)* (860 kcal)/kwh*(4186 J/kcal) = 3.59 E9 J/yr
Solar EMERGY inputs in sej per mwh:
Coal, 380 E12; Oil services, 80 E12; plant operational services, 109 E 12; capital, 58 E 12; transmission, 43 E12; total, 610 E12 sej/mwh.

10 Lignite power plant (S. Doherty and Bo Hector, 1991)
Values estimated per megawatthour electrical
(1 mwh)* (1000 kwh/mwh)* (860 kcal)/kwh*(4186 J/kcal) = 3.59 E9 J/yr
Solar EMERGY inputs in sej per mwh:
Lignite, 279 E12; mining services, 93 E12; plant operational services, 100 E 12; capital, 44 E12; transmission, 30 E12; total, 547 E12 sej/mwh

11 Big Brown Lignite power plant, Texas Odum, Odum, and Blissett, 1987)
(7.27 E13 J/day)(365 d/yr)=2.65 E16 J/yr electrical power produced.
Inputs evaluated in solar emjoules/day:
Mining inputs:
Lignite mined for power plant, 73.7 E17; topsoil lost, 3.1 E17; fuel used, 0.032 E17; electric power used, 0.49 E17; equipment maintenance, 0.93 E17; goods and services, 6.2 E17; and total, 84.45 E17 sej/day.
Power Plant inputs: cooling water 0.10 E17; equipment maintenance, 1.24; Goods and services, 40 E17; total 41.34 E17 sej/day.
Mining and power plant on a year basis: (365)*(84.45 +41.34)E17 = 4.59 E21 sej/yr
Tidal correction to global transformities: 4.59E21 * 1.18 = 5.4 E21 sej/yr

12 Geothermal electric power conversion in California updated from Gilliland (1975).
Efficiency of 11% generates 2.5 E11 J/yr
Economic feedbacks based on 1972 costs and EMERGY/USem$ for 1972
(9.7 E6$)(7 E12 sej/$) +0.68 E20 sej/yr
Geothermal heat contribution estimated from efficiency of 11% and 6% pipe loss of heat
2.4 E16 J/yr ; and solar transformity for deep heat from Appendix table A1,
(2.4E16 J/yr) (6055 sej/J.) = 1.45 E20 sej/J
Geothermal plus economic feedbacks: (1.45+ 0.68)E20 sej/yr= 2.13 E20 sej/yr

make much difference in comparative evaluations because they affect all of the systems similarly. In the future, after transformities have been calculated for more examples, better estimates for the average and the most efficient transformity will be found, but such refinements are not expected to change policy conclusions very much.

In the case of electric power, for many studies during the period 1983-1993 we standardized on a higher value for solar transformity of electric power (2 E5 sej/J) in order to be realistically conservative until further studies proved whether electric power could be made with less. The solar transformity of coal was standardized as 40,000 sej/J.

Using Transformities to Evaluate Energy Transformation Series

Using traditional energy process analysis, the efficiencies of each stage in a series of processes are combined (multiplied together) to obtain an overall efficiency for a whole series, as shown in Figure 2.3a. However, this method omits the controlling inputs, which often have a high transformity (which means that much energy was used previously to make them). A better evaluation using EMERGY includes all inputs on a common basis as shown in Figure 2.3c. For each stage, the sum of the input EMERGY divided by the energy flow is the transformity. Solar transformities for the series are given in Figure 2.3d.

Transformity Tables for EMERGY Evaluations

Transformities are useful for rapid EMERGY calculations, and tables of transformities from previous studies have been assembled. Transformities are used to convert data on energies of different types to EMERGY of the same type. Table 2.1 has a selection of solar transformities from earlier studies.

3. EMERGY Evaluation of Alternative Fuels for Transportation

H.T. Odum, G.G. McGrane, M.T. Brown, and S. Bastianoni

Good fuel policy is based on a knowledge of which sources are most efficient in supplying energy to maximize economic vitality. Plans are successful that develop those sources which will be competitive in free markets. Fuels which will be successful as primary energy sources and which should be given priority are those with the highest EMERGY yield ratios, and which generate the needed transportation with the lowest transformity (highest efficiency considering all inputs). Recommendations in this chapter are based on EMERY yield ratios and transformities, which were determined from the EMERGY evaluation of alternative fuels and systems for transportation

Rationale for comparisons and suggestions related to most favorable alternative fuel sources are based on the assumption that the fuels that contribute most to an economy are the ones with the greatest net EMERGY yield. These are the ones that contribute the most, compared to what is required from the economy for fuel processing and distribution. The EMERGY yield ratio measures the net contribution of a fuel. Figure 3.1 shows recently determined EMERGY yield ratios for several primary fuels and alternative sources. Fuels with high EMERGY yield ratios also provide more energy per unit of carbon dioxide released to the atmosphere.

When fuels are abundant and close to the surface so that mining is cheap, EMERGY yield ratios are high. When primary fuel sources have high EMERGY yield ratios, economies are prosperous. Before 1973, with prices of oil and gas very low, developed economies were purchasing fuels from the Middle East with EMERGY yields 40 to 60 times more than the EMERGY in the buying power of their payments. In other words, 40 to 60 times more wealth was generated in the economy by the fuels than was required for their processing. Since 1973, world prices have increased. EMERGY ratios for purchases of foreign oil declined, ranging between 3/1 and 12/1. Fossil fuels bought on markets in 1993 give the purchasers a EMERGY yield ratio on the order of 10/1.

The EMERGY yield ratios for the energy sources in Figure 3.1 vary from more than 13 /1 for Alaskan north slope oil, to palm oil having a net yield just barely above break-even (1.06/1). For the most part, energy sources with infra-structure for their distribution and use have yields between 13/1 and 3/1. With declining ratios, and therefore less available energy to support growth and luxury consumption, most of the world is exhibiting slower growth (some would say stagnant growth rates) than was characteristic in the period from 1950 to 1973. For growth rates to resume, we believe that primary fuel sources must have EMERGY yield ratios much higher than is

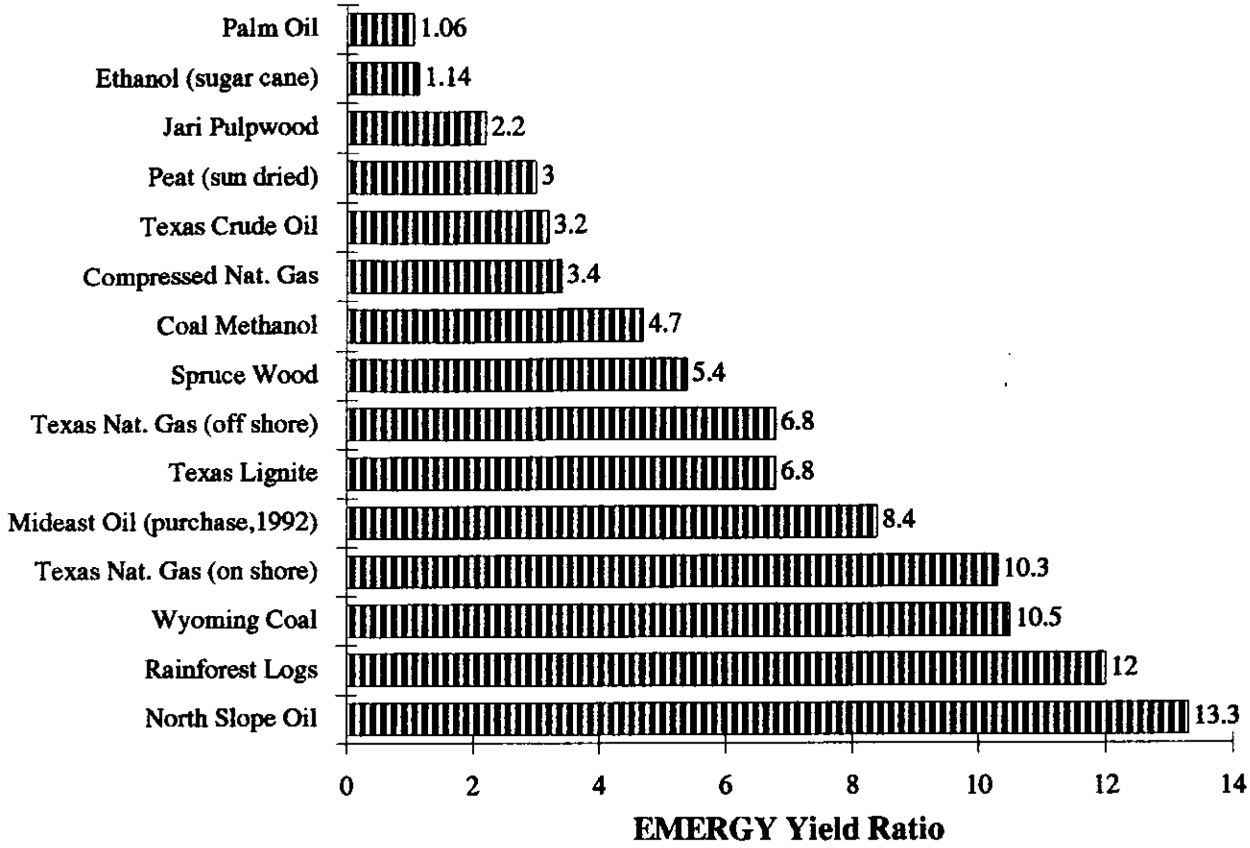


Figure 3.1. Net EMERGY evaluation of fuels. Rain forest logs (Odum et al., 1982); north slope oil (Brown,1993); Wyoming coal (Ballentine, 1976); Texas natural gas onshore, offshore, coal methanol, compressed natural gas, Texas crude oil (King,1992); oil purhase, Texas lignite (Odum, Odum, and Blissett, 1987); Jari pulpwood, palm oil (Odum, Brown, and Christianson, 1986); spruce wood (Doherty, Nilsson and Odum, 1992).

characteristic of most present sources. Alternative fuel sources should have high EMERGY yield ratios equal to or better than current primary sources, if they are to be net contributors to the economy.

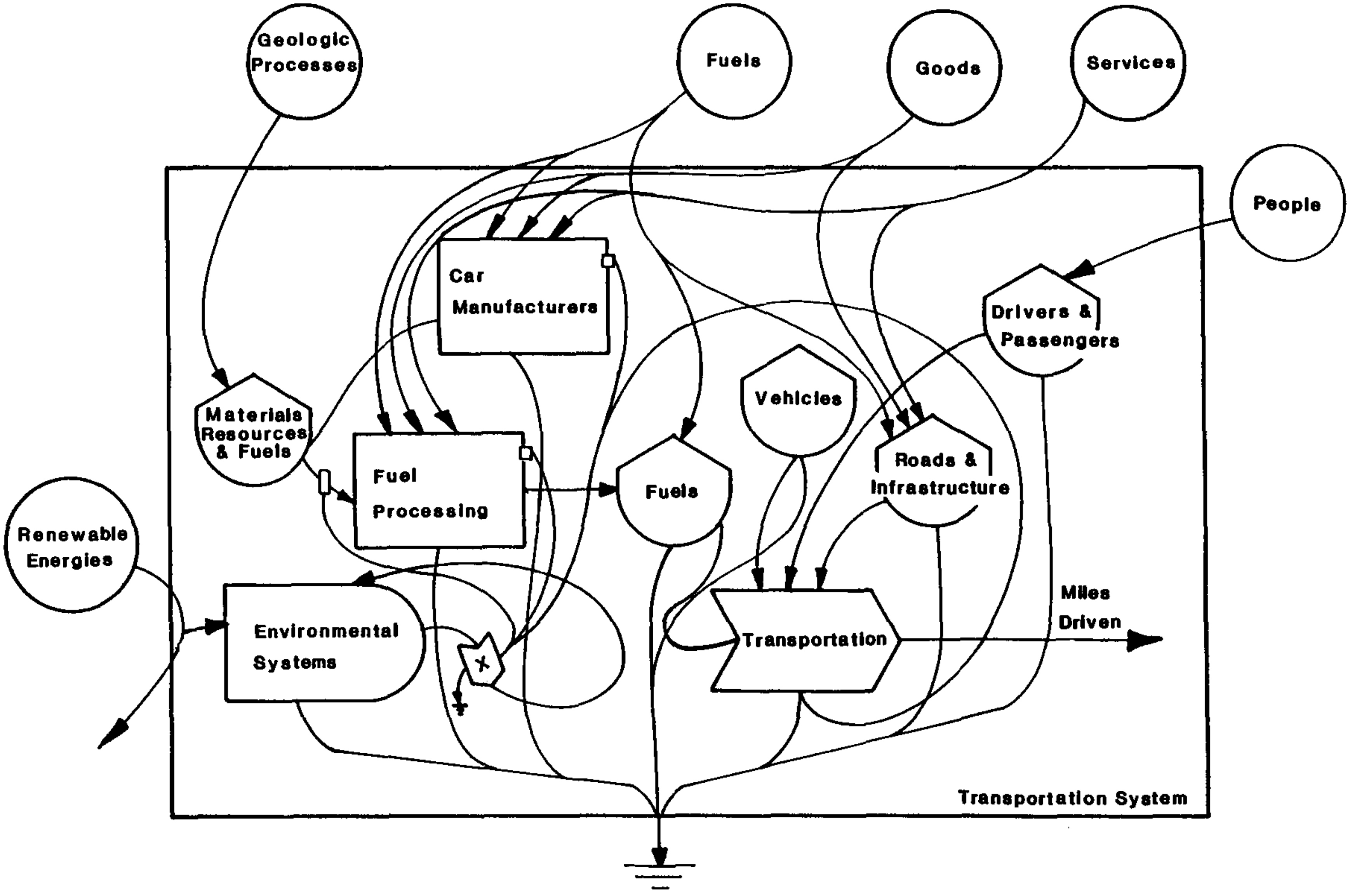
Evaluating Alternative Fuels and Systems for Transportation

Although determining the best transportation system involves the net EMERGY yield of the fuel to be used, transportation also requires vehicles, roads or rails, and people as well as fuels. To evaluate the EMERGY as well as the energy required for alternatives, both direct and indirect energy consumption were examined. Figure 3.2 is a diagram of the transportation system showing the inputs to transportation, including environment, fuel processing, vehicles, and infrastructure. the EMERGY of transportation was determined by evaluating these inputs. All of the energies were compared on a common basis--EMERGY, in solar emjoules (sej). EMERGY of vehicles was divided by their lifetime to obtain their yearly contribution. EMERGY of consumed fuel, services, vehicles modification, and materials were summed and compared between vehicle types. An overall index of transportation efficiency was the EMERGY required per mile driven, with the lowest values being best. That is, the best alternatives deliver the desired transport with the least inputs.

Figure 3.3 summarizes the ways of evaluating transportation fuels and systems. At each dashed, vertical line in the diagram, a net EMERGY analysis was made and EMERGY yield ratios were calculated. The EMERGY yield ratio is the ratio of the EMERGY yield at each dashed line (flow to the right--Y) to the EMERGY of resources, goods, and services consumed (flows to the left--I). See Chapter 1 for more detail.

Net EMERGY of alternative fuels was first evaluated at the point of production (Y_1 in Figure 3.3), and then a comparative analysis with conventional methods was done based on the EMERGY required per mile driven (Y_2 in figure 3.3). A complete analysis of transportation systems for comparison with alternative systems (i.e., comparisons of mass transit versus private automobiles) includes the EMERGY required for infrastructure. However, in these comparisons of alternative fuels, the EMERGY of infrastructure (roads, bridges, traffic devices, etc.) were assumed to be the same for each vehicle type driven.

For comparative purposes, the various alternative fuels were compared for a conventional vehicle (CV). This vehicle was a 4 passenger automobile, with an average fuel consumption of 30 miles per gallon. The electric vehicle (EV) evaluated had a projected range of slightly over 100 miles, and acceptable acceleration to highway speeds. The fuel-cell vehicle (FCV) was one of the few such vehicles that have actually been road tested, yet much of the data were estimated from



(a)

Figure 3.2 Energy systems diagram of a transportation systems showing inputs for fuels, vehicles, infrastructure, etc. (a) Main components and processes; (b) aggregate diagram with vertical dashed lines indicatin positions for calculation of net EMERGY ratios.

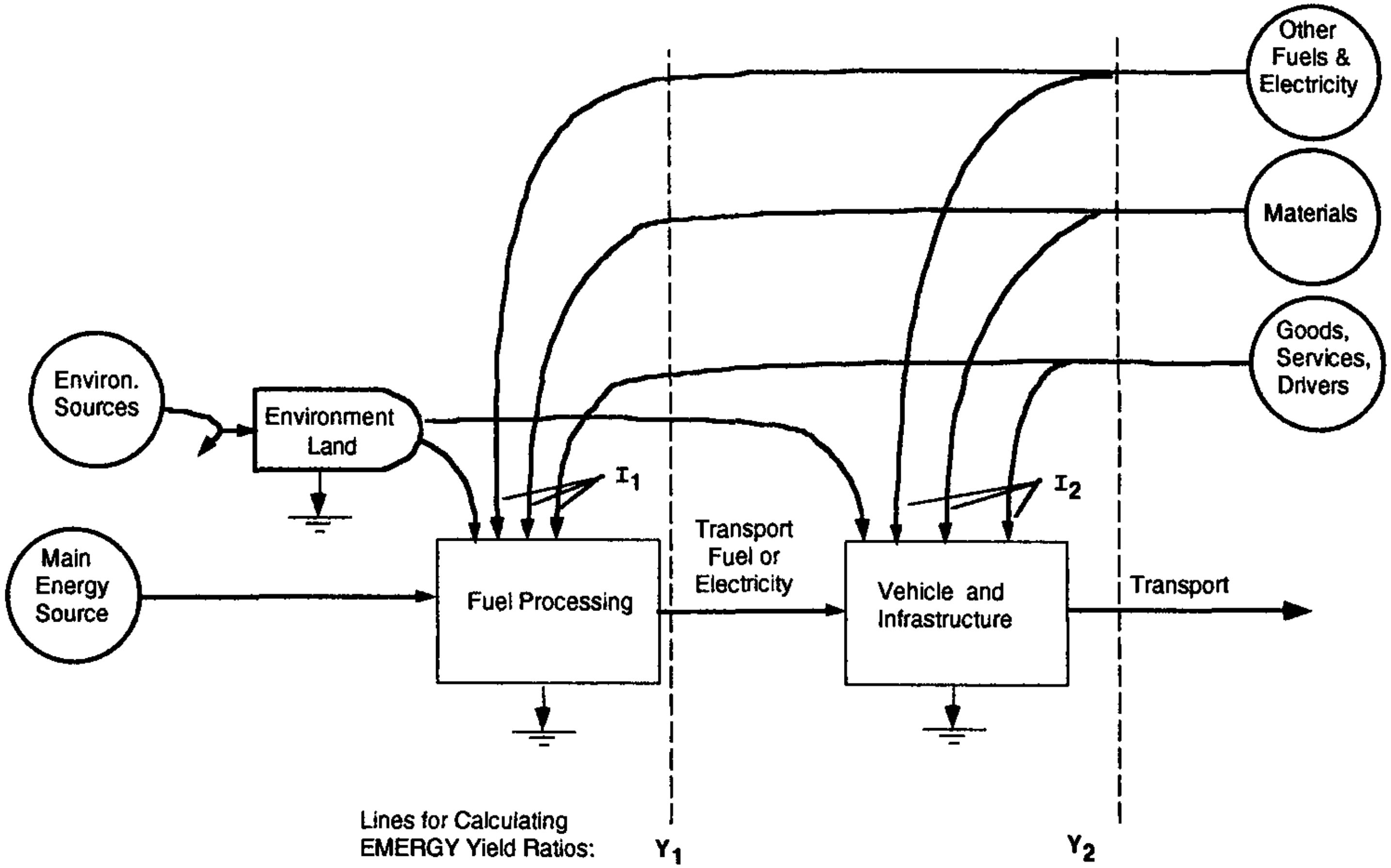


Figure 3.3 Aggregated systems diagram of transportation systems with vertical dashed lines indicating positions for calculation of EMERGY yield ratios.

several sources. To evaluate the compressed natural gas vehicle (CNGV), ethanol-fueled vehicle (E85), methanol-fueled vehicle (M85), and hydrogen-fueled, internal combustion engine vehicle (H_2), it was assumed they all were conventional vehicles that had been retrofitted with a fuel tank and different carburation as necessary to accommodate the alternative fuel type.

Results of Transportation Evaluations

Results of the EMERGY analyses for the various alternative transportation modes are given in Appendix Tables A.1 through A.7. Table 3.1 and Figure 3.4 summarize the evaluations, and compare the various fuel uses for transport on a per car basis. The conventional gasoline vehicle required 64.2 E15 sej over its lifetime, 64% of which was direct and indirect energy consumed in manufacturing and propelling the vehicle (46% of total EMERGY costs are gas and oil consumed directly in propulsion). The next lowest total EMERGY costs were for compressed natural gas and methanol.

Another way of expressing the input requirements and energy delivered is in terms of the EMERGY to travel a given distance. Efficiencies change as a result of the energy dispersed in friction due to the weights of vehicles, batteries and storage vessels. Figure 3.5 graphs the EMERGY per passenger mile for the different transportation alternatives. Considering all inputs, Metro Rail is the most efficient, since it uses the least amount of EMERGY per passenger mile.

Transformities of Alternative Transportation Fuels

Table 3.2 summarizes the transformities and EMERGY yield ratios for various fuels. The lowest transformity (best efficiency) was for natural gas, followed by gasoline and ethanol. EMERGY yield ratios were highest for oil and natural gas. These indices confirm the trend already underway to substitute natural gas for other fuels in transportation systems.

Comparing Energy and EMERGY Pathway Analysis

As introduced in Figure 2.3, energy systems involve chains of processes with many stages. Such diagrams show the pathway of successive energy conversions. With traditional pathway analysis, overall efficiencies may be estimated from data on the efficiencies of each transformation (Figure 2.3a). However, this method omits the goods, services, and controlling inputs whose energy flows are small, but whose embodied energy may be large. EMERGY evaluation of the same pathway was given in Figure 2.3c. From these numbers an overall transformity was calculated (Figure 2.3d), the "bottom line" of pathway efficiency.

Table 3.1. Comparison of Solar Emergy Required per Car
E15 solar emjoules/car

Fuel/Vehicle Type	Materials	Manufacture & Propulsion	Human Services	Total
Natural Gas	6.8	27.1	39.1	73
Gasoline	5.3	35.1	36.6	77
Methanol	5.5	30.8	47.8	84.1
Hydrogen	5.7	40.6	42.6	88.9
Electric	25.5	26.5	37.6	89.6
Ethanol	5.5	51.6	42.4	99.5
Fuel Cell	49.9	15.9	38.1	103.9

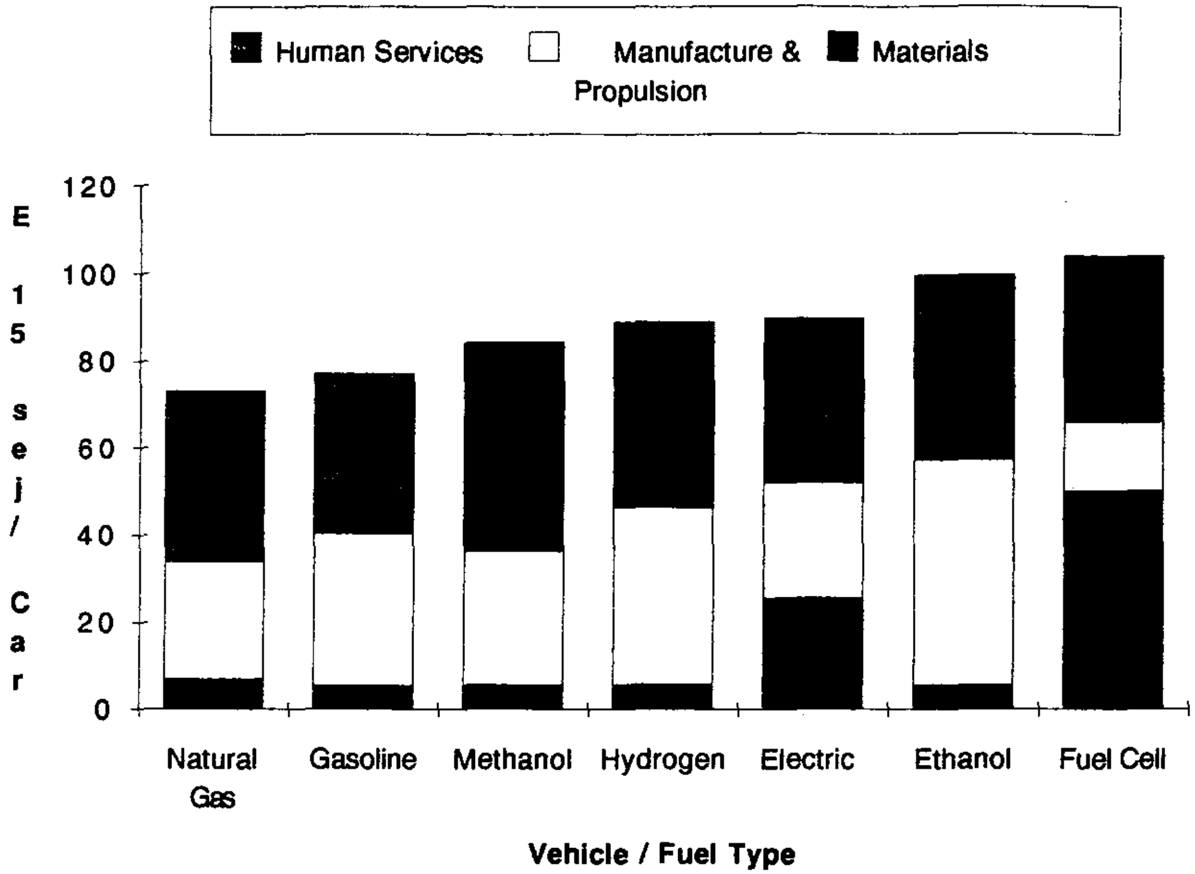


Figure 3.4. Comparison of the EMERGY requirements from manufacturing and propulsion, human services, and materials for alternative transportation systems.

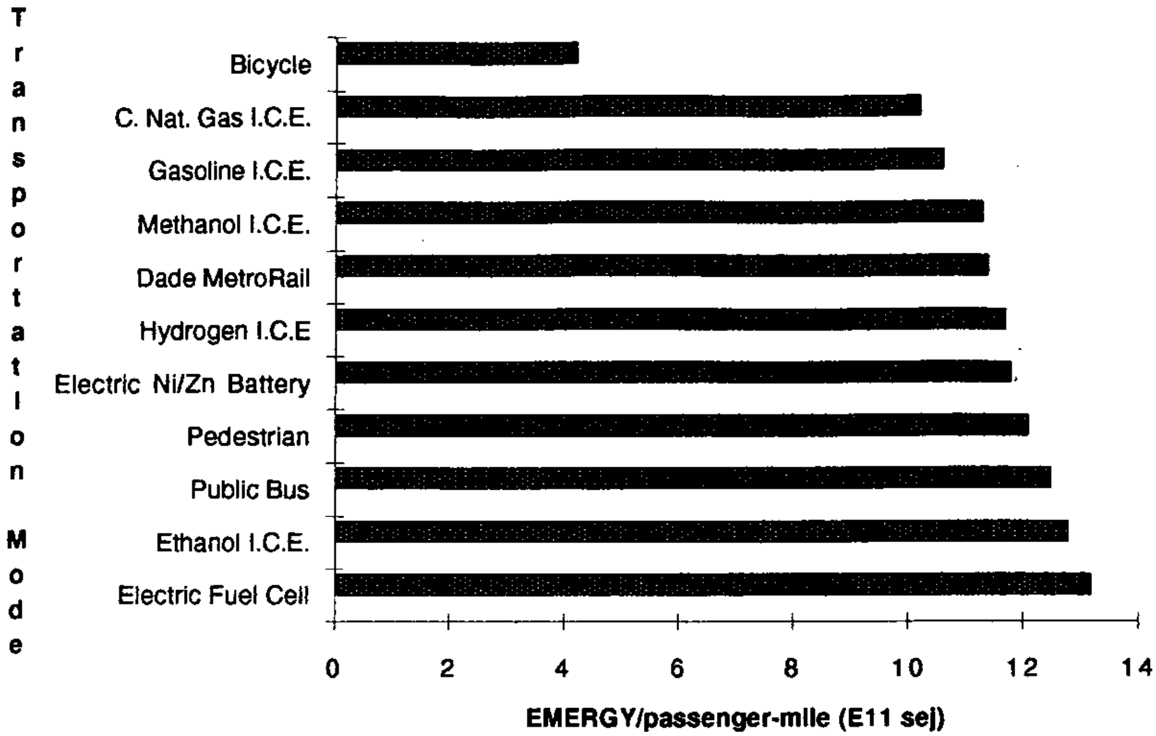


Figure 3.5. EMERGY per passenger-mile for alternative fuel transportation systems.

Table 3.2. Transformities and EMERGY Yield Ratios for Alternative Fuels

Fuel	Transformity (E 4 sej/J)	EMERGY Yield Ratio
1 Gasoline		
Alaskan North slope	6.4	13.3
Mid-East Oil @ $18/bbl	6.4	8.4
2 Natural Gas	4.8	6.8
3 Hydrogen		
from Natural Gas	7.63	4.5
from F. Fuel Elec. Generation	20.4	2.4
from Hydro-electric	11.06	4.9
from Nuclear Electric	20.4	4.7
from Photovoltaic Cells	6.9	0.4
4 Electricity		
Coal Power Plant	16.0	2.7
Wood Power Plant	20.3	2.6
From Methane	118.7	2.3
5 Ethanol	10.5	3.2
6 Biogas (Puerto Rico dairy wastes)	24.8	2.4
7 Ethyl Alcohol from Biomass	8.8	1.1

Notes to Table 3.2

1. Alaskan Oil from Brown et.al, 1993, mid east oil based on 6.11 E9 J/bbl, 20% refining and transportation costs, and emergy/money ratio of 1.2 E12 sej/$
2. Average of offshore and onshore Texas Natural Gas (King, 1991)
3. from Barbir, 1992
4. Coal & wood from Table 3.3;
5. This study
6. Methane from Appendix B
7. Odum et. al, 1986

Block (1993) provides an energy pathway analysis of fuel transportation alternative (see example in Figure 3.6a). In this analysis, efficiencies of energy conversion (given as percentages along the bottom line of Figure 3.6a) were used to determine the amount of primary energy required to produce "1000 units" of energy in vehicle propulsion. The energy pathway analysis shows that it requires 5638 crude oil Joules to produce 1000 Joules of vehicle propulsion. Pathway evaluation using EMERGY, including all inputs, is compared in Figure 3.5b. The EMERGY inputs come from two sources, in the fuels consumed (278 E8 sej) and the EMERGY in goods and services used (688.4 E6 sej). The total EMERGY required per 1000 Joules of vehicle propulsion is the sum of these two sources (966.4 E6 sej).

Table 3.3 contains the energy requirements for four transportation systems that were obtained using both energy pathway analysis (Block, 1993) and EMERGY pathway analysis. Energy pathway analysis expresses the numerator in energy units, treating energies of different kinds as if they were equal measures of work, while EMERGY analysis expresses the numerator in joules of one kind of energy required to deliver the transportation energy. Although the limitation is rarely stated, energy pathway analysis only includes energies of intermediate quality, those often considered under the group name "Exergy." To facilitate comparison, EMERGY evaluations in Table 3.3 are expressed in units of two kinds of EMERGY (solar EMERGY and coal EMERGY).

Energy pathway analysis indicates that the lowest ratio (presumably the most desirable) is the electric vehicle, followed by gasoline, fuel cell and natural gas. EMERGY analysis indicates that the lowest ratio is natural gas, followed by gasoline. Both the electric and fuel cell vehicles were highest, with approximately the same ratio. The two techniques give different results when vehicle and fuel types are compared with each other because EMERGY analysis includes the EMERGY costs of materials and services that are consumed indirectly in the production of the vehicle or fuel type. The evaluation of what is necessary to deliver a set amount of mechanical energy to the wheels should include all requirements, both direct and indirect (including, for example, those necessary to modify engines, add batteries, or add storage vessels).

Discussion of Alternative Fuels

Hydrogen

Hydrogen occurs as a gas with a molecule made of two hydrogen atoms (H_2). When burned with atmospheric oxygen, hydrogen gas has the most intense heat of all the fuels with 29.1

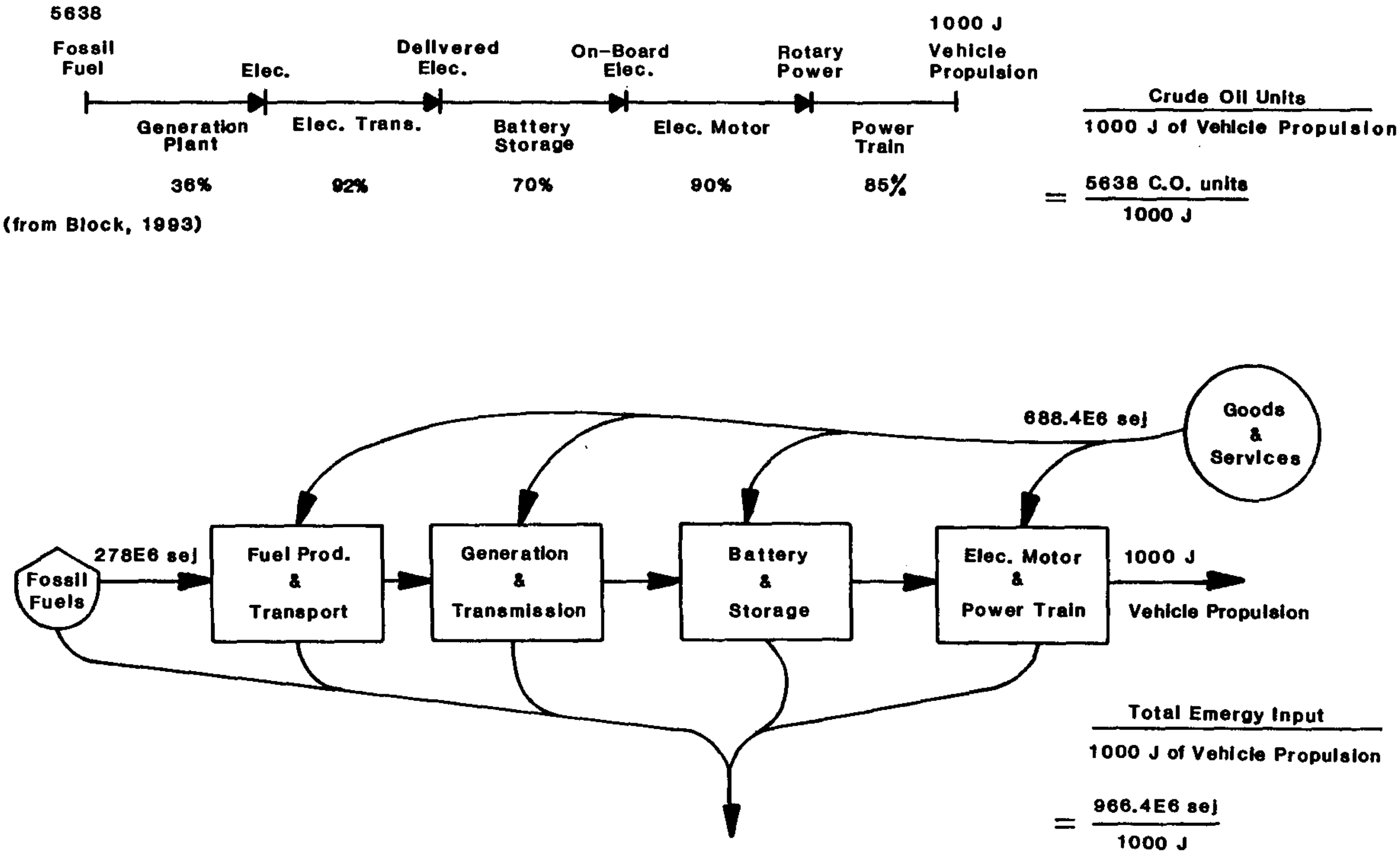


Figure 3.6. Comparison of methods of pathway analysis. (a) Energy analysis (Block, 1993); (b) EMERGY evaluation.

3.6

Table 3.3. Comparison of Methods of Pathway analysis

Note	Fuel/Vehicle Type	Ratio of Input Required to Output Delivered* Energy analysis	Emergy Analysis (sej/J)	(cej/J)
1.	Gasoline	9.7/1	9.9 E5/1	24.8/1
2.	Electricity	5.6/1	10.6 E5/1	26.5/1
3.	Natural Gas	12.7/1	7.6 E5/1	19/1
4.	Fuel Cell	11.9/1	10.6 E5/1	26.5/1

* Units of the ratio are as follows:
Energy analysis: (units of primary energy) / (unit of vehicle propulsion)
Emergy analysis: (Solar emjoules) / (Joule of propulsion)
(Coal emjoules) / (Joule of propulsion)

Notes to Table 3.3

1. Energy analysis includes refining and distribution losses, engine efficiency and power train efficiency from Block (1993)
   Emergy analysis includes solar energy cost of producing crude oil, emergy costs of refining and distribution, and efficiencies of engine and power train

2 Pathway analysis does not include the efficiencies of fossil fuel production If the efficiences used in the gasoline engine were used as the efficiency of producing and transporting fuel to a power plant, then the ratio would be about 7.0/1

3 In both cases, the engine type is an Internal Combustion engine

4 In both cases, the hydrogen for the fuel cell is derived from reforming natural gas

Calories per gram (121, 813 joules/gram). Compared with a gram of sugar (4 Calories per gram) its heat is intense. With an atomic weight of 1, hydrogen is also the lightest of all fuels. For these reasons, hydrogen is required for weight-dependent processes, such as sending rockets into space.

Hydrogen is the most abundant element in the Universe but in the earth biosphere it is rare as a gas for two reasons: (1) at the top of the atmosphere molecular collisions give hydrogen molecules (H_2) enough velocity to exceed that required to escape the earth's gravity, and (2) in the presence of sunlight or lightning, hydrogen combines with oxygen to form water.

Hydrogen is not a vapor at ordinary refrigerated temperatures, and must be compressed within heavy-walled containers to be stored. With a small, rapidly-moving molecule, hydrogen leaks from many containers and pipes more than other gases. Hydrogen can be dangerous as shown by the experience with fire in dirigibles. A compressed gas tank, at pressures of 3000 pounds per square inch or more, can be dangerous if its valve connections are broken, with the escaping gas driving the tank on an erratic path.

Hydrogen gas is among the alternative energy systems being considered for the future, when petroleum-based fuels are scarce and more expensive. How competitive would a hydrogen system be? Would it be energy conserving? Would it be economical? Should research initiatives and investment be made in hydrogen systems? A hydrogen system, including its sources and uses, was evaluated and compared with other alternative fuel sources and other uses of hydrogen, to see if hydrogen is a promising fuel alternative for the future.

At present, in the United States as in much of the world, reserves of natural gas are large. The net EMERGY contribution of such reserves is as large or larger than liquid petroleum, which means that natural gas is likely to continue to be economically competitive as a source of concentrated heat for industry, but locally dependent on the availability and investment in pipelines. Natural gas is being used increasingly for motor transport with government assisted programs in New Zealand, California, and Florida, for example. To use natural gas for fuel transportation, vehicles have to be fitted with compressed gas tanks and a system of gas recharging stations must be established. When and if natural gas becomes more important to vehicular transportation, as it already is for home heating and industry, the compressed gas infrastructure is likely to become more common. This system could be adapted to hydrogen if there is any net EMERGY advantage.

In the long run, proponents suggest that when natural gas supplies become scarce and expensive, hydrogen could be supplied from electric power sources, provided there are adequate electric sources. When the high net EMERGY fossil fuels are no longer available and prices are higher, fuel conservation measures will be greater and demand will be less.

Alternatives for Hydrogen Production and Use

There are several ways in which hydrogen can be concentrated for use as a fuel, including: separation from natural gas; by chemical processing from methane; and separation from water via electrolysis. Table 3.4 and Figure 3.7 summarize the EMERGY evaluations of 5 alternative methods for deriving hydrogen, and for comparison, an evaluation of natural gas as a transportation fuel source. The EMERGY yield ratios and transformities indicate which systems will be more important in the future. Evaluations of the 6 alternatives are given below.

Case 1. Natural gas. Natural gas can be drilled and supplied with EMERGY yield ratios in the range of 6/1 to 10/1, depending on transport distance. Figure 3.7a shows the net EMERGY yield for natural gas. Natural gas can be used in compressed tanks for vehicles, although this reduces the net EMERGY contribution by about half (approximately 3.4/1, according, to King's [1991] evaluation of its use in Texas busses). Since gasoline can currently be supplied to vehicles at a higher ratio, the natural gas compressed tank alternative will not be competitive until the general market price of liquid fuels rises. The rise in price reduces the EMERGY yield ratio of liquid fuels, causing the natural gas system to be more competitive as the net EMERGY of liquid fuels declines.

Case 2. Hydrogen produced from natural gas. Hydrogen can be produced from steam reforming of natural gas with a EMERGY yield ratio of 4.5/1 (Figure 3.7b). For general heating and motor transport, natural gas can suffice without the extra processing and additional costs that are necessary to derive hydrogen from it. Since natural gas has a higher EMERGY yield ratio than the hydrogen that is derived from it, it makes little sense to incur the additional energy costs to make a similar fuel for general heating or transportation.

Case 3. Hydrogen produced from electricity generated from fossil fuels. Hydrogen can be generated from water (H_2O) by electrolysis, which separates hydrogen from oxygen using electric power (Figure 3.7c). If the electric power is generated in a fossil fuel plant, the EMERGY yield ratio is about 2.4/1. Although this allows electric energy to be transformed into a form usable for moving vehicles, the EMERGY yield ratio is less than that of current fuels or natural gas. A better yield can be obtained by converting the coal, oil, or natural gas directly to motor fuel, with about a 60% or better conversion and a better net EMERGY yield.

Table 3.4. Transformity and Net EMERGY Yield Ratio of Hydrogen

Note	System	Solar transformity solar emjoules/Joule	Net EMERGY Yield Ratio
1	Natural gas	48,000	6.8
2	Hydrogen from Natural gas	76,300	4.5
3	Hydrogen from fossil fuel electric power plants	204,000	2.4
4	Hydrogen from hydropower	110,563	4.9
5	Hydrogen from nuclear power	203,956	4.7
6	Hydrogen from photovoltaic cells	69,000	1.007

1 Offshore natural gas in Texas (King 1992)

2 Steam reforming; EMERGY evaluation by Barbir (1992). Given the natural gas, the net EMERGY yield ratio of the conversion is 11.4, butif the net EMERGY yield ratio of the natural gas is 6.8, the combined feedbacks make the overall combined process of processing and transforming gas to be 4.5

3 Hydrogen production from electric power evaluated by Barbir (1992), given the electric power and using an electrical transformity from a coal power plant (160,000 sej/J). If coal fired net EMERGY yield ratio is 2.5, then the accumulated net EMERGY yield ratio is 2.4

4 Hydroelectric power evaluated with solar transformity of 85,437 and net EMERGY yield ratio 5.7

5 Requirements for conversion used in item #3 were combined with EMERGY analysis of U.S. Nuclear Fission power (Lapp, 1992). Transformity of Electric power used as that of fossil fuel plants, but net EMERGY yield ratio 4.9

6 Hydrogen from solar driven photovoltaic cells evaluated by Barbir (1992)

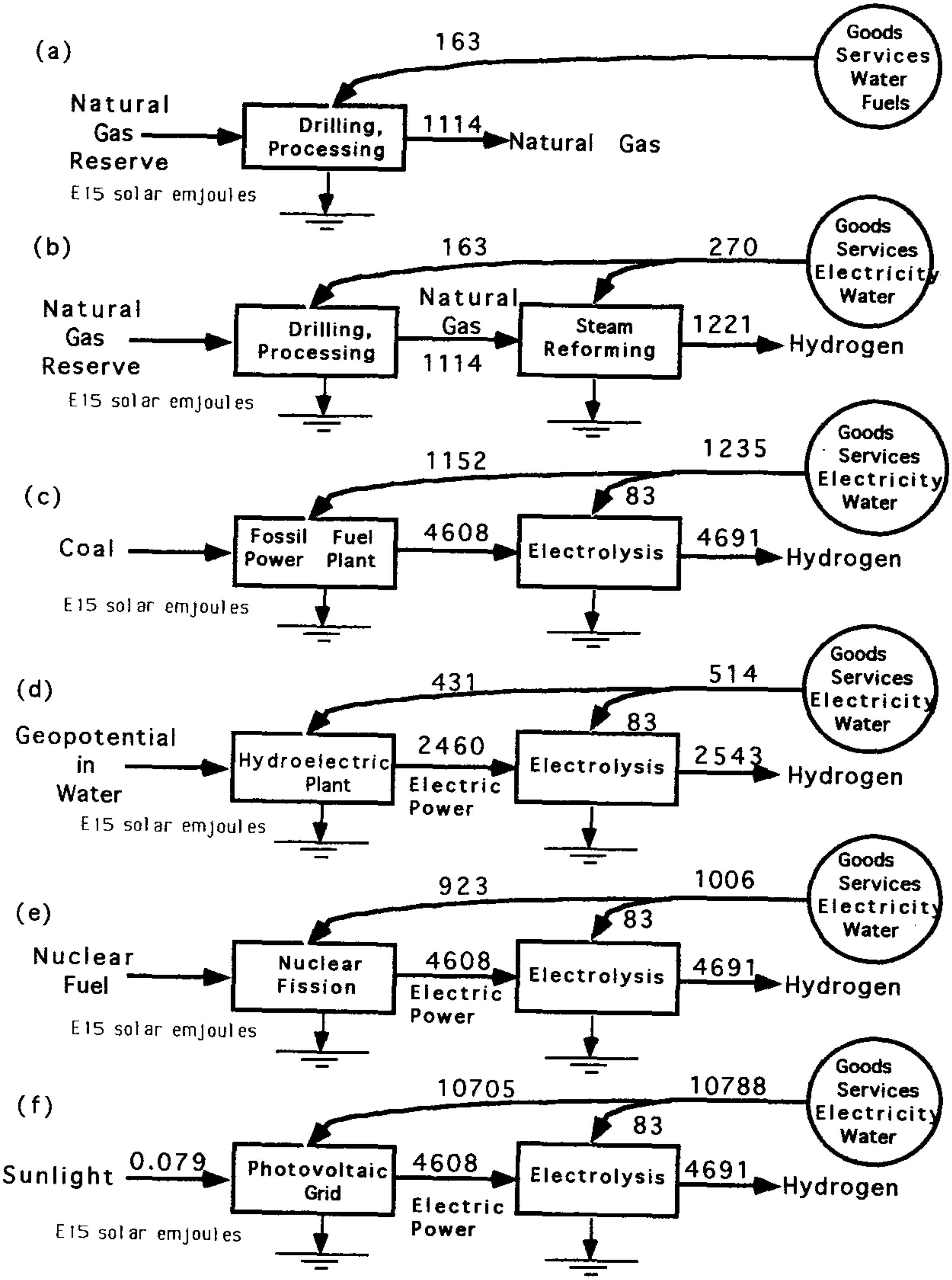


Figure 3.7 Summary diagrams of EMERGY evaluation of natural gas (a) and hydrogen (b-f) calculated in Table 3.4.

Case 4. Hydrogen produced from hydroelectric power. Hydrogen can be generated from water by electrolysis using hydroelectric power (Figure 3.7d). The EMERGY yield ratio (4.9/1) is lower than present fossil fuel alternatives for transport fuel, but has a much better yield ratio than some alternatives being proposed for fossil fuels that are less available (such as motor fuels from biomass). If EMERGY evaluations of hydroelectric power include the contributions of streams and rivers that are lost when a dam is built, a lower EMERGY yield ratio is found. However, there is little unutilized hydroelectric capacity in rivers of the United States. Because of its flat terrain, the potential for hydroelectric power in Florida is negligible.

Case 5. Hydrogen produced from nuclear power. Hydrogen can be produced by electrolysis from electricity generated by nuclear plants, and thus provides a way to harness nuclear energy to operate moving vehicles (Figure 3.7e). A recent EMERGY evaluation of U.S. nuclear fission power (Lapp, 1992) showed a EMERGY yield ratio of 4.9/1 and, when combined with the electrolysis process, yields an overall ratio for hydrogen production of 4.7/1. This could be competitive for motor transport after the fossil fuel period, for the years when high quality nuclear fission fuels are still available. However, large expansion of nuclear power in Florida would be necessary to provide the energy requirements for transportation, as well as household, commercial and industrial needs.

Case 6. Hydrogen from solar photovoltaic cells. Hydrogen can also be generated from electrolysis using electricity from photovoltaic cells that use direct sunlight (Figure 3.7f). However, the EMERGY yield ratio of solar voltaic systems is so low, there is no net EMERGY contribution to the economy (0.43/1). Making hydrogen from this electricity with additional input requirements makes the yield ratio even less. The ultimate reason for the poor conversion may be an inherent thermodynamic limit on converting dilute energy into a very concentrated one in a single step. After a billion years of evolution, green plants operate a chlorophyll solar voltaic cell which has higher conversion efficiencies, possibly representing the thermodynamic maximum conversion possible. This may be the ultimate limit for solar voltaic research. Appropriate comparison of chlorophyll with silicon cells evaluates the efficiency of both of these cases in the conversion of photons to displaced electrons.

Transformity of Hydrogen

In order to use the appropriate transformity principle to select the best energy alternatives, the best (lowest) transformity which is possible for each fuel must be established. The ultimate thermodynamic limit to the efficiency for generating hydrogen in open systems operating at maximum power is not yet known. Data on some solar transformities found for hydrogen are shown in Table 3.4. These include processes where there are unnecessary long sets of transformations which, as a result, are less efficient (higher than the minimum transformity). Although more examples need to be evaluated, one may infer from data available so far that the best possible transformity for hydrogen is higher than fossil fuels and less than electric power. If this is valid, then the methods that depend on electric power are wasteful and alternatives that can generate motor fuels more directly are likely to be more competitive economically. Where hydrogen can be made with a lower transformity than electricity, it can be used for more general heating purposes and to make electricity. If the solar transformity of hydrogen was higher than electricity--which is what is obtained when hydrogen is made from electrolysis of water--then it would not generally make economic or energetic sense to use hydrogen for lower transformity purposes such as heating and other current uses of electric power.

Since electric power generates hydrogen, the transformity of hydrogen calculated from this process (Table 3.4) is higher than that of electricity (Table 2.1). And since the reverse process can also be arranged, electricity can be generated from hydrogen (and oxygen). Barbir (1992) raises the question as to which has the higher transformity--hydrogen gas or electric power--when the most efficient chain of processes is used. This is a critical questioning energy conservation. Since energy is dispersed in each transformation, energy should net be transformed any more times than is necessary to accomplish a purpose.

In other words, if hydrogen is necessarily higher in the transformity scale than electricity, then its use can be justified only for very special purposes for which electricity is not adequate. If the transformity of hydrogen is lower than electricity, then it may be substituted for some processes, providing the net EMERGY yield is competitive. Tables 2.1 and 3.4 summarize the solar transformities of hydrogen and electric power as calculated for several processes.

An as yet to be determined effect is the pollution caused by each alternative, and the resulting energy costs for cleanup and the loss of natural and agricultural productivity. These effects could alter the results of the analysis. The electric vehicle system would act more as a point source of pollution (the electric power plant outlet), and may be easier to clean up. On the other hand, conventional vehicles act as non-point sources of pollution. In either case, the costs of pollution abatement could be substantial. Their pollution would probably be impossible to clean up to the same degree as a point source, and environmental impacts would have to be tabulated for both cases. The general question is whether it is more cost effective to concentrate or dilute pollution, since the earth must ultimately assimilate the pollution. For a complete analysis, environmental impacts should be considered as well.

3. EMERGY Evaluation of Alternative Fuels for Transportation

H.T. Odum, G.G. McGrane, M.T. Brown, and S. Bastianoni

Good fuel policy is based on a knowledge of which sources are most efficient in supplying energy to maximize economic vitality. Plans are successful that develop those sources which will be competitive in free markets. Fuels which will be successful as primary energy sources and which should be given priority are those with the highest EMERGY yield ratios, and which generate the needed transportation with the lowest transformity (highest efficiency considering all inputs). Recommendations in this chapter are based on EMERY yield ratios and transformities, which were determined from the EMERGY evaluation of alternative fuels and systems for transportation

Rationale for comparisons and suggestions related to most favorable alternative fuel sources are based on the assumption that the fuels that contribute most to an economy are the ones with the greatest net EMERGY yield. These are the ones that contribute the most, compared to what is required from the economy for fuel processing and distribution. The EMERGY yield ratio measures the net contribution of a fuel. Figure 3.1 shows recently determined EMERGY yield ratios for several primary fuels and alternative sources. Fuels with high EMERGY yield ratios also provide more energy per unit of carbon dioxide released to the atmosphere.

When fuels are abundant and close to the surface so that mining is cheap, EMERGY yield ratios are high. When primary fuel sources have high EMERGY yield ratios, economies are prosperous. Before 1973, with prices of oil and gas very low, developed economies were purchasing fuels from the Middle East with EMERGY yields 40 to 60 times more than the EMERGY in the buying power of their payments. In other words, 40 to 60 times more wealth was generated in the economy by the fuels than was required for their processing. Since 1973, world prices have increased. EMERGY ratios for purchases of foreign oil declined, ranging between 3/1 and 12/1. Fossil fuels bought on markets in 1993 give the purchasers a EMERGY yield ratio on the order of 10/1.

The EMERGY yield ratios for the energy sources in Figure 3.1 vary from more than 13 /1 for Alaskan north slope oil, to palm oil having a net yield just barely above break-even (1.06/1). For the most part, energy sources with infra-structure for their distribution and use have yields between 13/1 and 3/1. With declining ratios, and therefore less available energy to support growth and luxury consumption, most of the world is exhibiting slower growth (some would say stagnant growth rates) than was characteristic in the period from 1950 to 1973. For growth rates to resume, we believe that primary fuel sources must have EMERGY yield ratios much higher than is

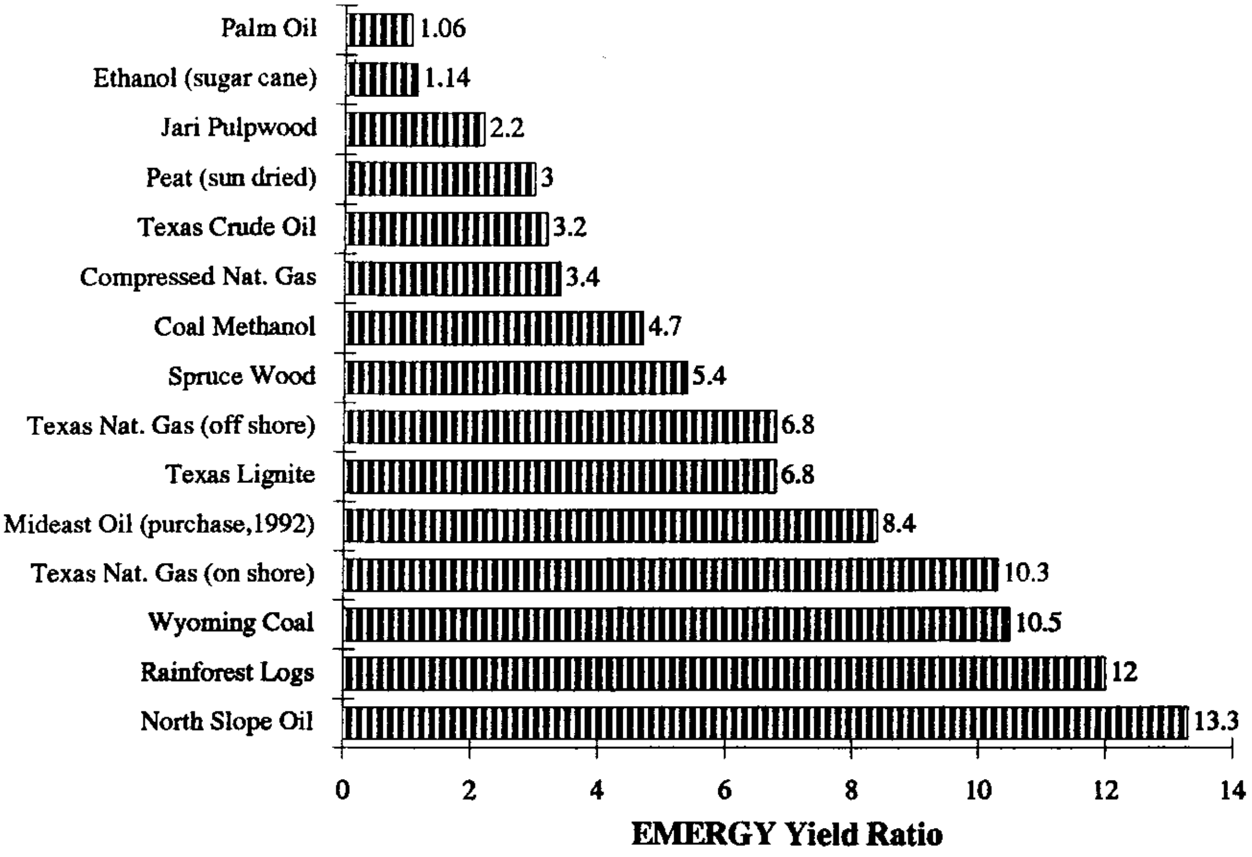


Figure 3.1. Net EMERGY evaluation of fuels. Rain forest logs (Odum et al., 1982); north slope oil (Brown,1993); Wyoming coal (Ballentine, 1976); Texas natural gas onshore, offshore, coal methanol, compressed natural gas, Texas crude oil (King,1992); oil purhase, Texas lignite (Odum, Odum, and Blissett, 1987); Jari pulpwood, palm oil (Odum, Brown, and Christianson, 1986); spruce wood (Doherty, Nilsson and Odum, 1992).

characteristic of most present sources. Alternative fuel sources should have high EMERGY yield ratios equal to or better than current primary sources, if they are to be net contributors to the economy.

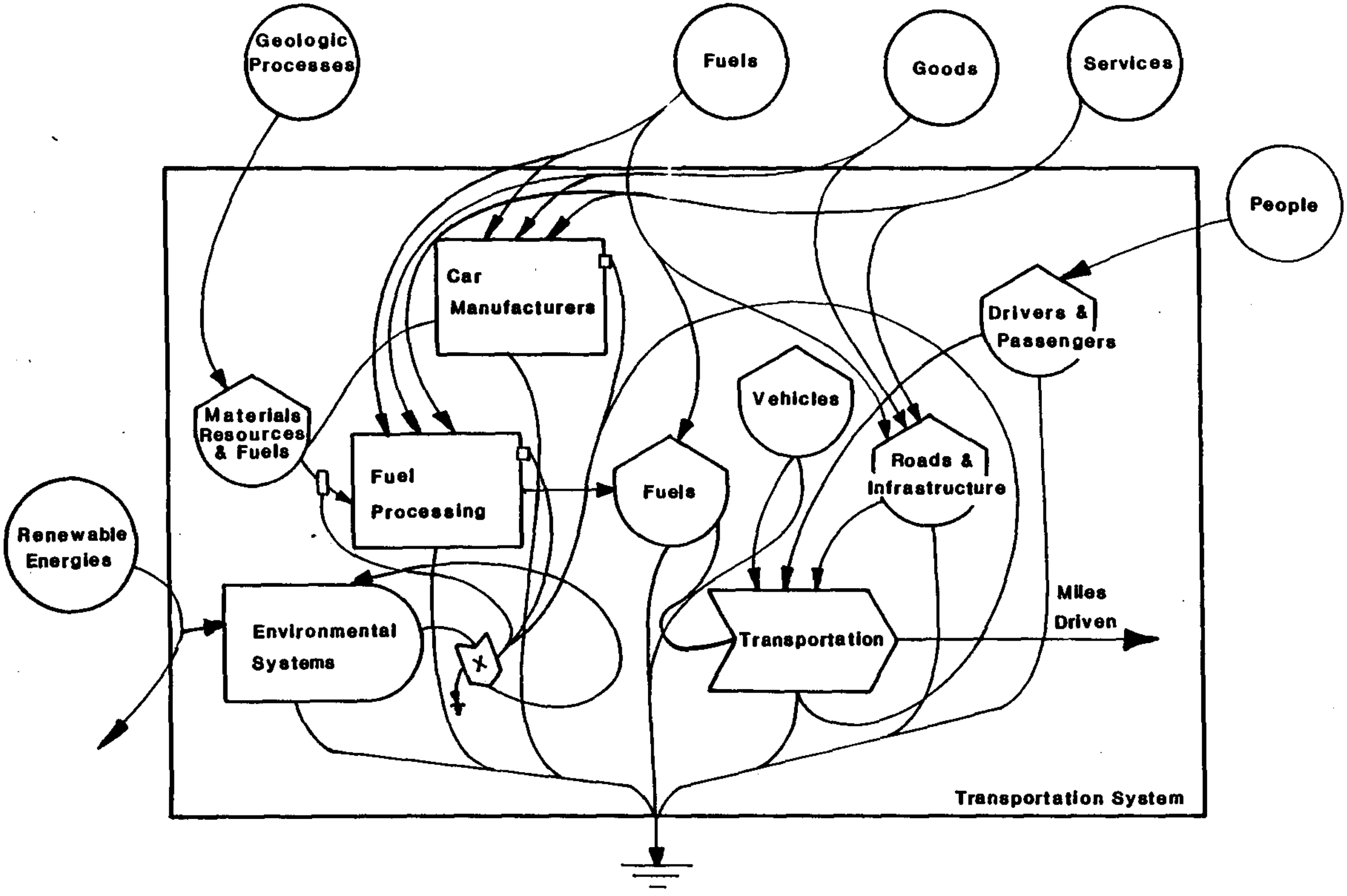
Evaluating Alternative Fuels and Systems for Transportation

Although determining the best transportation system involves the net EMERGY yield of the fuel to be used, transportation also requires vehicles, roads or rails, and people as well as fuels. To evaluate the EMERGY as well as the energy required for alternatives, both direct and indirect energy consumption were examined. Figure 3.2 is a diagram of the transportation system showing the inputs to transportation, including environment, fuel processing, vehicles, and infrastructure. the EMERGY of transportation was determined by evaluating these inputs. All of the energies were compared on a common basis--EMERGY, in solar emjoules (sej). EMERGY of vehicles was divided by their lifetime to obtain their yearly contribution. EMERGY of consumed fuel, services, vehicles modification, and materials were summed and compared between vehicle types. An overall index of transportation efficiency was the EMERGY required per mile driven, with the lowest values being best. That is, the best alternatives deliver the desired transport with the least inputs.

Figure 3.3 summarizes the ways of evaluating transportation fuels and systems. At each dashed, vertical line in the diagram, a net EMERGY analysis was made and EMERGY yield ratios were calculated. The EMERGY yield ratio is the ratio of the EMERGY yield at each dashed line (flow to the right--Y) to the EMERGY of resources, goods, and services consumed (flows to the left--I). See Chapter 1 for more detail.

Net EMERGY of alternative fuels was first evaluated at the point of production (Y_1 in Figure 3.3), and then a comparative analysis with conventional methods was done based on the EMERGY required per mile driven (Y_2 in figure 3.3). A complete analysis of transportation systems for comparison with alternative systems (i.e., comparisons of mass transit versus private automobiles) includes the EMERGY required for infrastructure. However, in these comparisons of alternative fuels, the EMERGY of infrastructure (roads, bridges, traffic devices, etc.) were assumed to be the same for each vehicle type driven.

For comparative purposes, the various alternative fuels were compared for a conventional vehicle (CV). This vehicle was a 4 passenger automobile, with an average fuel consumption of 30 miles per gallon. The electric vehicle (EV) evaluated had a projected range of slightly over 100 miles, and acceptable acceleration to highway speeds. The fuel-cell vehicle (FCV) was one of the few such vehicles that have actually been road tested, yet much of the data were estimated from



(a)

Figure 3.2 Energy systems diagram of a transportation systems showing inputs for fuels, vehicles, infrastructure, etc. (a) Main components and processes; (b) aggregate diagram with vertical dashed lines indicatin positions for calculation of net EMERGY ratios.

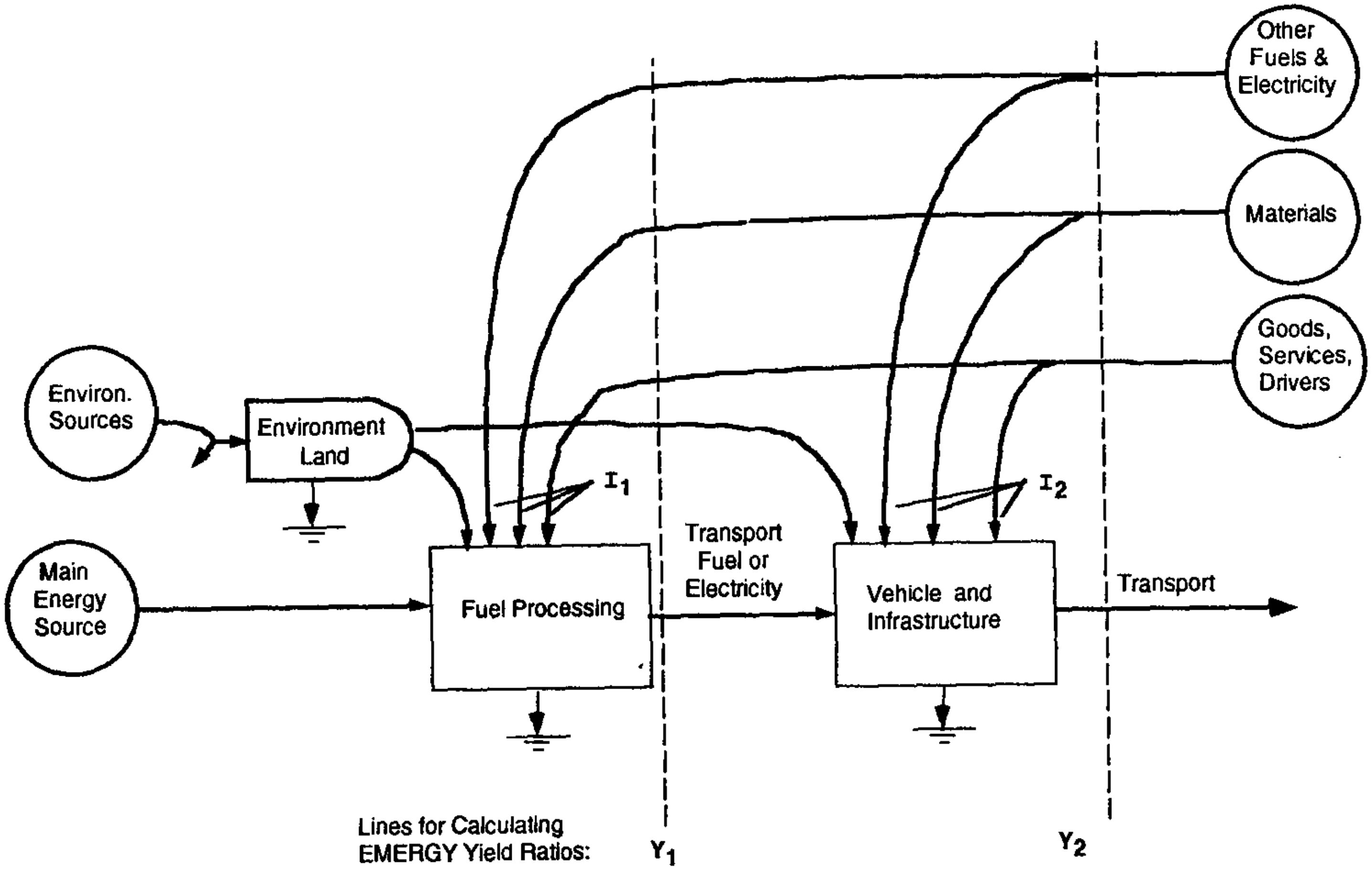


Figure 3.3 Aggregated systems diagram of transportation systems with vertical dashed lines indicating positions for calculation of EMERGY yield ratios.

several sources. To evaluate the compressed natural gas vehicle (CNGV), ethanol-fueled vehicle (E85), methanol-fueled vehicle (M85), and hydrogen-fueled, internal combustion engine vehicle (H_2), it was assumed they all were conventional vehicles that had been retrofitted with a fuel tank and different carburation as necessary to accommodate the alternative fuel type.

Results of Transportation Evaluations

Results of the EMERGY analyses for the various alternative transportation modes are given in Appendix Tables A.1 through A.7. Table 3.1 and Figure 3.4 summarize the evaluations, and compare the various fuel uses for transport on a per car basis. The conventional gasoline vehicle required 64.2 E15 sej over its lifetime, 64% of which was direct and indirect energy consumed in manufacturing and propelling the vehicle (46% of total EMERGY costs are gas and oil consumed directly in propulsion). The next lowest total EMERGY costs were for compressed natural gas and methanol.

Another way of expressing the input requirements and energy delivered is in terms of the EMERGY to travel a given distance. Efficiencies change as a result of the energy dispersed in friction due to the weights of vehicles, batteries and storage vessels. Figure 3.5 graphs the EMERGY per passenger mile for the different transportation alternatives. Considering all inputs, Metro Rail is the most efficient, since it uses the least amount of EMERGY per passenger mile.

Transformities of Alternative Transportation Fuels

Table 3.2 summarizes the transformities and EMERGY yield ratios for various fuels. The lowest transformity (best efficiency) was for natural gas, followed by gasoline and ethanol. EMERGY yield ratios were highest for oil and natural gas. These indices confirm the trend already underway to substitute natural gas for other fuels in transportation systems.

Comparing Energy and EMERGY Pathway Analysis

As introduced in Figure 2.3, energy systems involve chains of processes with many stages. Such diagrams show the pathway of successive energy conversions. With traditional pathway analysis, overall efficiencies may be estimated from data on the efficiencies of each transformation (Figure 2.3a). However, this method omits the goods, services, and controlling inputs whose energy flows are small, but whose embodied energy may be large. EMERGY evaluation of the same pathway was given in Figure 2.3c. From these numbers an overall transformity was calculated (Figure 2.3d), the "bottom line" of pathway efficiency.

Table 3.1. Comparison of Solar Emergy Required per Car
E15 solar emjoules/car

Fuel/Vehicle Type	Materials	Manufacture & Propulsion	Human Services	Total
Natural Gas	6.8	27.1	39.1	73
Gasoline	5.3	35.1	36.6	77
Methanol	5.5	30.8	47.8	84.1
Hydrogen	5.7	40.6	42.6	88.9
Electric	25.5	26.5	37.6	89.6
Ethanol	5.5	51.6	42.4	99.5
Fuel Cell	49.9	15.9	38.1	103.9

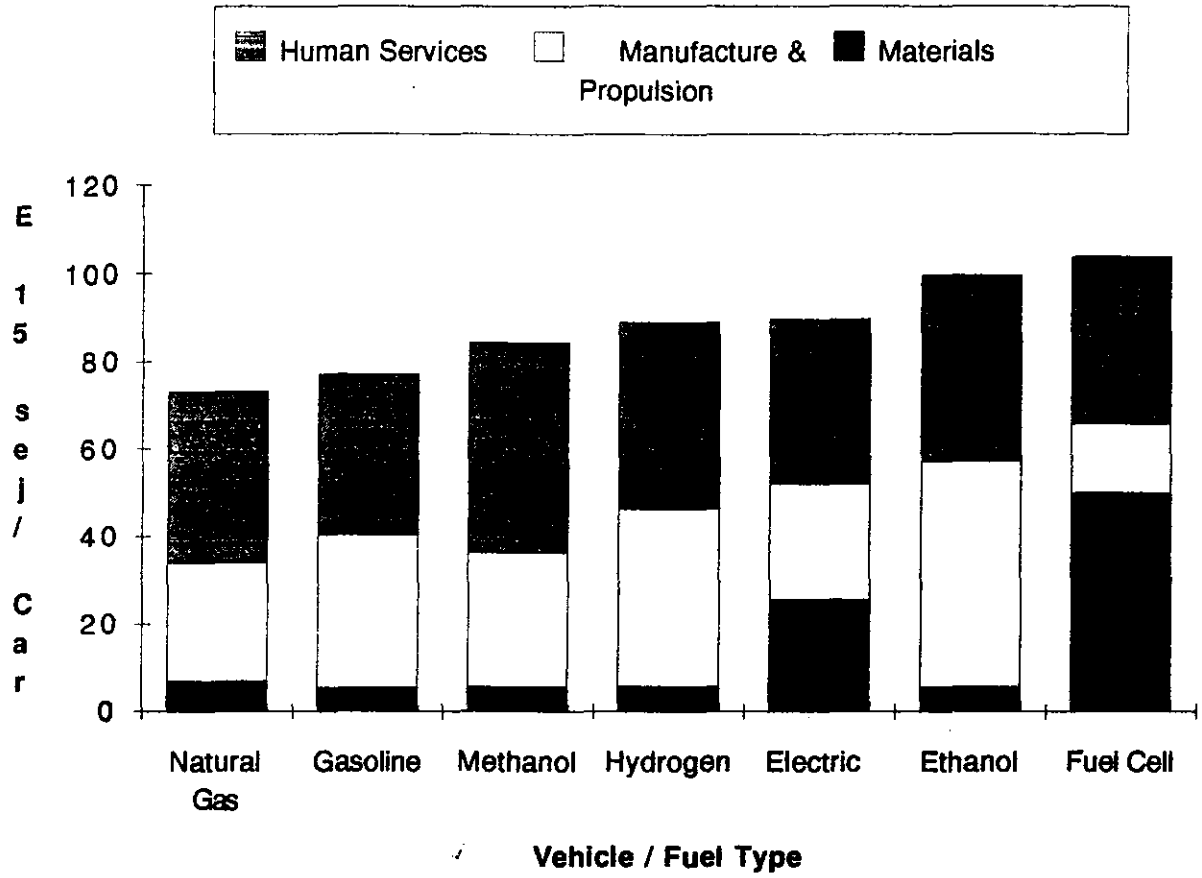


Figure 3.4. Comparison of the EMERGY requirements from manufacturing and propulsion, human services, and materials for alternative transportation systems.

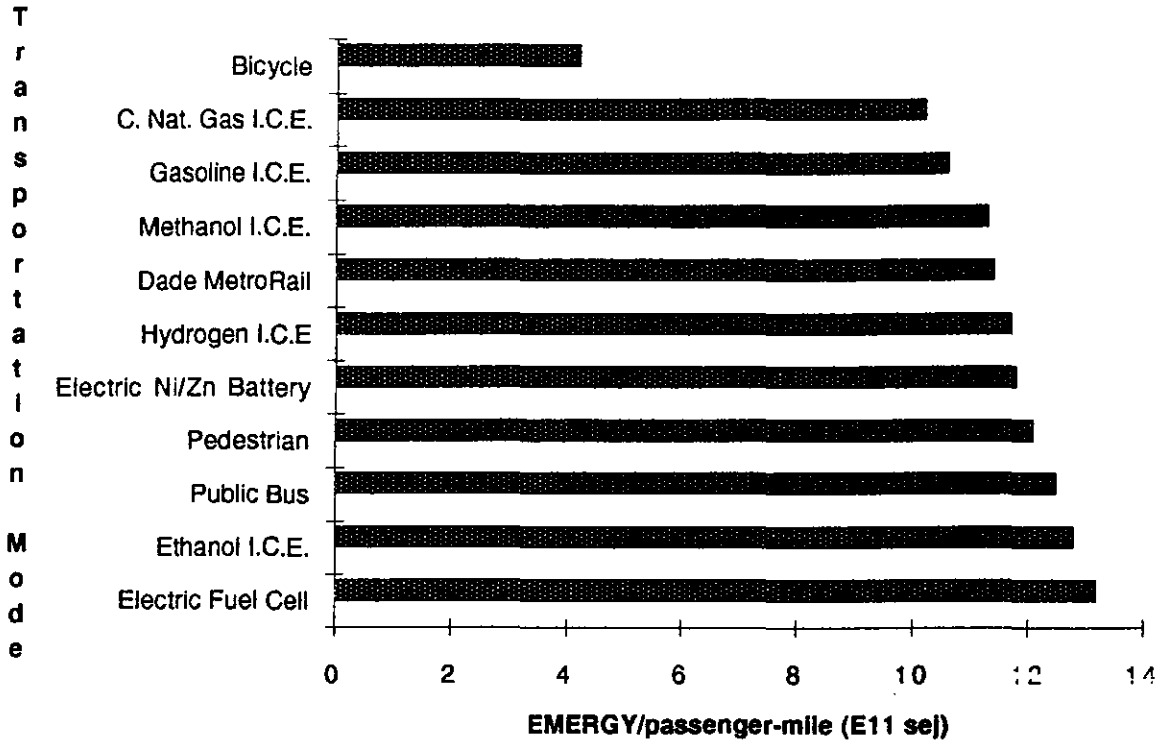


Figure 3.5. EMERGY per passenger-mile for alternative fuel transportation systems.

Table 3.2. Transformities and EMERGY Yield Ratios for Alternative Fuels

Fuel	Transformity (E 4 sej/J)	EMERGY Yield Ratio
1 Gasoline		
Alaskan North slope	6.4	13.3
Mid-East Oil @ $18/bbl	6.4	8.4
2 Natural Gas	4.8	6.8
3 Hydrogen		
from Natural Gas	7.63	4.5
from F. Fuel Elec. Generation	20.4	2.4
from Hydro-electric	11.06	4.9
from Nuclear Electric	20.4	4.7
from Photovoltaic Cells	6.9	0.4
4 Electricity		
Coal Power Plant	16.0	2.7
Wood Power Plant	20.3	2.6
From Methane	118.7	2.3
5 Ethanol	10.5	3.2
6 Biogas (Puerto Rico dairy wastes)	24.8	2.4
7 Ethyl Alcohol from Biomass	8.8	1.1

Notes to Table 3.2

1. Alaskan Oil from Brown et.al, 1993, mid east oil based on 6.11 E9 J/bbl, 20% refining and transportation costs, and emergy/money ratio of 1.2 E12 sej/$
2. Average of offshore and onshore Texas Natural Gas (King, 1991)
3. from Barbir, 1992
4. Coal & wood from Table 3.3;
5. This study
6. Methane from Appendix B
7. Odum et. al, 1986

Block (1993) provides an energy pathway analysis of fuel transportation alternative (see example in Figure 3.6a). In this analysis, efficiencies of energy conversion (given as percentages along the bottom line of Figure 3.6a) were used to determine the amount of primary energy required to produce "1000 units" of energy in vehicle propulsion. The energy pathway analysis shows that it requires 5638 crude oil Joules to produce 1000 Joules of vehicle propulsion. Pathway evaluation using EMERGY, including all inputs, is compared in Figure 3.5b. The EMERGY inputs come from two sources, in the fuels consumed (278 E8 sej) and the EMERGY in goods and services used (688.4 E6 sej). The total EMERGY required per 1000 Joules of vehicle propulsion is the sum of these two sources (966.4 E6 sej).

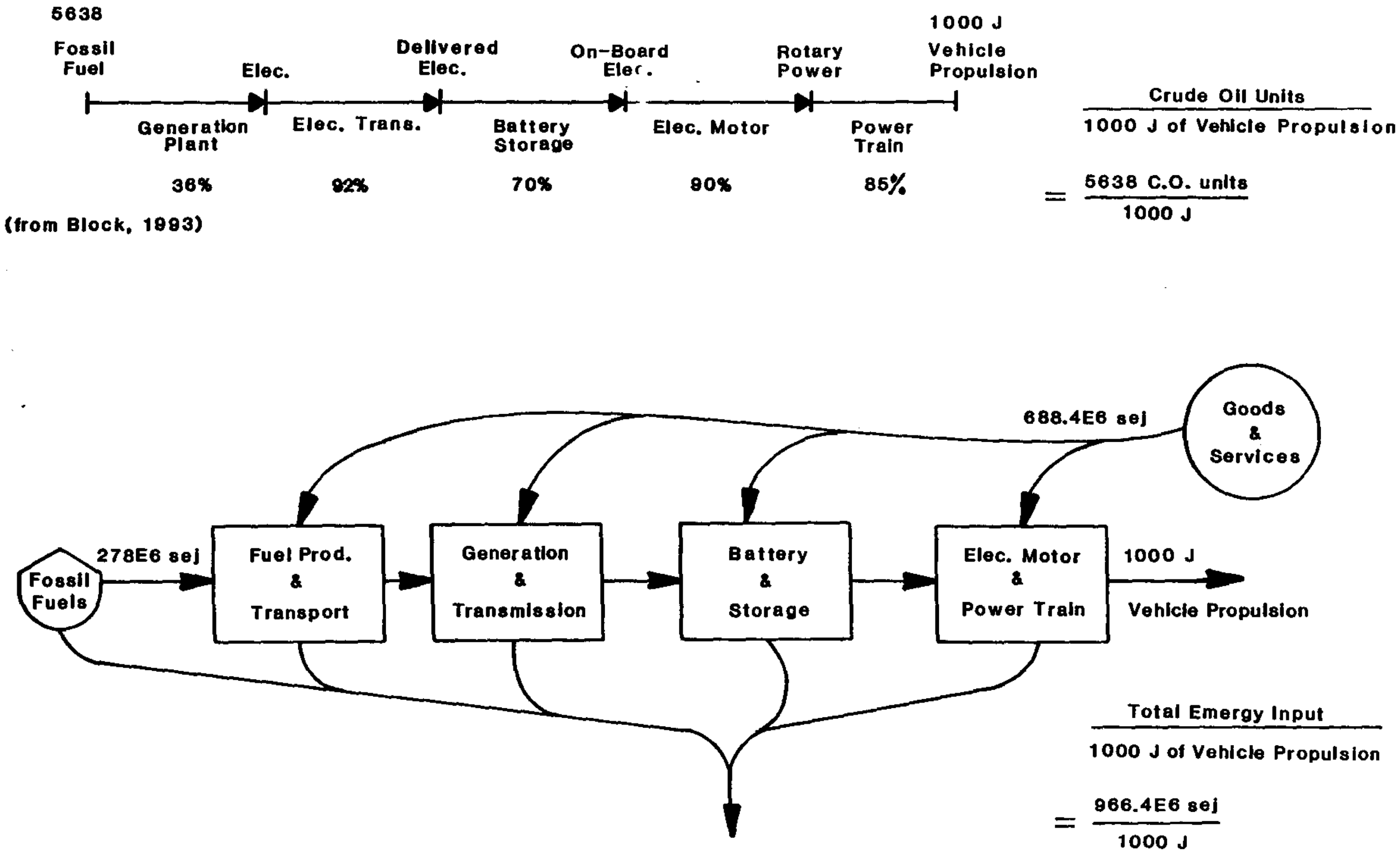
Table 3.3 contains the energy requirements for four transportation systems that were obtained using both energy pathway analysis (Block, 1993) and EMERGY pathway analysis. Energy pathway analysis expresses the numerator in energy units, treating energies of different kinds as if they were equal measures of work, while EMERGY analysis expresses the numerator in joules of one kind of energy required to deliver the transportation energy. Although the limitation is rarely stated, energy pathway analysis only includes energies of intermediate quality, those often considered under the group name "Exergy." To facilitate comparison, EMERGY evaluations in Table 3.3 are expressed in units of two kinds of EMERGY (solar EMERGY and coal EMERGY).

Energy pathway analysis indicates that the lowest ratio (presumably the most desirable) is the electric vehicle, followed by gasoline, fuel cell and natural gas. EMERGY analysis indicates that the lowest ratio is natural gas, followed by gasoline. Both the electric and fuel cell vehicles were highest, with approximately the same ratio. The two techniques give different results when vehicle and fuel types are compared with each other because EMERGY analysis includes the EMERGY costs of materials and services that are consumed indirectly in the production of the vehicle or fuel type. The evaluation of what is necessary to deliver a set amount of mechanical energy to the wheels should include all requirements, both direct and indirect (including, for example, those necessary to modify engines, add batteries, or add storage vessels).

Discussion of Alternative Fuels

Hydrogen

Hydrogen occurs as a gas with a molecule made of two hydrogen atoms (H_2). When burned with atmospheric oxygen, hydrogen gas has the most intense heat of all the fuels with 29.1



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In the long run, proponents suggest that when natural gas supplies become scarce and expensive, hydrogen could be supplied from electric power sources, provided there are adequate electric sources. When the high net EMERGY fossil fuels are no longer available and prices are higher, fuel conservation measures will be greater and demand will be less.

Alternatives for Hydrogen Production and Use

There are several ways in which hydrogen can be concentrated for use as a fuel, including: separation from natural gas; by chemical processing from methane; and separation from water via electrolysis. Table 3.4 and Figure 3.7 summarize the EMERGY evaluations of 5 alternative methods for deriving hydrogen, and for comparison, an evaluation of natural gas as a transportation fuel source. The EMERGY yield ratios and transformities indicate which systems will be more important in the future. Evaluations of the 6 alternatives are given below.

Case 1. Natural gas. Natural gas can be drilled and supplied with EMERGY yield ratios in the range of 6/1 to 10/1, depending on transport distance. Figure 3.7a shows the net EMERGY yield for natural gas. Natural gas can be used in compressed tanks for vehicles, although this reduces the net EMERGY contribution by about half (approximately 3.4/1, according, to King's [1991] evaluation of its use in Texas busses). Since gasoline can currently be supplied to vehicles at a higher ratio, the natural gas compressed tank alternative will not be competitive until the general market price of liquid fuels rises. The rise in price reduces the EMERGY yield ratio of liquid fuels, causing the natural gas system to be more competitive as the net EMERGY of liquid fuels declines.

Case 2. Hydrogen produced from natural gas. Hydrogen can be produced from steam reforming of natural gas with a EMERGY yield ratio of 4.5/1 (Figure 3.7b). For general heating and motor transport, natural gas can suffice without the extra processing and additional costs that are necessary to derive hydrogen from it. Since natural gas has a higher EMERGY yield ratio than the hydrogen that is derived from it, it makes little sense to incur the additional energy costs to make a similar fuel for general heating or transportation.

Case 3. Hydrogen produced from electricity generated from fossil fuels. Hydrogen can be generated from water (H_2O) by electrolysis, which separates hydrogen from oxygen using electric power (Figure 3.7c). If the electric power is generated in a fossil fuel plant, the EMERGY yield ratio is about 2.4/1. Although this allows electric energy to be transformed into a form usable for moving vehicles, the EMERGY yield ratio is less than that of current fuels or natural gas. A better yield can be obtained by converting the coal, oil, or natural gas directly to motor fuel, with about a 60% or better conversion and a better net EMERGY yield.

Table 3.4. Transformity and Net EMERGY Yield Ratio of Hydrogen

Note	System	Solar transformity solar emjoules/Joule	Net EMERGY Yield Ratio
1	Natural gas	48,000	6.8
2	Hydrogen from Natural gas	76,300	4.5
3	Hydrogen from fossil fuel electric power plants	204,000	2.4
4	Hydrogen from hydropower	110,563	4.9
5	Hydrogen from nuclear power	203,956	4.7
6	Hydrogen from photovoltaic cells	69,000	1.007

1 Offshore natural gas in Texas (King 1992)

2 Steam reforming; EMERGY evaluation by Barbir (1992). Given the natural gas, the net EMERGY yield ratio of the conversion is 11.4, butif the net EMERGY yield ratio of the natural gas is 6.8, the combined feedbacks make the overall combined process of processing and transforming gas to be 4.5

3 Hydrogen production from electric power evaluated by Barbir (1992), given the electric power and using an electrical transformity from a coal power plant (160,000 sej/J). If coal fired net EMERGY yield ratio is 2.5, then the accumulated net EMERGY yield ratio is 2.4

4 Hydroelectric power evaluated with solar transformity of 85,437 and net EMERGY yield ratio 5.7

5 Requirements for conversion used in item #3 were combined with EMERGY analysis of U.S. Nuclear Fission power (Lapp, 1992). Transformity of Electric power used as that of fossil fuel plants, but net EMERGY yield ratio 4.9

6 Hydrogen from solar driven photovoltaic cells evaluated by Barbir (1992)

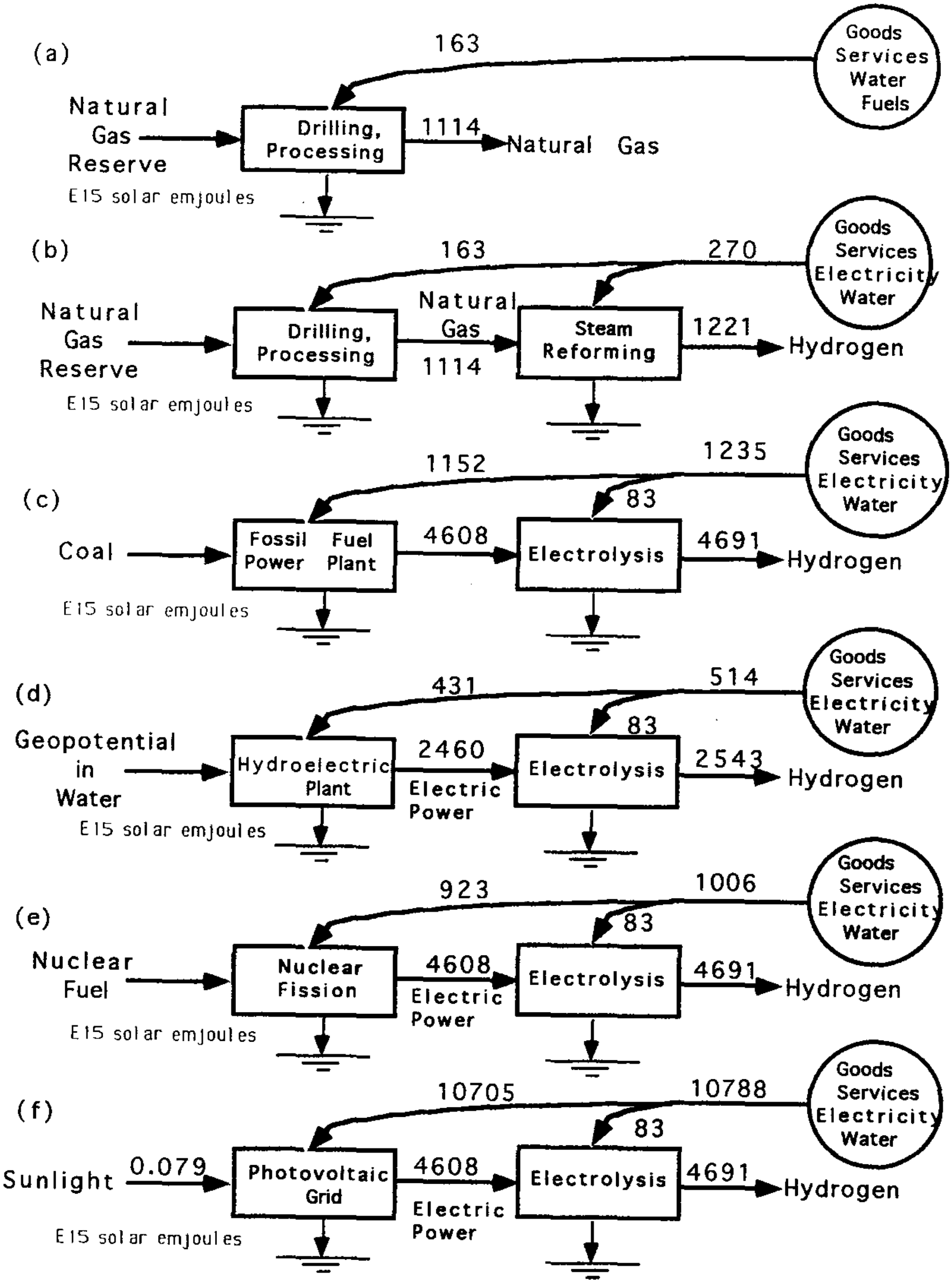


Figure 3.7 Summary diagrams of EMERGY evaluation of natural gas (a) and hydrogen (b-f) calculated in Table 3.4.

Case 4. **Hydrogen produced from hydroelectric power.** Hydrogen can be generated from water by electrolysis using hydroelectric power (Figure 3.7d). The EMERGY yield ratio (4.9/1) is lower than present fossil fuel alternatives for transport fuel, but has a much better yield ratio than some alternatives being proposed for fossil fuels that are less available (such as motor fuels from biomass). If EMERGY evaluations of hydroelectric power include the contributions of streams and rivers that are lost when a dam is built, a lower EMERGY yield ratio is found. However, there is little unutilized hydroelectric capacity in rivers of the United States. Because of its flat terrain, the potential for hydroelectric power in Florida is negligible.

Case 5. **Hydrogen produced from nuclear power.** Hydrogen can be produced by electrolysis from electricity generated by nuclear plants, and thus provides a way to harness nuclear energy to operate moving vehicles (Figure 3.7e). A recent EMERGY evaluation of U.S. nuclear fission power (Lapp, 1992) showed a EMERGY yield ratio of 4.9/1 and, when combined with the electrolysis process, yields an overall ratio for hydrogen production of 4.7/1. This could be competitive for motor transport after the fossil fuel period, for the years when high quality nuclear fission fuels are still available. However, large expansion of nuclear power in Florida would be necessary to provide the energy requirements for transportation, as well as household, commercial and industrial needs.

Case 6. Hydrogen from solar photovoltaic cells. Hydrogen can also be generated from electrolysis using electricity from photovoltaic cells that use direct sunlight (Figure 3.7f). However, the EMERGY yield ratio of solar voltaic systems is so low, there is no net EMERGY contribution to the economy (0.43/1). Making hydrogen from this electricity with additional input requirements makes the yield ratio even less. The ultimate reason for the poor conversion may be an inherent thermodynamic limit on converting dilute energy into a very concentrated one in a single step. After a billion years of evolution, green plants operate a chlorophyll solar voltaic cell which has higher conversion efficiencies, possibly representing the thermodynamic maximum conversion possible. This may be the ultimate limit for solar voltaic research. Appropriate comparison of chlorophyll with silicon cells evaluates the efficiency of both of these cases in the conversion of photons to displaced electrons.

Transformity of Hydrogen

In order to use the appropriate transformity principle to select the best energy alternatives, the best (lowest) transformity which is possible for each fuel must be established. The ultimate thermodynamic limit to the efficiency for generating hydrogen in open systems operating at maximum power is not yet known. Data on some solar transformities found for hydrogen are shown in Table 3.4. These include processes where there are unnecessary long sets of transformations which, as a result, are less efficient (higher than the minimum transformity). Although more examples need to be evaluated, one may infer from data available so far that the best possible transformity for hydrogen is higher than fossil fuels and less than electric power. If this is valid, then the methods that depend on electric power are wasteful and alternatives that can generate motor fuels more directly are likely to be more competitive economically. Where hydrogen can be made with a lower transformity than electricity, it can be used for more general heating purposes and to make electricity. If the solar transformity of hydrogen was higher than electricity--which is what is obtained when hydrogen is made from electrolysis of water--then it would not generally make economic or energetic sense to use hydrogen for lower transformity purposes such as heating and other current uses of electric power.

Since electric power generates hydrogen, the transformity of hydrogen calculated from this process (Table 3.4) is higher than that of electricity (Table 2.1). And since the reverse process can also be arranged, electricity can be generated from hydrogen (and oxygen). Barbir (1992) raises the question as to which has the higher transformity--hydrogen gas or electric power--when the most efficient chain of processes is used. This is a critical questioning energy conservation. Since energy is dispersed in each transformation, energy should net be transformed any more times than is necessary to accomplish a purpose.

In other words, if hydrogen is necessarily higher in the transformity scale than electricity, then its use can be justified only for very special purposes for which electricity is not adequate. If the transformity of hydrogen is lower than electricity, then it may be substituted for some processes, providing the net EMERGY yield is competitive. Tables 2.1 and 3.4 summarize the solar transformities of hydrogen and electric power as calculated for several processes.

An as yet to be determined effect is the pollution caused by each alternative, and the resulting energy costs for cleanup and the loss of natural and agricultural productivity. These effects could alter the results of the analysis. The electric vehicle system would act more as a point source of pollution (the electric power plant outlet), and may be easier to clean up. On the other hand, conventional vehicles act as non-point sources of pollution. In either case, the costs of pollution abatement could be substantial. Their pollution would probably be impossible to clean up to the same degree as a point source, and environmental impacts would have to be tabulated for both cases. The general question is whether it is more cost effective to concentrate or dilute pollution, since the earth must ultimately assimilate the pollution. For a complete analysis, environmental impacts should be considered as well.

4. Hurricane Andrew:
EMERGY Analysis of Dade County, The Hurricane Impact Area and Evaluation of Damages and Costs

by
Mark T. Brown and Robert Woithe

The normal suit of renewable and non-renewable energies driving an economy can be thought of as "ordering" energies since they act, for the most part, to develop ordered storages, structures, and work processes. While working economies generate disorder in the form of waste heat , pollutants, and some local disordering of ecological systems, for instance, the net effect in growing, robust economies is the creation of order that is greater than the disordering influences of work processes. This net effect is a spatial and temporal concentration of order. If the larger system is considered, that is, the biosphere as a whole, the net effect according to the 2nd energy law is an increase in disorder. Thus the balance of order and disorder is spatially and temporally constrained. Any temporary increase in order at one location is accompanied by disorder in another location equal to or greater than the ordering influence.

The normal suit of energies driving any system also contains energies whose magnitude, transformity, and frequency are such that the system is not necessarily adjusted to them. Examples are extreme rainfall events that cause floods, tornadoes, earth quakes, and of course hurricanes. Because these energies are not constant, but appear from time to time with much force, they often act in disaster like fashion, since the system is not adapted to them. When this happens there is a temporary increase in disorder, often followed by a burst of rebuilding activity. Energies are converged at the point of disaster to rebuild and renovate. The net effect of which may be an overall increase in ordered structure immediately following the disaster.

Energies that cause disasters have magnitudes, frequencies, and transformities that are greater than the normal suite of driving energies in any system. They are pulses of energy that when released can cause momentary disorder. Yet these disordering energies are variable. Their frequency and magnitude vary from occurrence to occurrence. Lower magnitude events occur more frequently than higher magnitude events. Thus often areas experience relatively minor hurricanes every couple of years, while the very large storms occur only once every 50 years or so.

A hurricane represents a disordering energy to terrestrial systems including those of humanity when the magnitude is greater than that which the systems are adapted. Adaptation may be related to the frequency of occurrence, and the turnover time (useful life) of the structure

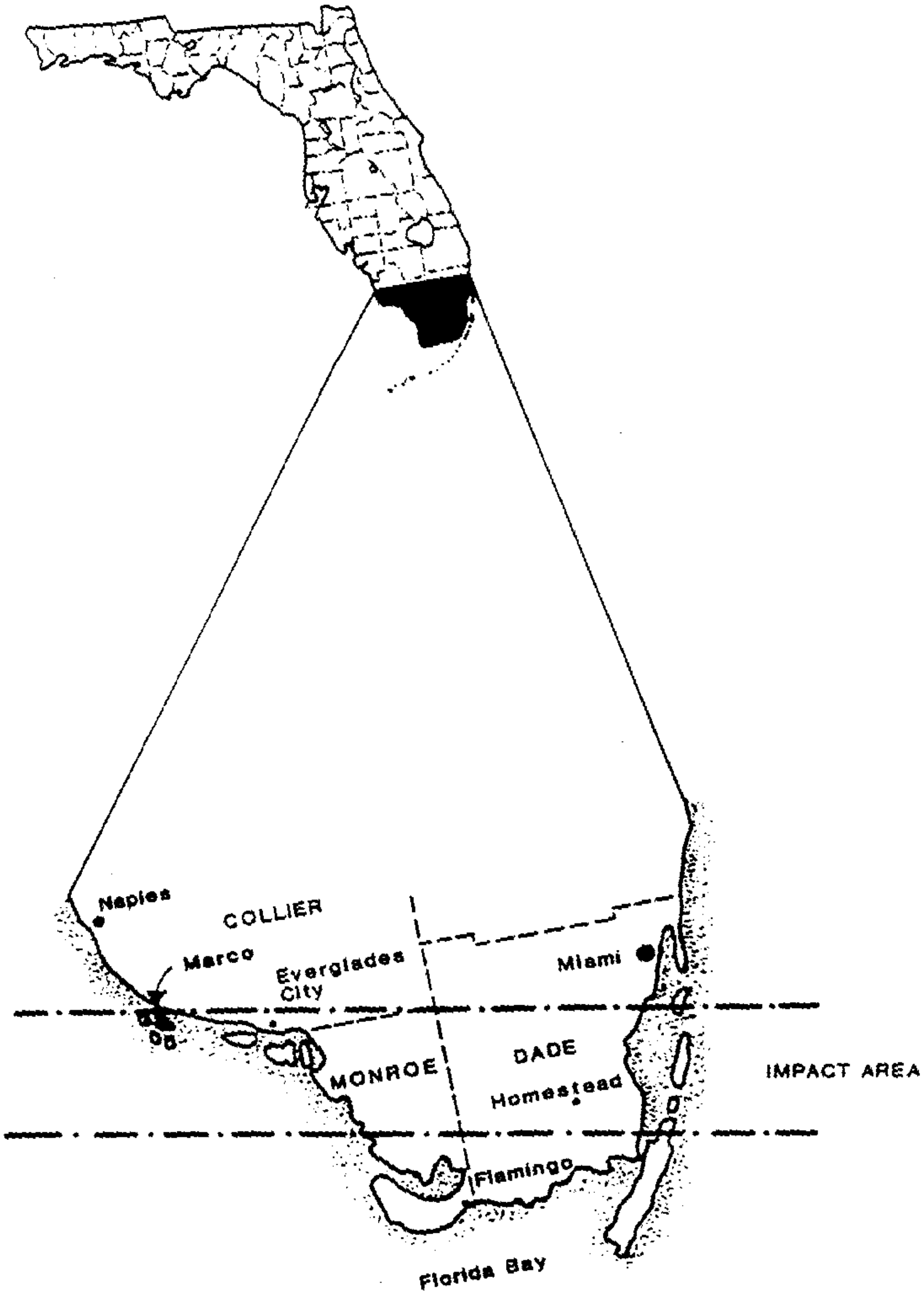


Figure 4.1. Map showing the Hurricane Andrew Impact Area

affected. Theory would suggest that systems organize themselves to withstand pulses of a frequency that is less than the useful life of their structure. In other words, it becomes more "efficient' to allow the destruction of easily replaced (and therefore relatively inexpensive and short life) structure than it is to build it more expensively to withstand larger magnitude events. Another way of saying this is that if the frequency of a pulse event is longer than the turnover time of the structure, it does not make energetic sense to build the structure to withstand its forces.

Quite frequently systems respond to disorder with an outburst of ordering process to rebuild and replace that which is lost. This frenzy of activity is tempered in intensity and duration only by the availability of energies with which to support it. In this analysis of Dade County, the ordering energies inflowing on an annual basis and the disordering energies of the hurricane are evaluated and compared. The response to the hurricane was an inflow of workers, money, and resources to rebuild and repair the damage. These ordering energies are also evaluated and compared to the economy and the disordering influences of the hurricane.

EMERGY Evaluations of Dade County and the Impact Area

EMERGY evaluations of Dade County (1991, the latest year for which there is data) and the area of hurricane impact (Figure 1) were conducted to develop insight into the magnitude of hurricane damage and rebuilding efforts, and to provide the background for growth scenarios for the south Dade region. The evaluations were done for both the impact area and Dade County as a whole to evaluate what effect the hurricane had at different scales. The impact area, the smaller of the two scales, is that area in south Dade, Monroe, and Collier Counties over which the hurricane passed. Total EMERGY budget, or driving energies, of the region were evaluated and compared to the energy in the pulse of hurricane Andrew and the EMERGY in the response and rebuilding efforts. For purposes of perspective, the same comparisons were made with the economy of Dade County as a whole.

Tables 4.1 through 4.3 provide the details and indices of the EMERGY evaluation (footnotes to the tables are found in Appendix C). Total EMERGY use in Dade County was 66.1 E21 sej/yr in 1990 (Table 4.1), while for the impact region, total EMERGY use was 15.4 E21 sej/yr (Table 4.2). By far the largest renewable energy contribution to the Dade County economy was from rain, followed by tidal energy. These energies were relatively insignificant when compared to purchased energies. Only 3.4% of the total EMERGY use in Dade County was from renewable sources (and 96.6% was purchased). The impact area, on the other hand, had a renewable EMERGY base equal to about 20% of the total EMERGY budget. Table 4.3 gives these summary indices and others for both Dade county and the impact area. As a result of the vast

Table 4.1. Annual EMergy support for Dade County, Florida in 1990,

Note	Item	Raw Units (J,$ or g)		Trans- formity (sej/unit)	Solar EMergy (E19 sej)	Emdollars (1990US) (E8 em$)
RENEWABLE RESOURCES:						
1	Sunlight	3.56E+19	J	1	3.56	0.22
2	Wind, kinetic	6.00E+17	J	620	37.20	2.33
3	Rain, geopotential	6.25E+13	J	8900	0.06	0.00
4	Rain, chemical	9.19E+16	J	15000	137.90	8.62
5	Tide	3.89E+16	J	24000	93.43	5.84
6	Waves	8.07E+15	J	26000	20.99	1.31
INDIGENOUS RENEWABLE ENERGY:						
7	Agriculture product.	5.50E+12	J	2.00E+05	0.11	0.01
8	Shellfish	2.00E+12	J	8.00E+05	0.16	0.01
9	Finfish	1.90E+12	J	2.00E+06	0.38	0.02
NONRENEWABLE SOURCES FROM WITHIN SYSTEM:						
10	Groundwater	1.22E+13	J	41000	0.05	0.00
11	Limestone	4.70E+11	g	6.70E+06	0.31	0.02
IMPORTS AND OUTSIDE SOURCES:						
12	Fuel	1.60E+17	J	5.30E+04	848.00	53.00
13	Electicity	2.20E+17	J	1.59E+05	3498.00	218.63
14	Net migration	5.12E+13	J	4.06E+07	207.87	12.99
15	Services in Imports	1.27E+10	$	1.60E+12	2032.00	127.00
EXPORTS:						
16	Agriculture prods.	1.05E+14	J	2.00E+05	2.09	0.13
17	Limestone	4.70E+11	g	6.70E+06	0.31	0.02
18	Services in Exports	3.12E+08	$	1.60E+12	49.92	3.12

Footnotes to Table 4.1 can be found in Appendix C

Table 4.2. Annual EMergy support for Hurricane Andrew Impact Area in 1990

Note	Item	Raw Units (J,$ or g)		Trans-formity (sej/unit)	Solar EMergy (E19 sej)	Emdollars (1990US) (E8 em$)
RENEWABLE RESOURCES:						
1	Sunlight	3.12E+19	J	1	3.12	0.20
2	Wind, kinetic	4.00E+17	J	620	24.80	1.55
3	Rain, geopotential	1.68E+13	J	8900	0.01	0.00
4	Rain, chemical	9.45E+16	J	15000	141.80	8.86
5	Tide	7.79E+16	J	24000	186.87	11.68
6	Waves	5.44E+15	J	26000	14.15	0.88
INDIGENOUS RENEWABLE ENERGY:						
7	Agriculture product.	2.48E+12	J	2.00E+05	0.05	0.00
8	Shellfish	5.62E+12	J	8.00E+05	0.45	0.03
9	Finfish	2.07E+12	J	2.00E+06	0.41	0.03
NONRENEWABLE SOURCES FROM WITHIN SYSTEM:						
10	Groundwater	2.31E+12	J	41000	0.01	0.00
11	Limestone	1.18E+11	g	6.70E+06	0.08	0.00
IMPORTS AND OUTSIDE SOURCES:						
12	Fuel	3.04E+16	J	5.30E+04	161.12	10.07
13	Electicity	4.18E+16	J	1.59E+05	664.62	41.54
14	Net migration	1.28E+13	J	4.06E+07	51.97	3.25
15	Services in Imports	2.41E+09	$	1.60E+12	386.08	24.13
EXPORTS:						
16	Agriculture prods.	4.70E+13	J	2.00E+05	0.94	0.06
17	Shellfish	5.06E+12	J	8.00E+05	0.40	0.03
18	Finfish	1.86E+12	J	2.00E+06	0.37	0.02
19	Limestone	1.18E+11	g	6.70E+06	0.08	0.00
20	Services in Exports	2.70E+08	$	1.60E+12	43.18	2.70

Footnotes to Table 4.2 can be found in Appendix C

Table 4.3. Dade County and Hurricane Andrew impact area EMergy indicies derived from Tables 4.1 and 4.2.

Name of Index Expression	Impact Area	Dade County
Total imported emergy	1211.8 E+19 sej/y	6378.0 E+19 sej/y
Total EMergy inflows	1540.7 E+19 sej/y	6610.0 E+19 sej/y
Economic component	1263.1 E+19 sej/y	6584.1 E+19 sej/y
Total exported emergy	43.3 E+19 sej/y	50.2 E+19 sej/y
% EMergy Use locally renewable	20.6 %	3.4 %
Ratio of Nonrenewable to renewable	3.8	28.5
Ratio of imports to exports	28.0	127.0
Imports minus exports	1168.6 E+19 sej/y	6327.8 E+19 sej/y
% of emergy use purchased	76.1 %	93.6 %
Fraction imported service	0.2	0.3
% of emergy use derived from home sources	20.7 %	3.4 %
% of use that is free	20.6 %	3.4 %
Use per unit area	0.5 E+13 sej/m^2-y	1.2E+13 sej/m^2-y
Use per person	4.1 E+16 sej/per-y	3.5 E+16 sej/per-y
Renewable carrying capacity at present living standard	79494.2 people	65846.8 people
Ratio of use to GDP	2.4 E+12 sej/$	2.0E+12 sej/$
Fraction Electric	0.4	0.5
Fraction Fossil Fuels	0.1	0.1
Fuel use per person	4.2 E+15 sej/per-y	4.4 E+15 sej/per-y

differences in population density and development status, the two regions are quite different. EMERGY use per unit area in Dade County is nearly three times the EMERGY use per unit area characteristic of the impact area. On the other hand, because of the relatively low population in the impact area EMERGY per capita is 20% greater than in Dade County.

Table 4.4 summarizes the total EMERGY in structure of the various subsystems of the impact area. The greatest structural components are within the urban systems, many of which are 1 to 2 orders of magnitude greater than the structure in ecological communities. The final column in Table 4.4 gives estimates of EMdollars for each subsystem. EMdollars are the estimated amount of Gross Domestic Product (GNP) that would be reguired to replace the structure.

EMERGY Evaluation of Hurricane Andrew

EMERGY evaluations of the damages and costs resulting from Hurricane Andrew are given in Table 4.5 and summarized in Figure 4.2. The diagram summarizing EMERGY disordering and ordering shows the hurricane interacting with natural and urban structure (for simplicity, agricultural systems have been incorporated into the urban systems in the diagram). The interaction is a disordering stress, pulling from each compartment ordered structure. In natural systems, much of the disordered parts are recycled and reused in building new structure. Unlike natural systems, the disordered parts from urban and agricultural systems are not recycled locally, but are shown accumulating in a storage of wastes and slowly degrading away. A pathway of recycle is shown, but very little of the disordered urban and agricultural structure is recycled. Some of the disordered urban and agricultural structure may have been recycled (aluminum, steel, glass, etc) as exported material, shown leaving the system to the right. No data were found on the magnitude of this pathway.

The diagram shows the exodus of population, in response to the disordering of urban structure. The loss was estimated at about 50,000 people (Powers, 1993). However, because of rebuilding efforts, there was also an inflow of population. Newspaper articles suggested that the inflow of this temporary work force was about 100,000 people; or about twice the number of residents that moved away after the hurricane. The hurricane disaster caused an outburst of local activity that was financed by aid and insurance money that flowed into the local economy from elsewhere. The inflow of money (about 20 billion dollars) was used to purchase goods and services, as well as to pay the salaries of reconstruction workers.

Table 4.4 summarizes the EMERGY evaluation of hurricane impacts and costs of rebuilding. First the EMERGY in hurricane winds was estimated as 2.2 E21 sej. This is an estimate of the wind energy absorbed by the terrestrial ecosystems and urban structure of the impact area. Not included is

Table 4.4. EMergy value of storages of the Hurricane Andrew Impact Area by land use catagory

Note	Item	Raw Units (J,$ or g)	Transformity (sej/unit)	Solar EMergy (E19 sej)	Emdollars (1990US) (E8 em$)
1	Beaches, dunes & salt flats	9.5E+10 J	3.5E+04	0.003	0.002
2	Emerging systems	3.0E+11 J	3.5E+04	0.01	0.01
3	Scrub mangroves	6.5E+12 J	3.5E+04	0.23	0.14
4	Lakes and ponds	1.3E+12 J	3.5E+04	0.04	0.03
5	Urban parks	6.3E+12 J	3.5E+04	0.22	0.14
6	Wet prairie	3.8E+14 J	3.5E+04	13.4	8.4
7	Scrub cypress	5.2E+13 J	3.5E+04	1.8	1.1
8	Pine uplands	1.5E+13 J	3.5E+04	0.54	0.34
10	Agriculture	5.0E+14 J	3.5E+04	17.4	10.9
11	Mangroves & salt marshes	2.0E+15 J	3.5E+04	71.4	44.6
12	Cypress domes & strands	9.0E+14 J	3.5E+04	31.5	19.7
13	Hardwood hammocks	1.6E+14 J	3.5E+04	5.7	3.6
14	Sawgrass marsh	5.1E+15 J	3.5E+04	177.1	110.7
15a	Single-family residential-wood	4.8E+16 J	3.5E+04	1688.1	1055.0
15b	-concrete	8.5E+12 g	7.0E+07	593.6	371.0
16a	Transportation-asphalt	6.5E+15 J	5.3E+04	346.0	216.2
16b	-subbase rock	4.0E+11 g	6.7E+06	2.7	1.7
17a	Multi-family residential-wood	1.4E+16 J	3.5E+04	484.0	302.5
17b	-concrete	2.6E+12 g	7.0E+07	179.2	112.0
18	Commercial & industrial	2.3E+12 g	7.0E+07	161.7	101.1

Footnotes to Table 4.4 can be found in Appendix C

Table 4.5 Emergy Damages and Costs Resulting From Hurricane Andrew

Item	Storage or Flow	Amount (units)		Transformity (sej/unit)	Emergy (E+18 sej)	Emdollars (E6 em$)
Damages						
	Environmental Systems					
1	Structure (biomass)	5.16E+14	J	35000	18.05	9.50
2	Productivity	3.07E+16	J	3500	107.54	56.60
	Agricultural Systems					
3	Buildings & Equip	9.65E+08	$	1.9E+12	1833.50	965.00
4	Structure (biomass)	8.57E+14	J	35000	30.01	15.79
5	Productivity	2.67E+15	J	7000	18.71	9.85
	Urban Systems					
6	Infra-struct. (wood)	1.71E+11	g	100000000	17.12	9.01
	Infra-struct. (conc)	5.83E+12	g	92600000	540.32	284.38
	Infra-struct (services)	6.97E+09	$	1.9E+12	13243.00	6970.00
7	Productivity			6052.50	3185.53	
8	Electricity	4.61E+15	J	160000	737.60	388.21
	Social Systems					
9	Population	5.00E+04	p	9.4E+16	4700.00	2473.68
Cleanup and Restoration Costs						
10	Dollar payments					
	Federal Sources	9.00E+09	$	1.6E+12	14400.00	9000.00
	State Sources	5.00E+08	$	1.6E+12	800.00	500.00
	Insurance Co.	1.00E+10	$	1.6E+12	16000.00	10000.00
	Private Sources	2.30E+07	$	1.6E+12	36.80	23.00
11	Human pop. inflow					
	Temporary workers	5.71E+04		9.4E+16	5371.29	2826.99
12	Productivity Increase					
	Permanent Jobs	8.00E+04		9.4E+16	7520.00	3957.89

Footnotes to Table 4.5 can be found in Appendix C

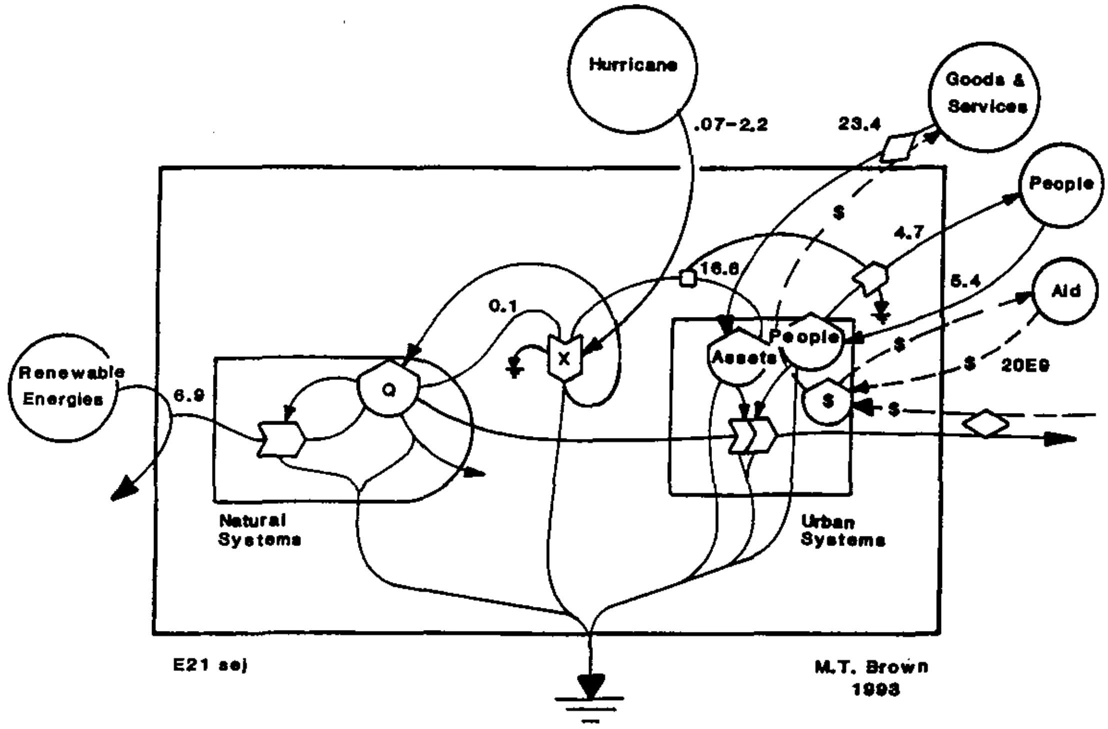


Figure 4.2. Systems diagram of the impacts and resulting inflows of ordering energies that resulted from Hurricane Andrew

the wave energy resulting from the hurricane that was absorbed along the coast. Second estimates of damages incurred by ecological, agricultural, and urban systems are given. In each category, both the losses associated with damaged structure and the loss of productivity are given separately. Productivity losses were calculated based on estimated recovery times.

Damages to ecological, agricultural, and urban systems were approximately 16.8 E21 sej and population loss was 4.7 E21 sej, giving a total loss of about 21.5 E21 sej. The costs of cleanup and rebuilding were 23.4 E21 sej and the gain from temporary population increase was 5.4 E21 sej. A productivity increase based on the creation of 80,000 new permanent jobs results in an increase of 7.5 E21 sej. In all it appears that the EMERGY value of damages was about equal to the EMERGY in the rebuilding effort.

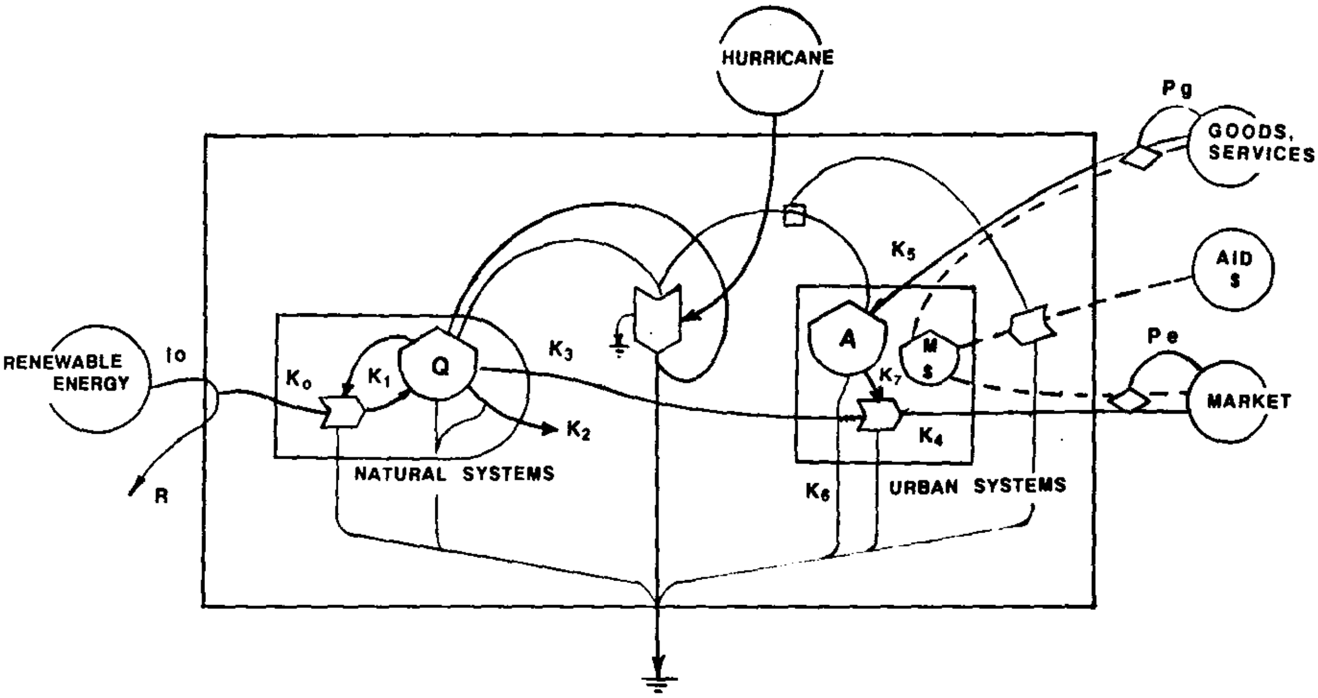
The relative impact of the hurricane was evaluated by comparing the total EMERGY budget of the region (Table 4.2) and the EMERGY value of storages within the impact area (Table 4.4) with the disordering effect of Andrew. The losses of ecological system structure was about 6% of the total structure and urban system structural losses were about 18% of total. Combined losses of productivity from natural, agricultural, and urban systems was 15% of the annual EMERGY budget of Dade county and about 64% of the annual EMERGY budget of the impact area. The EMERGY value of total disordered structure (including natural, agricultural, and urban) was about 32% of the annual EMERGY budget of Dade County and represented about 135% of the annual budget of the impact area. The EMERGY value of cleanup and rebuilding was about 34% of the annual EMERGY budget of Dade county and about 147% of the EMERGY budget of the impact area.

In all, the hurricane represented a significant impact to the south Florida region, and as a result, questions concerning the long term implications of hurricane disordering on economies were addressed using a simplified simulation model of the south Florida economy and environment.

Simulations of Hurricane Disordering

The effects of hurricane disordering and benefits from increasing the quality of structure to minimize hurricane damages was tested and evaluated using a simulation model. Given in Figure 4.3 is an aggregated systems diagram of the economy of south Dade county including its environmental support base, and external trade. Equations for the state variables (natural structure, urban structure, and money) are given below the diagram. These equations were programmed in a simple simulation of 250 years of growth of urban structure. Figure 4.4 gives 4 graphs which summarize some of the simulation results of the model.

In the first graph (Figure 4.4a), the amount of natural structure is shown as it might have been before any significant human presence in south Florida. Each break in the graph line represents



$$R = I_o / (1+Ko * Q)$$
$$E = K_4 * A * Q$$
$$\frac{dQ}{dt} = K_1 * R * Q - K_2 * Q - K_3 * A * Q$$
$$\frac{dM}{dt} = Pe * E - K_5 * M$$
$$\frac{dA}{dt} = K_5 * M / Pg - K_6 * A - K_7 * A * Q$$

Figure 4.3 Simulation Model of Hurricane disordering in South Dade

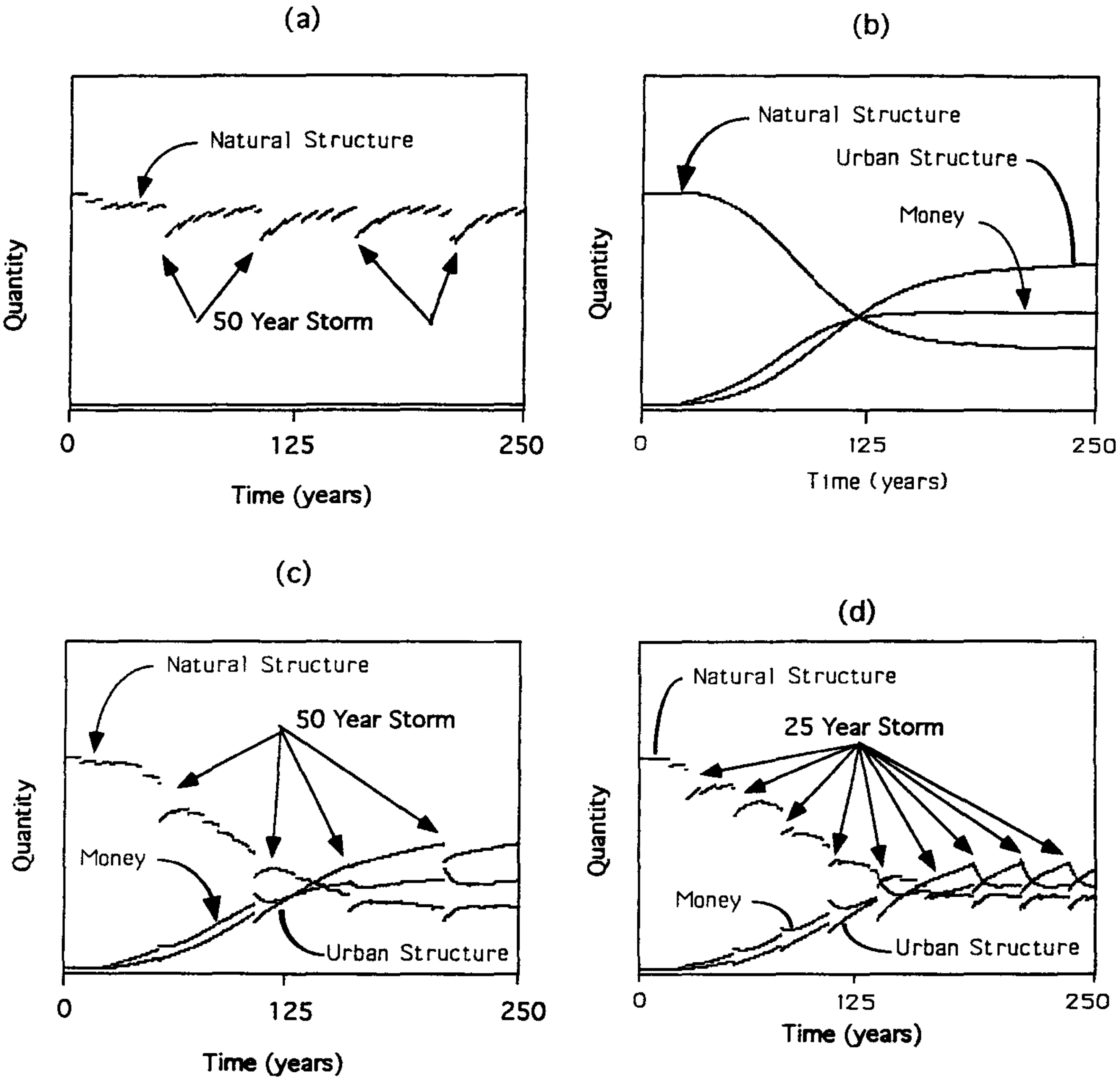


Figure 4.4. Simulation results of the model in Figure 4.3 showing (a) graph of natural structure affected by small hurricanes on a 7 year cycle and major storms on a 50 year cycle, with no urban development; (b) graphs of natural structure, urban development, and money supply with no hurricane damage; (c) graphs of natural structure, urban development, and money supply with small hurricanes on a 7 year cycle and major storms on a 50 year cycle; (d) graphs of natural structure, urban development, and money supply with small hurricanes on a 7 year cycle and major storms on a 25 year cycle

a hurricane event. The smaller events occur on 7 year cycle, while the larger storms occur on a 50 year cycle. The size of the events were programmed to be somewhat random. After each storm event, the regrowth of natural structure occurs until the region is "hit" by another storm.

In the second graph (Figure 4.4b), the amounts of natural structure, urban structure, and money over time are shown as they might be if there were no hurricanes. The human presence in south Florida begins to increase in the first 20 years, and grows significantly over the next 100 years. Natural structure declines as more and more land is converted to urban uses. There is a leveling of the economy (ie minor net growth) after the 150th year of the simulation, as a result of the limiting effect of the reduction of the natural support base.

The third graph (Figure 4.4c) shows the effect of hurricanes on the growth and development of the region. Hurricane frequency is the same as in Figure 4.4a, that is, small hurricanes every 7 years and larger storms every 50 years. The breaks in the graphs of money and natural and urban structure result from disordering influence of the hurricanes. Since each hurricane was programmed to be different, the amount of disorder varies from one storm to the next. The effect of each major storm is to disorder structure and cause a temporary increase in the money within the region (resulting from outside aid). The regrowth of urban structure after each major storm is facilitated by the additional aid.

In the fourth graph (Figure 4.4d) the effect of increased frequency of major hurricane events is simulated. The frequency was increased to 25 years instead of 50 years. The increased frequency results in lower levels of urban and natural structure and a smaller local money supply. Since aid is sent to the region with each hurricane, the regrowth of urban structure is facilitated. Yet the total amount of urban structure never reaches levels that are characteristic of the region with longer intervals between hurricanes. Simulations of the model when aid is reduced after a hurricane, slows down recovery of the urban systems and results in even lower total structure. The aid has a stimulating effect rebuilding the structure much quicker than would be possible without it.

Benefits of Increased Structural Quality

To address questions related to the relative benefits of increasing the quality of built structure and thus minimizing damages from future hurricanes, varying levels of increased quality were programmed and related to damages from hurricanes. A benefit -cost analysis resulted where the benefit was the difference between damages incurred with the present quality of structure and lower damages that would result with increased structural quality. The costs in this analysis were the increased EMERGY costs of the added structural quality. The model was simulated with varying hurricane strengths, 50 year storm events, and a 250 year time horizon.

The graph in Figure 4.5 shows the relative benefit-cost ratio (X axis) for hurricanes of varying damage intensity (Y axis). Each set of symbols represents a different expenditure for increasing structural quality, and each data point results from a 250 year simulation of the model where the relative damage by hurricanes during that time varied from those that resulted in 20% of Andrew damages to those that resulted in about 130% of Hurricane Andrew damages. The highest line (dashed data points) represents a 2% increase in expenditures for higher quality structure, while the lowest line (solid square data points) represents a 20% increase in expenditures. A benefit-cost ratio of 1.0 represents a break even point, thus data points above 1.0 have positive benefit-cost ratios and those below 1.0 have negative ratios.

The simulation results suggested that, generally, increased expenditures on the order of 2% to 4% of current structural costs resulted in positive benefit-cost ratios across all hurricane damage intensities, with very high yields for hurricanes of the magnitude of hurricane Andrew. Increased expenditures on the order of 6% to 8% resulted in positive B-C ratios for hurricanes of the magnitude of Andrew, but lower for the smaller hurricanes. Increased expenditures in the range of 10% of current structural costs resulted in positive benefit-cost ratios for only the most intense hurricanes, and expenditures greater than 12% of current costs resulted in B-C ratios less than 1.0. In other words, there is a diminishing return on increasing the quality of urban structure as a means of minimizing hurricane damage. Small incremental increases in costs that increase the quality of structure have positive B-C ratios, while larger increases can only be justified for for the most sever hurricane damage intensities.

There is an important assumption built into this analysis that should be considered. It was assumed that expenditures for increased structural quality would result in a direct saving in damages proportional to the expenditure. As can often happen, increased construction costs may not necessarily mean better quality. The assumption, however that increased construction costs provide increased protection against hurricane damage is valid if taken in the aggregate, that better quality structure lessens hurricane damage.

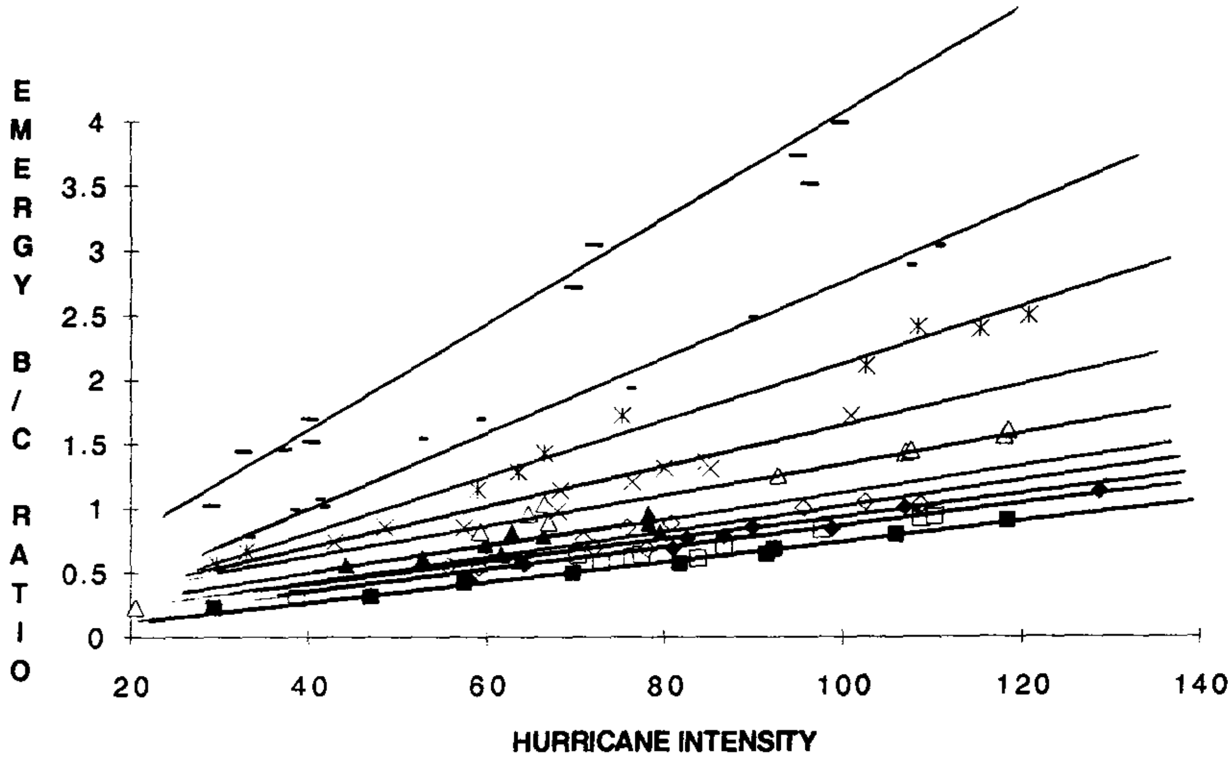


Figure 4.5. Graphs of EMERGY cost/benefit of increasing the quality of urban structure that result from repeated simulations of the model in Figure 4.3. Each line represents a 2% increase in construction costs.

5. South Dade County:
Emergy Analysis of Rebuilding Options After Hurricane Andrew

by
Mark T. Brown and Sergio Lopez

INTRODUCTION

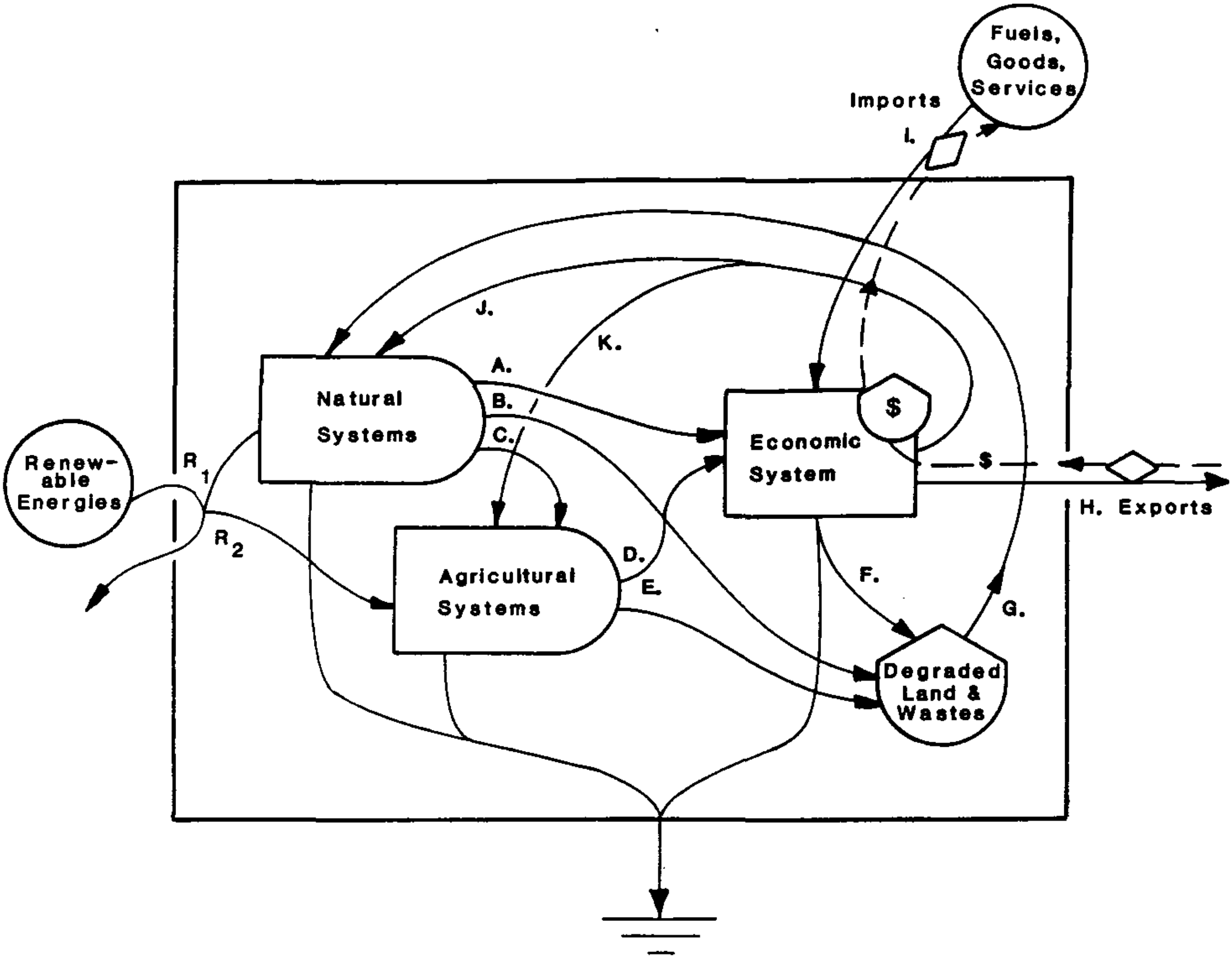
Questions concerning sustainability, carrying capacity, and the welfare of developing regions center on the role of natural resources, or what economists term "natural capital," in economies. Economists are beginning to take a hard look at resource depletion and loss of environmental quality and their effect on economic productivity and net capital formation, suggesting that when taken into account, many otherwise growing economies may in fact be declining, since declining levels of natural capital threaten long term economic sustainability. Increasingly there is a call for factoring into economic production functions the contributions of environmental systems and the negative consequences of resource depletion. Carrying capacity and the welfare of growing populations in developing regions may be tied, ultimately, to natural resources instead of capital formation. This section investigates the resource base of the economy of south Dade and its relationship to sustainability and carrying capacity.

Sustainable Development

Figure 5.1 is a systems diagram of a region showing the interplay of natural and agricultural systems and the human economy. The inflow of renewable resources power the natural and agricultural systems and recycle and feedback pathways provide limited resources and energies from the larger economy. Resources are "harvested" from natural and agricultural systems, and either consumed locally, or exported. The proceeds from exported goods are used to purchase imported fuels, goods, and services. Degraded lands and "waste-by-products" are often slow to recycle to productive uses.

Sustainability can be defined from at least four different perspectives using the diagram in Figure 5.1.; (1) sustainable development of natural systems; (2) sustainable yields from agricultural systems; (3) sustainable use of resources at the regional scale; and (4) sustainable inter-regional trade. The equalities given below the diagram describe each of these perspectives on sustainable use of resources.

In a larger sense, since all systems are embedded within bigger systems, and, in some measure influence lessor systems (i.e. a farm is driven by larger economic forces and in turn



Sustainability Criteria :

Natural Systems	$A+B+C \leq R_1+G+J$
Agricultural Systems	$D+E \leq R_2+C+K$
Regional System	$F+H+J+K \leq A+D+I$
International Trade	$H \leq I$

Figure 5.1. Systems diagram of a regional economy that is the interplay of renewable and non-renewable energies. Shown are three scales for which sustainability should be determined: ecological scale, regional scale, and intra-regional scale

influences what crops and management techniques are used at the field level) truly sustainable development should satisfy stainability criteria at all levels simultaneously.

Conceptually, the diagram and equations may help to define sustainability. Yet to be truly useful, the diagram should be evaluated to determine if the outflows exceed inflows at each of the various compartments and for the regional systems as a whole. Evaluation in several different units (kg of soil, tons of wood, hours of labor, liters of fuel, etc.) however will only serve to increase confusion. Common units for all pathways are necessary. A new unit of evaluation called "emergy" (which is somewhat analogous to embodied energy. . . in other words the energy used to make something) may offer the potential of evaluating all resources in a regional economy in the same units so that comparisons and judgements concerning sustainability can be made.

It is absolutely essential that a quantitative method be employed to judge sustainability so that policy decisions are informed decisions. A systems perspective and the use of emergy analysis techniques may provide the needed tools.

We have evaluated numerous systems of production, from primitive rice cultivation in Thailand, to oil palm plantations in Brazil and have related them using several emergy indices to criteria for sustainability. The basic criteria is simply that all systems of production (agricultural field, farm, community, or region) should strive to at least balance that which is "harvested" with the inflows of energy and resources that drive productive processes. If there is net negative balance, in other words if more outflows than inflows, the enterprise is not sustainable, in the long run, the greater the deficit, the shorter the time horizon before production ceases.

A Definition of Carrying Capacity

Carrying capacity for human populations is the population size that can be sustained at some consumptive level for a given period of time. With a given amount of resources the population level can vary depending on per capita resource consumption. Since resources are not infinite in their availability (both temporally and spatially), increasing local carrying capacity becomes an issue of increasing resource availability. In most economies this means increasing the rates of resource extraction and imports of resources that are in short supply. The rub is that to increase imports, often exports must be increased and therefore even greater rates of resource extraction result. Thus the imports on the one hand may increase carrying capacity in the short run, but the exports, ultimately, decrease carrying capacity in the long run. Clearly the balance between short run increases in carrying capacity and long term decreases has been tipped in favor of the short run as populations and “standards of living” have increased in most nations throughout the developed and developing world. The following question begs to be answered...can these short run increases in carrying capacity be sustained in the long run , in light of the fact that natural capital is being depleted at ever increasing rates?

Determining Carrying Capacity

One theory for determining carrying capacity is that the scale or intensity of development[1] in relation to existing conditions may be critical in predicting its effect and ultimately its sustainability (Odum et al. 1980; Odum and Arding 1991). If a development's intensity is much greater than that which is characteristic of the surrounding landscape, on average, the development has greater capacity to disrupt existing social, economic, and ecologic patterns (Brown 1980, Odum 1980). If it is similar in intensity it is more easily integrated into existing patterns. For example, because of the differences between a heavily urbanized area and an undeveloped wilderness area, the appropriate intensity of development in each environment is much different. At the regional scale, the appropriate scale of urbanization is the level that is characteristic of the economy within which the region is embedded.

Large-scale developments and those with greater intensity than the surroundings can be integrated into the local economy and environment if there is sufficient regional area to balance its effect. Much like the ecological concept of carrying capacity, where differing environments require different aerial extent of photosynthetic production for support of a given biomass of animals, environmental carrying capacity for human populations and their economies depends on the area of "support" over which development can be integrated. As the intensity of development increases (and therefore its consumption of resources and environmental impacts increase), the area of natural undeveloped environment required for its support must increase. All other things being equal, the more intensely an area is developed, the greater the area of environment necessary to balance it. Thus, if planned in advance, the spacing between urban centers should increase as their intensity increases. The methodology described in this section uses EMergy analysis to evaluate intensity of urban development and the support base of the local environment and then uses a ratio of purchased, nonrenewable EMergy to the resident renewable EMergy of the environmental support base as a means of determining carrying capacity.

---

[1] Intensity may be measured using any quantity (energy, materials, money, or information) per unit time per unit area. If one uses energy per unit time, or power, expressed over a unit area, the intensity is power density (Brown 1980).

Carrying Capacity and Economic Competitiveness: EMERGY INVESTMENT RATIO

Given in Figure 5.2 is a diagram illustrating the use of nonrenewable and renewable EMergies in a regional economy. The interaction of indigenous EMergies (both renewable [I] and nonrenewable [N] with purchased resources from outside [F]) is the primary process by which humans interface with their environment.

The Investment Ratio (IR) is the ratio of purchased inputs (F) to all EMergies derived from local sources (the sum of I and N) as follows:

$$IR = F/(I+N) \tag{1}$$

The name is derived from the fact that it is a ratio of "invested" EMergy to resident EMergy. The Investment Ratio is a dimensionless number; the bigger the Investment Ratio the greater the intensity of development. Regional or state-wide IRs are useful for comparing the intensity of individual developments or smaller regions embedded within the larger. The U.S.Investment Ratio is about 8 to 1 and the State of Florida IR is 7.75 to 1, while Dade County's is about 18 to 1. In this analysis we used both the ratio for Florida (calculated previously) and that for Dade County

Determining Regional Carrying Capacity

Once the annual flux of renewable EMergy per year per unit area of landscape (renewable EMergy density) is known and the nonrenewable EMERGY flux for a region is known , the Investment Ratio can be calculated. Renewable EMergy density is derived from regional a EMERGY analysis such as that for Dade County in Section 4.. Using the calculated Investment Ratio for the larger region, the Investment Ratio for a subregion is set equal and then the equation for IR is solved for the nonrenewable EMERGY flux as follows:

$$IR(_{lr}) = IR(_{r}) \tag{2}$$

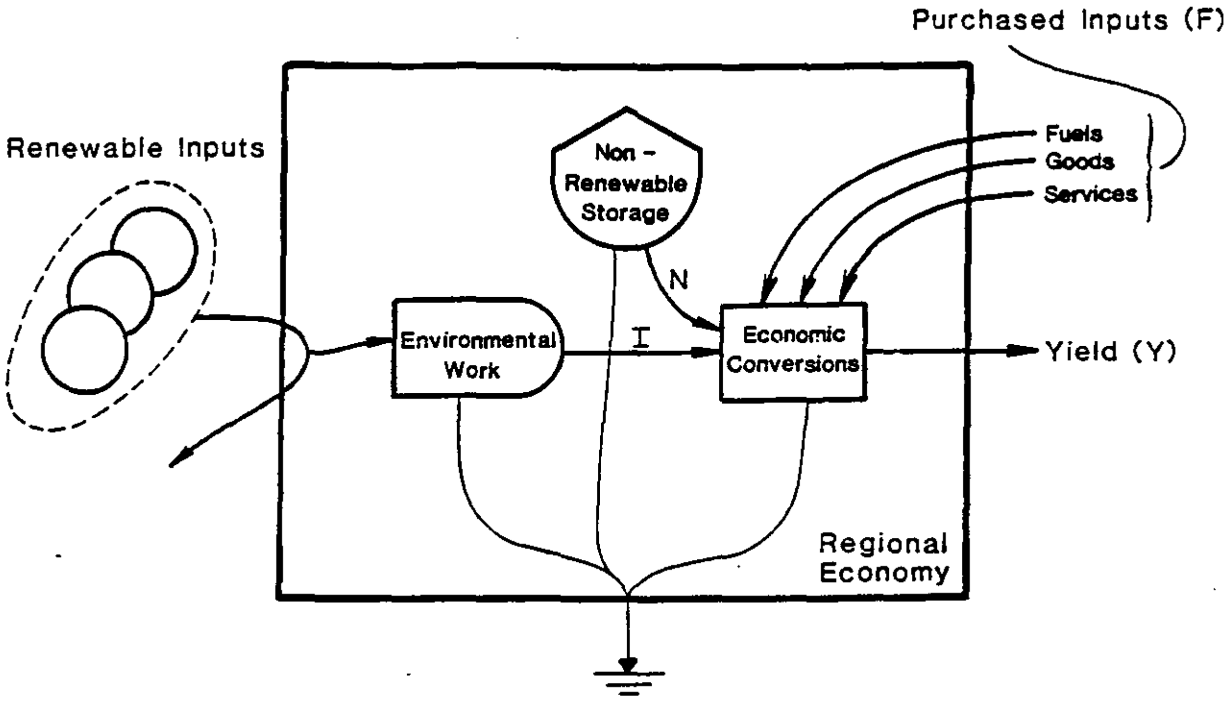
where:

$IR(_{lr})$ =Investment Ratio of the larger region = known

$IR(_{r})$ =Investment Ratio of the sub-region = $[F_r] / [I_r + N_r]$

since $I_r + N_r$ is known, the equation is solved as follows:

$$F_r = [IR_{(lr)}][I_r + N_r] \tag{3}$$



Investment Ratio of Regional Economy: $IR = F/I+N$

Figure 5.2 Systems diagram illustrating Investment Ratio

Once F_r is known , it is added to the quantity $[I_r+N_r]$ yielding the total EMERGY flux for the sub- region. Total population at a given per capita EMERGY use is then determined by dividing total EMERGY flux by EMERGY per capita. EMERGY use per capita is the sum of the emergy used directly or indirectly by the population. This index is a measure of the quality of life in a region that accounts not only for the resources provided by the economy, but also for the ones supplied by the environment. In this sense, it has the advantage of accounting for resources that improve life quality, but are invisible when the measures of economic income are used. The population that can be supported at the given EMERGY per capita is calculated as follows;

$$\text{Population} = (F+N)_r + I_r \,/\, \text{EMERGY per capita} \tag{4}$$

An awareness has recently developed that sustainability is a key factor to consider when considering issues of regional development. Yet sustainability remains an elusive concept. It can be argued that sustainable development, in the long run (100 years or more?), is that which can be supported by the renewable flows of EMergy of a region. Development that depends on purchased resources may not ultimately be sustainable since purchased EMergy is composed of nonrenewable flows and subject to fluctuations in world prices. Yet, development that does not allow for the possibility of using purchased resources to amplify a region's environmental basis cannot give an economic return and becomes a moot point. Thus sustainability should reflect the current intensity of development of an economy and match it. In this way, it is no more dependent on limited supplies of nonrenewable EMergies than the economy as a whole. As the economy's use of nonrenewable purchased energies may decline, new development under these circumstances does not draw more of these energies on the average than the rest.

Determinations of sustainability should take into account the relative mix of: (1) an economy's environmental basis (renewable EMergy sources), (2) its use of nonrenewable storages from within, and (3) its purchased goods, resources, and services. These flows drive the economy and ultimately influence what is sustainable by defining an upper boundary to the present mix of purchased EMergy, resources from within, and renewable EMergy flows. The investment ratio is a ratio of purchased EMergy to resident EMergy and when the ratios of development proposals are compared to the ratio for the economy in which they are imbedded, may provide one means of defining sustainable carrying capacity. Development proposals that have investment ratios that are higher than the economy require more purchased EMergy per unit of resident EMergy and therefore are more vulnerable, on the average, to changes in availability of purchased

EMergy. Developments with lower ratios than the local economy are less vulnerable, but also yield less, on average.

Evaluations of South Dade's Carrying Capacity

In addition to using the Investment Ratio to determine a sustainable EMERGY intensity for the region, carrying capacity using the sustainable water "crop" was also calculated. For each method, several alternative scenarios were analyzed in order to produce a range of population levels.

Water Crop Method

Water crop is a theoretical amount of water that can be harvested from ground water sources without depleting reserves. Based on best estimates of local recharge, the water crop is that amount of local rainfall that can be withdrawn from the drinking water aquifer without causing draw down. We assumed an average annual rainfall in the region of 60 inches, with 75 % evaporation. The receiving area was considered to comprise all of the study area, about 1.6E+9 square meters (395.4E+3 acres), yielding an average of 2.32E+9 cubic meters of water a year (612.94E+9 gallons). With an evapotranspiration and a runoff of 75% and 24 % respectively, the remaining 1 %, 2.32E+7 cubic meters, was assumed as available for human use. Water use per capita was assumed as 346.8 cubic meters a year (251 gallons a day) (Morin, 1987), including agriculture.

Two water use regimes were analyzed in order to determine their corresponding water crop carrying capacity. Under the first, water available from infiltration of rainfall is used and disposed without any recycling effort. Under the second, the rain water available is reused after treatment in a wetlands system designed for the purpose, and then released to estuaries. This increases local infiltration somewhat (0.4% of rainfall) resulting in a higher water crop.

Investment Ratio Scenarios

Investment ratios of Dade County and Florida were used in combination with the renewable emergy density in the south Dade region and two different emergy use per capita levels to calculate several different population levels. When the IR for Florida (7.75 / 1) was used to calculate carrying capacity of south Dade, a development intensity that is more rural in character was obtained. This is the average of the State as a whole, and reflects the average statewide intensity of land utilization. When the Dade County IR (18 / 1) was used to calculate carrying capacity, a development intensity resulted that reflects the average for Dade County, more urban in character.

If the influences of Latin America continue to grow, and Miami continues to act as a hub for business activity with Latin America, development in the south Dade region may continue to grow. Population levels may eventually match the population densities that are characteristic of the northern portions of the County. Local commerce will expand to match the population levels, and international commerce may expand as well, leading to a relatively dense urban economy with less reliance on production of agricultural products. The Dade county Investment Ratio was used to calculate the population level that would be characteristic of this scenario.

On the other hand, if the Latin American "connection" is not as influential, and there is no growth in the south Florida economy, the population level of the south Dade region may be more sustainable if the region is developed to the intensity if Florida on the average. The economy would be an agriculturally based economy with some local commerce and some tourism activity. In fact, much like the present day economy. The State of Florida Investment Ratio was used to calculate the population level that would be characteristic of this scenario

A third scenario was calculated as well. This is the lower population level sustainable at current EMERGY per capita consumption, but relying only on the renewable resource base of the region. This scenario represents a lower limit to population carrying capacity based on current EMERGY consumption patterns.

Table 5.1 summarize the carrying capacity of south Dade based on the Water Crop and Investment Ratio calculations. The sustainable water crop assuming no recycle of treated wastewater locally yielded a population of about 67,000 people. When recycle of treated wastewater is included the sustainable water crop method yielded a population of almost 94,000 people. Carrying capacity using the Investment Ratios of Florida and Dade County was 718,000 and 1.7 million people respectively. The renewable carrying capacity of the region was 82,000 people using Florida's per capita EMERGY consumption and 94,500 using Dade County's per capita EMERGY consumption.

In all, the four population carrying capacities represent differing sustainable population levels under the various scenarios. The lower bound, that which is sustainable on a renewable basis, was calculated to be between about 70,000 and 95,000 people. At higher levels of development intensity, and relying on a continued flux of purchased EMERGY from outside the region, the carrying capacity of south Dade is between 700,000 and 1.7 million people. At these higher levels, water crop calculations suggested that local rainfall/recharge will not be sufficient to

Table 5.1 Summary of Carrying Capacity for South Dade County

Method	Carrying Capacity (1000 people)	Total EMERGY Use (E21 sej/yr)	Area of Dev. Land (E3 hectares)
Water Crop			
1% of Rainfall	67.0	1.8	19.0
1% rainfall + recycle	93.8	2.5	26.0
1% rainfall + Miami wastewater	342.5	9.2	76.4
Investment Ratio			
At Florida's IR	718.0	19.6	85.4
At Dade Co.'s IR	1700.0	40.3	85.4
Renewable EMERGY only	82.0	2.2	18.9

Note: See Appendix B for Tables and Calculations supply water needs of the population. Additional outside water sources will need to be transferred from other areas of south Florida to meet the higher demand.

A Proposal for Increasing Carrying Capacity of South Dade

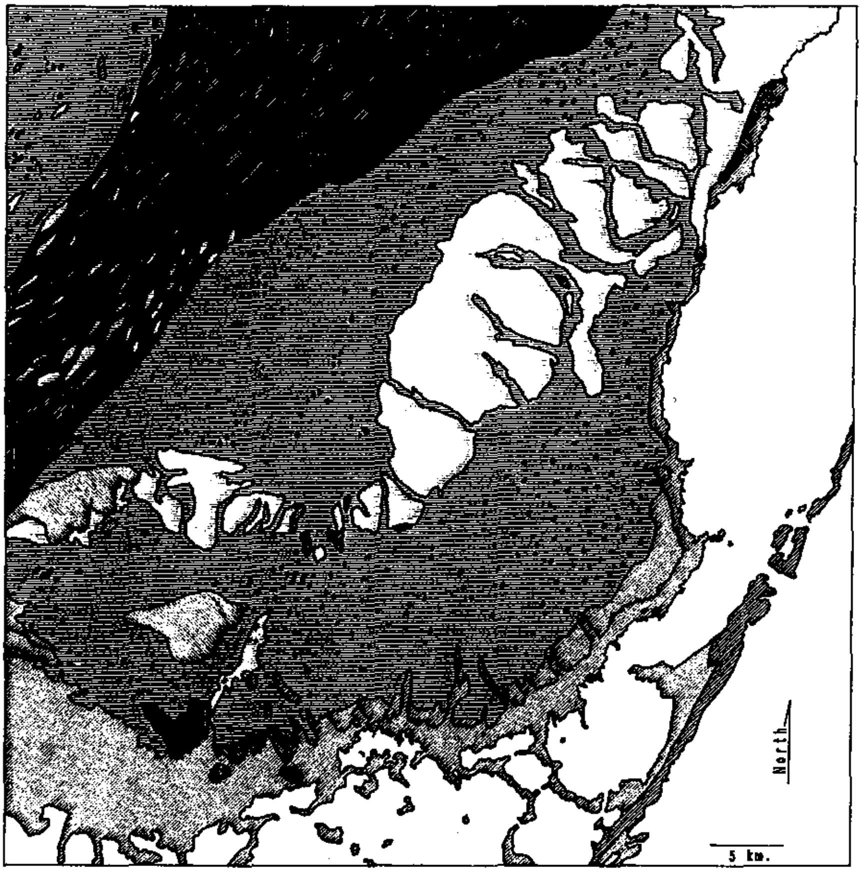
In this analysis a proposal is made to reuse wastewater more effectively and thus increase the development potential of the hurricane impact area in south Dade County. If natural productivity is enhanced and those areas that have been experiencing declines in productivity and are stressed are restored the entire region benefits through better use of resources. Our concept of carrying capacity is based on the ability of a natural system to support economic development, thus if natural areas are restored and enhanced, there is greater support of economic development.

The rebuilding of south Dade County offers a unique opportunity to reestablish wetland sloughs that once drained through the pine ridge connecting the Everglades with Biscayne Bay. During the wet season, waters from inland used to flow through broad sloughs called "finger 'glades" southeastward to Biscayne Bay. The map in Figure 5.3 shows historical land cover (c. 1990) of the south Dade region with the pine ridge actually more resembling a series of islands surrounded by wet prairie. Drainage projects begun in the early part of this century lowered ground water tables and decreased wet season flooding. The map in Figure 5.4 shows present land use and the canal network that is now in place.

The objective of this analysis was to develop a wetland slough system that would allow for effective recycle of reclaimed wastewater and increased flow of Everglades water during the wet season toward the east. The map in Figure 5.5 shows one wetland slough scheme. Reclaimed wastewater from greater Miami would be discharged to the system in its upper northwestern segment and in the wetland area in the vicinity of Homestead. Water flows southwest through the western segment, then southeast to Biscayne Bay.

Tables 5.2 and 5.3 evaluate the emergy in yearly productivity and the emergy associated with structure of the various land uses and land cover of the area that would be converted to wetland slough. The total area is 38,967 hectares (96,287 acres) or about 150 square miles. The single most affected land cover is the classification called Protected Area, which is primarily eastern Everglades. Protected area and "Open Land", together, comprise about 62% of the area affected. When combined with agricultural lands, the area of relatively "undeveloped land" comprises about 90% of the total.

It is important to note that the land use and land cover was compiled from projected land use map by Metro-Dade County Planning, and does not represent the as-built condition. It is our thought that these numbers represent the maximum costs associated with a wetlands slough



Emergy Evaluation of Development
Alternatives for

South Dade County

Hurricane Impact Area

Prepared for
The Florida Energy Office

By

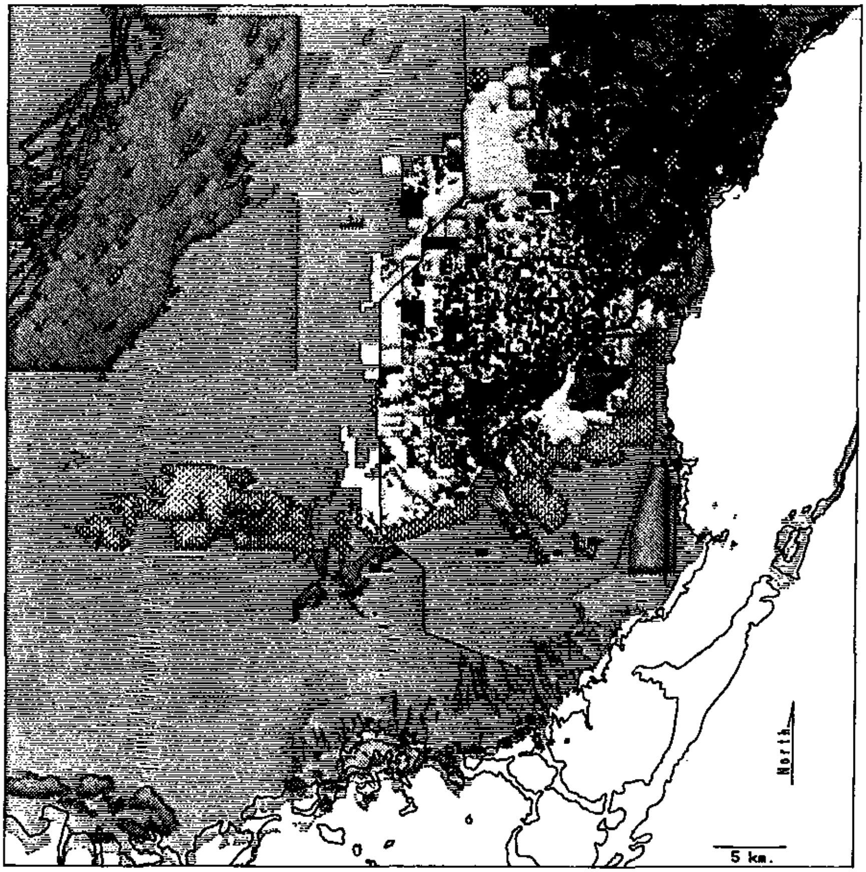
The Center for Environmental Policy
Department of Environmental Engineering Sciences
GIS Analysis and Presentation by Sergio A. Lopez
University of Florida, Gainesville, Fl 32611

Land Cover C. 1900

Sawgrass Marsh
Salt Water
Salt Water Marsh
Scrub Cypress
Hardwood Systems
Scrub Mangrove
Marshes and Slough
Mangrove
Medium Salinity Estuary
Wet Prairie
Pineland System

Adapted from map prepared by the Center for Wetlands
Mark T. Brown and Howard T. Odum 1980

Figure 5.3



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Existing Land Use
C. 1990

- Roads
- Canals
- Commercial and Industrial
- High density residential
- Transportation
- Institutional
- Medium and low density residential
- Parks and protected areas
- Agriculture
- Open land
- Upland forest
- Range lands
- Wetlands
- Open water

Adapted from cover prepared by the South Florida
Water Management District

Figure 5.4

Emergy Evaluation of Development
Alternatives for

South Dade County

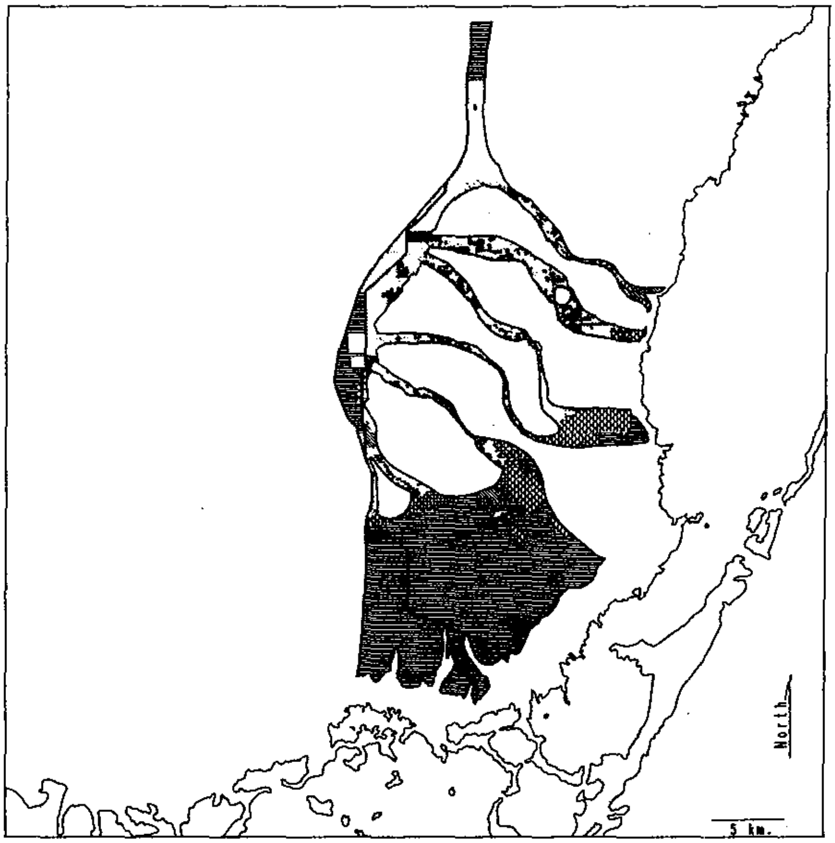
Hurricane Impact Area

Prepared for
The Florida Energy Office

By

The Center for Environmental Policy
Department of Environmental Engineering Sciences
GIS Analysis and Presentation by Sergio A. Lopez
University of Florida, Gainesville, Fl 32611

Land Areas Affected by the Proposed Wetlands



- Roads
- Canals
- Commercial and Industrial
- High density residential
- Transportation
- Institutional
- Medium and low density residential
- Parks and protected areas
- Agriculture
- Open land
- Upland forest
- Range lands
- Wetlands
- Open water

Based on a land use cover prepared by
the South Florida Water Management District.

Figure 5.5

Table 5.2. Productivity loss of land uses within the proposed wetland system

Land Use	Area (acres)	Emergy Density (E12sej/ac./yr)	Empower (E 18sej/yr)
Open Land	14066	33.49	0.47
Protected Area	45285	45.21	2.05
Agriculture	27171	167.44	4.55
Institutional	676	837.20	0.57
Transportation	26	4186.00	0.11
Low/Med Residential	7476	2093.00	15.65
Med/High Residential	122	4353.44	0.53
Bus/Industrial	1465	13395.20	19.62
Total Land Use	96287		43.54

Table 5.3. EMERGY loss associated with structure on land uses within the proposed wetland system

Land Use	Area (acres)	Structure (E12sej/ac)	EMERGY (E 18 sej)
Open Land	14066	4.19	0.06
Protected Area	45285	33.49	1.52
Agriculture	27171	837.20	22.75
Institutional	676	8372.00	5.66
Transportation	26	16744.00	0.44
Low/Med Residential	7476	6279.00	46.94
Med/High Residential	122	10465.00	1.28
Bus/Industrial	1465	50232.00	73.59
Total Land Use	96287		152.23

proposal. The map indicates that about 7,476 acres of low/med residential, 122 acres of med/high residential, and 1,465 acres of business/industrial lands are affected. In addition, about 676 acres of institutional and 26 acres of transportation are affected by the slough system.

The costs associated with conversion of present land uses to wetland can be divided into two areas. First there is the loss associated with loss of yearly productivity. Table 5.2 summarizes these losses. The highest losses are in Business and Low/Med. Residential categories comprising about 81% of the total. The second loss is the structure associated with each land use and land cover type. Table 5.3 summarizes these losses. The highest losses, again, are from Business/Industrial and Low/Med. Residential, comprising about 33% of the total. Agricultural structure, because of the magnitude of area affected is the third largest emergy loss, about 15% of total losses. If some minor modifications were made to the alignment of the slough system, and actual viable structure were taken into account, instead of assuming that all structure is in place, these costs would be substantially reduced. It is quite apparent from the analysis of the hurricane impacts that much of the structure in the south Dade impact area has been damaged and that a large percentage (about 30%) has been damaged beyond usefulness. Thus losses associated with conversion to a wetland slough given in Tables 5.2 and 5.3 are highest losses and when analyzed in greater detail by determining the actual viability of structure within the slough system alignment, we can expect them to decrease.

Table 5.4 summarizes an emergy benefit cost analysis for the proposed wetland slough system. Total costs result from losses of yearly production and structure associated with land uses and land cover types, that are within the "footprint" of the slough, the sloughs capital costs, and its yearly operation and maintenance costs. The largest costs are associated with operation and maintenance (90.7 E18 sej/yr) and capital costs (73.9 E18 sej/yr). Emergy benefits total 1575.9 E18 sej/yr, and the largest of which is the value of the reclaimed wastewater that is used more effectively through the wetland system. The ratio of value received to costs if the wetland slough system were constructed is about 7.3/1, if no additional development occurs.

Additional development could be supported as a result of the increases in productivity in the landscape and good use of reclaimed wastewater. We have estimated that the "multiplier" effect, or matching effect that natural systems have on the economy is about 8/1, thus if this potential increased development is included in the analysis, the total benefits are about 8 times as high, or 12.606 E21 sej/yr. In this case, the benefit received for the losses incurred would be almost 60/1.

The effect on the calculated carrying capacity of south Dade should the wetland slough system be constructed and treated wastewater recycled through it was significant. Assuming

Table 5.4. EMERGY costs and benefits of reclaimed wastewater wetland system in south Dade

Flow or Storage (units)	Amount	Transformity (sej/unit)	EMERGY (E18 sej)
EMERGY Costs			
Yearly Production			43.54
Structural losses			7.61
Capital Costs (E6 $/yr)	46.2	1.60E+12	73.92
O & M (E6 $/yr)	56.7	1.60E+12	90.72
Total Costs			215.80
EMERGY Benefits			
Created Wetlands	96878	66.98	6.49
Reclaimed Water (J/yr)	1.57E+15	1.00E+06	1569.41
Total Benefits			1575.90

345E+6 cubic meters a year (250 MGD), produced by the city is recycled through the system and a volume of 8.62E+7 (25 %), is available for reuse through recharge of local aquifers the water crop carrying capacity population would increase to 342,530 people.

A Proposal for Rebuilding South Dade

We carried the analysis of south Dade one step farther. Using theories of the hierarchical organization of cities in landscapes first enunciated by Chrystaller in 1933 (Brown, 1980), and found to follow a power law distribution by Zipf (1941) and others, we developed hypothetical spatial designs of development for south Dade. Using the calculated population levels from the analysis of carrying capacity to set development density and the wetland slough system as a backdrop, we designed three urban landscapes that represented low, medium, and high development intensity.

The hierarchy of urban centers described by Zipf (1941) and found by Brown (1980) in two regions of Florida, was simulated for south Dade with the simple formula:

$$p=(P/n)/N \tag{5}$$

where

p = is the population of each urban center

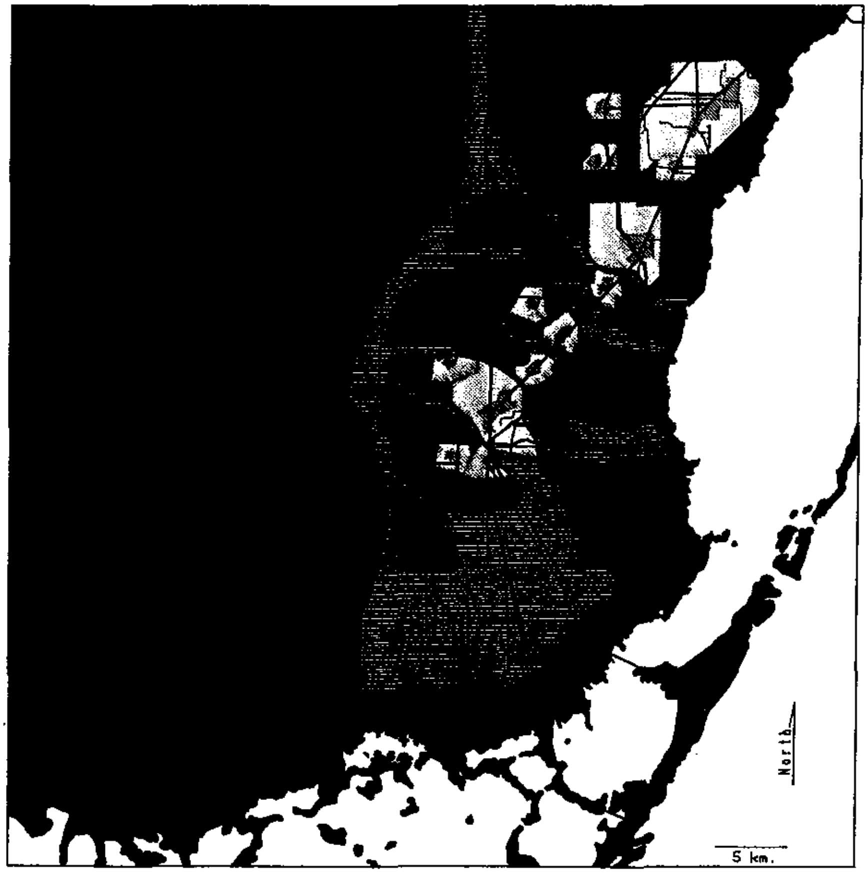
P = is the population of the region,

n = is the number of towns in each class of city, and

N = is the number of classes of cities used

For all the scenarios calculated the number of classes of cities was set at three, with one central, two secondary and ten third level cities.

The area for each urban center was assigned based on the emergy required by the population of that center. Land uses within each city were aggregated in eight categories defined by their empower density. The categories used were: (1) Business and Industrial; (2) medium -high density residential; (3) transportation (including streets and highways); (4) low- medium residential; (5) institutional; (6) agriculture; (7) parks and protected areas; and (8) natural lands. These land uses are arranged in a decreasing order from high empower levels representing the central business district to low empower of the outskirts of the cities and the rural and natural areas.



Emergy Evaluation of Development
Alternatives for

South Dade County

Hurricane Impact Area

Prepared for
The Florida Energy Office

By

The Center for Environmental Policy
Department of Environmental Engineering Sciences
GIS Analysis and Presentation by Sergio A. Lopez
University of Florida, Gainesville, Fl 32611

Low Density Scenario
Table III a.

- Roads
- Canals
- Commercial and Industrial
- High density residential
- Transportation
- Institutional
- Medium and low density residential
- Parks and protected areas
- Agriculture
- Wetlands system
- Mangrove

Map adapted from map produced by Odum and Brown, 1980

Figure 5.6

Emergy Evaluation of Development
Alternatives for

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High Density Scenario
Table V d.

- — Roads
- — Canals
- ▩ Commercial and industrial
- ▩ High density residential
- ▨ Transportation
- ▨ Institutional
- ■ Medium and low density residential
- ■ Parks and protected areas
- □ Agriculture
- ▤ Wetlands systems
- ▩ Mangrove

Adapted from map produced by Odum and Brown, 1980

Figure 5.7

Emergy Evaluation of Development
Alternatives for

South Dade County

Hurricane Impact Area

Prepared for
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Medium Density Scenario
Table III b.

- Roads
- Canals
- Commercial and Industrial
- High density residential
- Transportation
- Institutional
- Medium and low density residential
- Parks and protected areas
- Agriculture
- Wetlands system
- Mangrove

Adapted from map produced by Odum and Brown, 1980

Figure 5.8

The percentage of land for each category was adapted from land use distributions found by Brown (1980) for two regions of Florida, and from Bartholomew (1965)for 53 central cities in the United States. Smaller cities received a higher proportion of low emergy land categories, like agriculture, as they are devoted to concentrate resources from the fields around. Large urban centers concentrate the products from smaller towns, serving as central places, therefore a higher proportion of high emergy land uses, like industrial, commerce and institutional, were concentrated in them.

Figures 5.6 through 5.8 are GIS generated maps of the spatial distribution of cities based on three development intensities. Cities are located along the existing ridge corridor and utilizing the established highway infrastructure. The largest central place is located in the northern portion of the study area closest to greater Miami, near the present day city of Kendal. Other cities are located along the highway infrastructure and at central locations in the surrounding agricultural regions.

In the first scenario (Figure 5.6), representing the population sustainable on renewable EMERGY, the population was about 75,000. The area required for this population was calculated at about 20,000 hectares. The number of city classes was fixed at three, with one central city (25,000 people), two secondary cities (12,500 people each) and ten third class centers (1,250 people each). The medium development scenario (Figure 5.7) represents a sustainable population based on renewable EMERGIES and recycled wastewater from greater Miami. The population in this scenario was about 340,000 people distributed in the three classes of cities as follows: one central city (112,000 people), 2 secondary cities (56,000 people), and 10 third class cities (5,600 people). The final development scenario (Figure 5.8) is based on Investment Ratio calculations and developing the region to levels equal in intensity to the State as a whole. The total population was 1.7 million people distributed in three classes of cities as follows: one central city (567,000 people), 2 secondary cities (283,000 people), and 10 third class cities (28,300 people).

Summary

Questions concerning the impacts of economic development, its costs and benefits and ultimate sustainability, and the carrying capacity of regions for expanded development are relative to the economy in which they are imbedded. The carrying capacity of south Dade County was evaluated using EMergy flows and the EMERGY Investment Ratio and availability of long term storages of water on a sustainable basis. The carrying capacity of the region, using the Investment Ratio was based on setting aside sufficient undeveloped "support area" so that the contributions of environmental resources to the developed economy equaled that which was characteristic of the State economy. Population levels calculated in this manner were between 700,000 and 1.7 million people. In addition, several carrying capacity levels were calculated based on sustainable use of water resources, or "water crop". These suggested that between 70,000 and 90,000 people could be supported without "mining" water resources of the region, and that if treated wastewater were imported from greater Miami, and recycled through constructed wetland sloughs, the sustainable water crop would increase population levels to about 340,000 people.

A range of population levels have been generated using the Investment Ratio and water crop methods. The range has an almost 30 fold difference between the lowest and highest values. Our intention was to suggest that carrying capacity is a dynamic concept, depending on resource availability. With little or no resources available from outside sources, the carrying capacity in south Dade is probably more on the order of 70,000 people. With moderate availability of outside resources, the carrying capacity is probably on the order of 350,000 people. And under full development to intensities characteristic of Dade county, the population level would be over 1.7 million people. Which scenario is appropriate for south Dade, depends on global and national economies, and the degree to which the area is integrated into them.

The use of EMergy flows as a means of evaluating the carrying capacity of regional economies may lend insight into the complex questions surrounding the increased integration of regional economies with outside economies and whether over development is beneficial and sustainable in the long run. The proposed methods of quantitative evaluation are tendered more as a means of helping guide public policy decisions than as the means to once and for all predict ultimate carrying capacity. The intensity to which a region develops, and thus the number of people that are sustainable within it are serious questions that communities should be wrestling with. The age of unlimited resource availability is behind us, requiring more accurate awareness of what over development may mean in the long run.

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Final Report

EMERGY EVALUATION OF ENERGY POLICIES FOR FLORIDA

APPENDICES

Report to the Florida Energy Office

By

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January 31, 1995

APPENDIX A

Emergy Evaluation of Ethanol and Methane

by
S. Bastianoni and M.T. Brown

Emergy Evaluation of Ethanol and Methane
by
S. Bastianoni and M.T. Brown

Ethanol

Figure A-1 is a summary diagram of ethanol production from sugar cane in south Florida. Cane is harvested, transported and fermented to produce ethanol. Renewable inputs include sunlight, wind, and rain. Surface water is pumped into and out of the agricultural fields depending on rainfall patterns and crop needs. An important source for cane production is the storage of soils that are being depleted. Purchased inputs include fuels, goods, and services.

Table A-1 is an emergy evaluation of the ethanol production system. Data for sugar cane production are from Fluck (1992) while data for ethanol production are from Giampietro and Piemental (1990). Renewable energy inputs totaled 12.54 E15 sej/ha*yr^{-1}, the largest of which was topsoil loss (9.97 E15 sej/ha*yr^{-1}). Topsoil loss was about 6 times greater than the emergy inputs of rain and surface water combined.

Purchased inputs to sugar cane production totaled 5.33 E15 sej/ha*yr^{-1}. Largest purchased inputs were labor (1.56 E15 sej/ha*yr^{-1}) and services "embodied" in purchased goods (5.33 E15 sej/ha*yr^{-1}). Total emergy inputs to sugar cane production were 17.87 E 15 of which top soil loss represents almost 57% of the total.

The inputs to ethanol production include sugar cane and water and the steel and cement used in construction of fermentation equipment In addition an important input is services "embodied" in purchased goods. Water and services were the largest of the inputs to ethanol production totaling 0.99 E15 sej/ha*yr^{-1} and 0.82 E15 sej/ha*yr^{-1} respectively.

Total inputs to ethanol production were 19.84 E15, and the energy content of ethanol produced was 1.89 E11 Joules. When expressed as a net emergy yield ratio (the emergy yield divided by nonrenewable energy consumed in its production), ethanol is relatively low (3.15/1). Primary energy sources that support the economy have higher ratios and therefore ethanol will not be competitive until these other sources decline in availability. Such declines will lower their yield ratios , making ethanol more competitive.

Methane

Figure A-2 is a summary diagram of methane production from dairy cow manure. The methane production is part of an "energy integrated dairy farm system in Puerto Rico" (Sasscer and Morgan (1986) and is a by-product of the system. Electricity is generated from combustion of the methane, some of which is used by the farm and some of which is sold during times when on farm demand is low. Renewable inputs to the farm system include sunlight, wind and rain. In addition, groundwater is pumped for irrigation. Purchased inputs include fuels, goods and services. Outputs from the farm system include milk, electricity, and soil loss and pollutants.

Table A-2 is an emergy evaluation of the dairy farm system and its methane production. Non-purchased emergy inputs totaled 508 E15 sej/yr. Rainfall was the largest of the renewable inputs totaling 370.97 sej/yr or about 73% of the total, while agricultural water (126.24 sej/yr) was the largest of the nonrenewable free inputs.

Purchased inputs totaled 388.66 sej/yr, the largest of which were services (117.76 sej/yr), fuel (102.93 sej/yr) and purchased electricity (115.14 sej/yr). Combined these three inputs represent about 86% of the purchased inputs.

The net emergy yield ratio for the methane generated by the system is about 2.4/1. While the operation has a positive net emergy yield ration, it does not compete with richer sources that have higher yields.

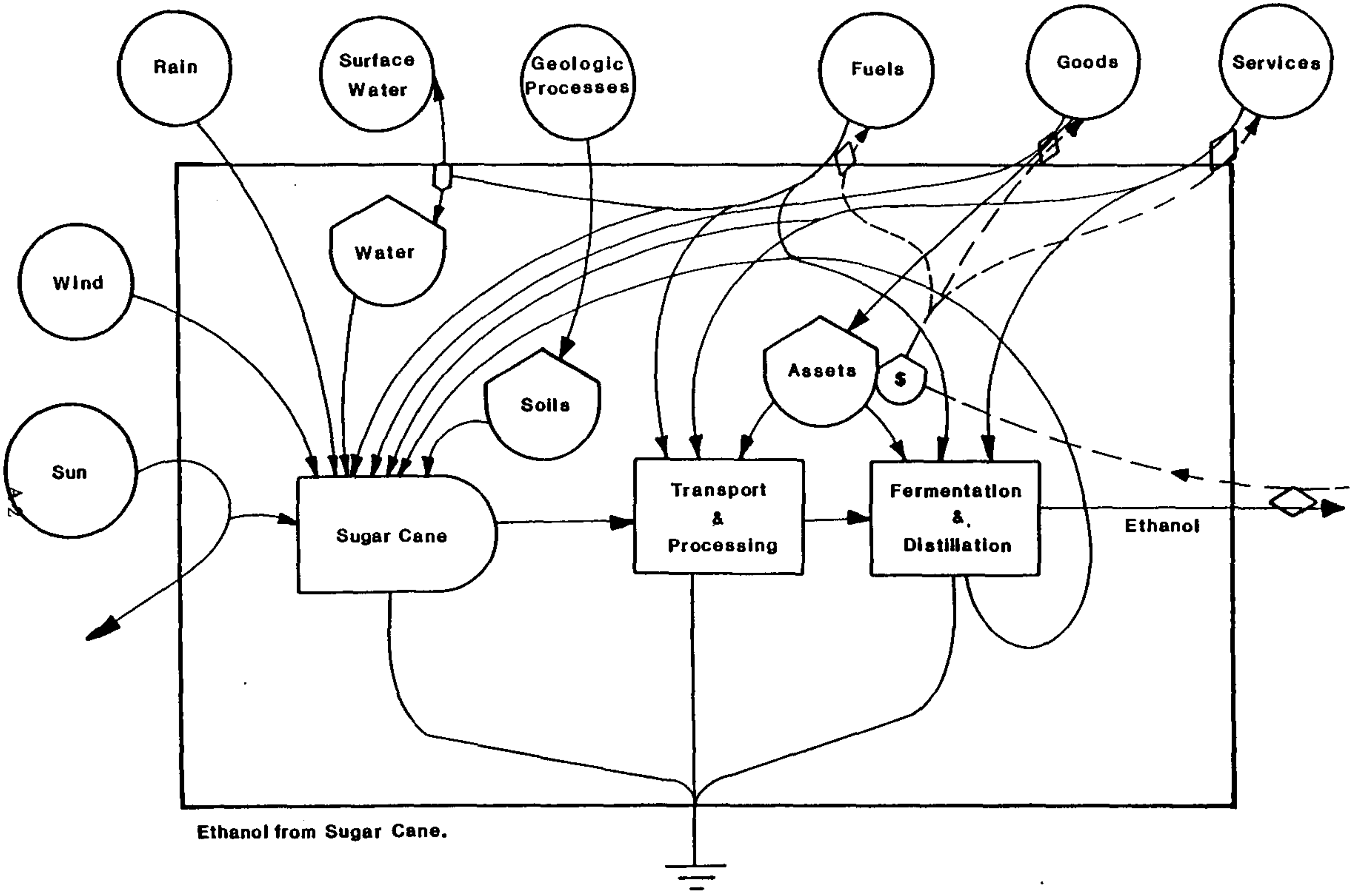

Figure B-1. EMERGY systems diagram of ethanol production from sugarcane.

Table A.1. Emergy analysis of ethanol production from sugarcane for South Florida (data from UF data base [sugarcane production] and Giampietro and Piementel, 1990 [ethanol production])

Note	Item	Unit	Units/ha/yr.	Transformity (sej/unit)	Solar Emergy (E14 sej/ha/yr)
RENEWABLE FREE RESOURCES					
1	Sunlight	J	5.40E+13	1.00E+00	0.54
2	Wind	J	9.89E+11	1.50E+03	14.80
3	Rain	J	2.76E+10	1.54E+04	4.26
NONRENEWABLE FREE RESOURCES					
4	Surface water	J	2.26E+10	4.85E+04	10.95
5	Loss of Topsoil	J	1.59E+11	6.25E+04	99.68
	Sum of indipendent free inputs				125.42
PURCHASED INPUTS FOR SUGARCANE PRODUCTION					
6	Phosphate	g	4.77E+04	6.88E+09	3.28
7	Potash	g	1.91E+05	2.96E+09	5.64
8	Insecticides	J	3.06E+06	1.97E+07	0.60
9	Pesticides	J	5.98E+06	1.97E+07	1.18
10	Other Chemicals	g	2.03E+04	3.00E+09	0.61
11	Diesel	J	4.07E+09	6.60E+04	2.69
12	Lubricants	J	1.75E+08	6.60E+04	0.12
13	Human Labor	hr	3.31E+01	4.70E+13	15.56
14	Services	$	1.57E+03	1.50E+12	23.62
	Sum of purchased inputs for sugarcane production				53.29
	Sum of inputs for sugarcane production				178.72
INPUTS FOR THE ETHANOL PRODUCTION					
15	Sugarcane	g	8.80E+07	2.03E+09	178.72
16	Water	J	3.88E+09	2.55E+05	9.91
17	Steel	g	4.40E+04	2.64E+09	1.16
18	Cement	g	5.03E+04	7.48E+08	0.38
19	Services	$	5.47E+02	1.50E+12	8.20
	Sum of free inputs for ethanol production				135.33
	Sum of purchased inputs for ethanol production				63.03
PRODUCT					
20	Ethanol	J	1.89E+11	1.05E+05	198.36

Notes to Table A.1

1 Sunlight - 1.29 E6 Kcal/m^2/day Ref: Odum et al. (1992)
(1.29 E6 Kcal/m^2/yr)(1 E4 m^2/ha)(4186 J/Kcal) =
5.40E+13 J/ha/yr

2 Wind - eddy diffusion 1.7 m3/m2/s; vertical gradient 1.5 E-3 m/s/m Ref: Odum (1992)
(1000 m)(1.23 kg/m3)(1.7 m3/m2/s)(3.154 E7 s/yr)(1.5 E-3 m/s/m)(1 E4 m^2/ha) =
9.89E+11 J/ha/yr

3 Rain - 22 in/yr
(22 in/yr)(.0254 m/in)(1 E4 m^2/ha)(1000kg/m^3)(4.94 E3 J/kg)=
2.76E+10 J/ha/yr

4 Surface water - 18 in/yr Ref: Brown et al. (1991)
(18in/yr)(.0254 m/in)(1 E4 m^2/ha) (4.94J/g)(1000000g/t)
2.26E+10 J/ha/yr

5 Loss of Topsoil - 1 in/yr Ref: Stephens (1984)
(.0254 m/yr)(1 E4 m^2/ha)(10% organic matter)(.3 E6 g/m3)(5 kcal/g)(4186 J/kcal)
1.59E+11

6 Phosphate (P2O5) - 42.5 lb/acre/yr Ref: Brown et al. (1991)
(42.5 lb/acre/yr)(2.47 acre/ha)(454 g/lb)
4.77E+04 g/ha/yr

7 Potash (K2O) - 170 lb/acre/yr Ref: Brown et al. (1991)
(170 lb/acre/yr)(2.47 acre/ha)(454 g/lb)
1.91E+05 g/ha/yr

8 Insecticides - .65 lb/acre/yr Ref: Odum et al. (1992)
(.65 lb/acre/yr)(2.47 acre/ha)(454 g/lb)(4.2 E3 J/g)
3.06E+06 J/ha/yr

9 Pesticides - 1.27 lb/acre/yr Ref: Odum et al. (1992)
(1.27 lb/acre/yr)(2.47 acre/ha)(454 g/lb)(4.2 E3 J/g)
5.98E+06 J/ha/yr

10 Other chemicals - 18.1 lb/acre/yr
(18.1 lb/acre/yr)(2.47 acre/ha)(454 g/lb)
2.03E+04 J/ha/yr

11 Diesel - 15.56 gal/acre/yr Ref: Brown et al. (1991)
(15.56 gal/acre/yr)(2.47 acre/ha)(3.8 l/gal)(2.79 E7 J/l) =
4.07E+09 J/ha/yr

12 Lubricants - 0.67 gal/acre/yr Ref: Brown et al. (1991)
(0.67 gal/acre/yr)(2.47 acre/ha)(3.8 l/gal)(2.79 E7 J/l) =
1.75E+08 J/ha/yr.

13 Human Labor - 13.4 man-hr/yr/acre Ref: Odum (1988)
(13.4 man-hr/yr/acre)(2.47 acre/ha)
3.31E+01 man-hr/ha/yr

14 Services - 637.5 $/acre/yr Ref: Odum et al. (1992)
(637.5$/acre/yr)(2.47 acre/ha)
1.57E+03 $/ha/yr

15 Sugarcane - 88000 kg/ha
(88000 kg/ha)(1000 g/kg) =
8.80E+07 g/ha/yr

16 Water - 125 E3 l/1000 l ethanol Ref: Brown et al. (1991)
(6285.7 l/ha)(125 E3 l water/1000 l ethanol)=785.7 E3 l/acre/yr

(785.7 E3 l/acre/yr)(4.94 E3 J/l) =
3.88E+09 J/ha/yr

17 Steel - 7 kg/1000 l of ethanol Ref: Brown et al. (1991)
(6285.7 l/ha)(7 kg steel/1000 l ethanol)=44 kg/acre
(44 kg/acre)(1000 g/kg)=
4.40E+04 g/ha/yr

18 Cement - 8 kg/1000 l ethanol Ref: Brown et al. (1991)
(6285.7 l/ha)(8 kg cement/1000 l ethanol)=50.3 kg/acre
(50.3 kg/acre)(1000 g/kg)=
5.03E+04 g/ha/yr

19 Services - 546.5 $/ha/yr Ref: Brown et al. (1991)
5.47E+02 J/ha/yr

20 Ethanol - 6285.7 l/acre
(6285.7 l/ha)(3 E7 J/l)=
1.89E+11 J/ha/yr

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Net Emergy Ratio for Sugarcane Production	3.35
Net Emergy Ratio for Ethanol production	3.15
Free/Purchased Ratio	2.15

References

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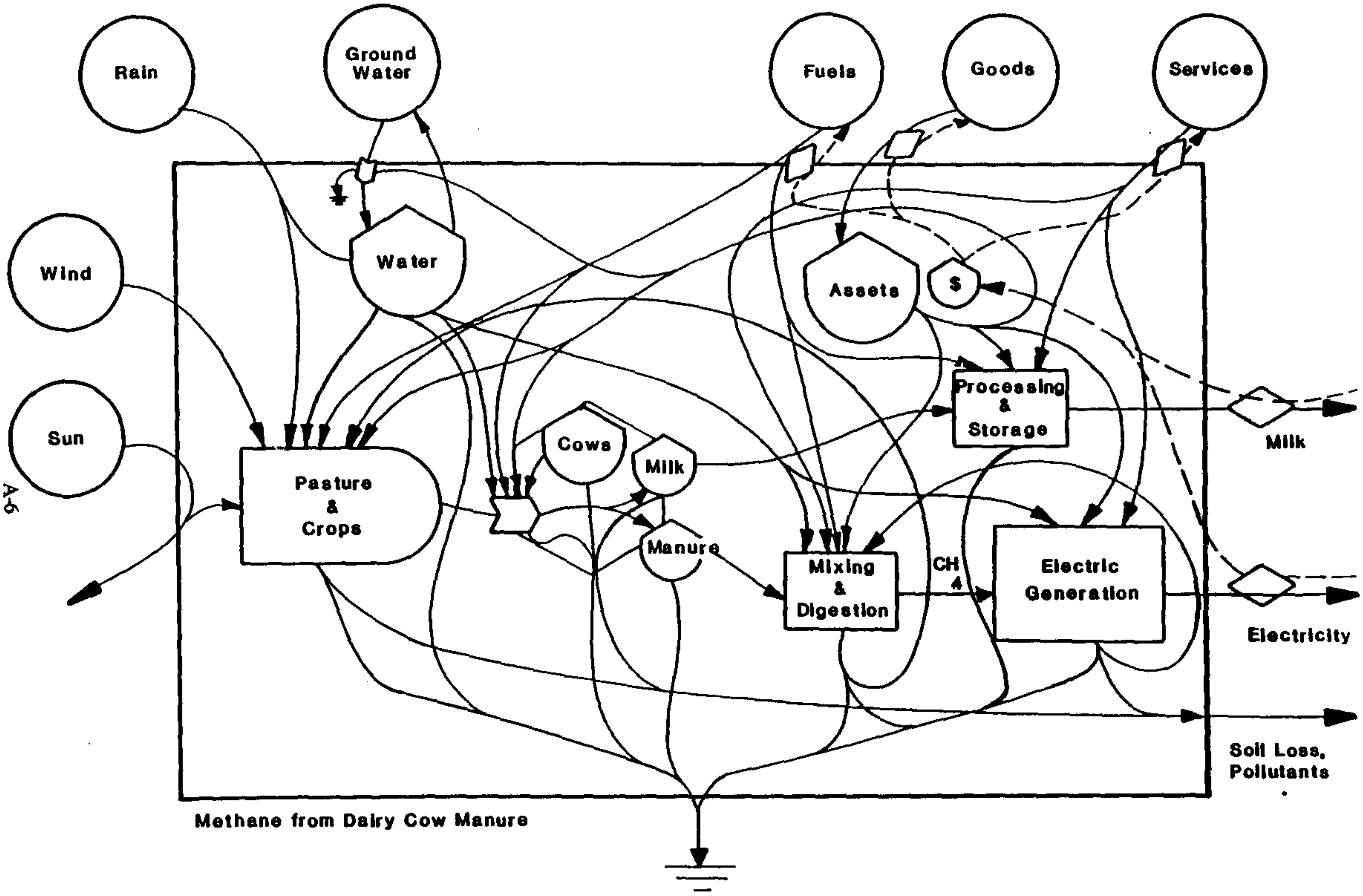

Figure B-2. Methane production from dairy cow manure in Puerto Rico.

Table A.2. Emergy Analysis of Methane Production in Puerto Rico

Note	Item	Unit	Units/Yr.	Transformity (sej/unit)	Solar Emergy (E15 sej/yr)	1986 Macroeconomic Value (E4 $)
RENEWABLE RESOURCES						
1	Sunlight	J	2.98E+16	1.00E+00	29.84	0.99
2	Wind	J	1.89E+12	1.50E+03	2.83	0.09
3	Rain	J	2.40E+13	1.54E+04	370.97	12.37
NONRENEWABLE RESOURCES						
4	Ground water	J	4.47E+10	2.55E+05	11.41	0.38
5	Agricult. water	J	2.61E+12	4.85E+04	126.24	4.21
	Sum of free inputs (sun,wind,waves omitted)				508.63	16.95
PURCHASED INPUTS						
6	Seeds	J	1.15E+10	8.60E+04	0.99	0.03
7	Fertilizer (N)	g	6.48E+06	3.45E+09	22.36	0.75
8	Forage	J	4.10E+10	6.60E+04	2.70	0.09
9	Concrete	g	2.85E+07	9.26E+07	2.64	0.09
10	Machinery	g	1.00E+06	6.70E+09	6.70	0.22
11	Services	$	3.93E+04	3.00E+12	117.76	3.93
12	Fuel	J	1.56E+12	6.60E+04	102.93	3.43
13	Electricity	J	5.76E+11	2.00E+05	115.14	3.84
14	Human Labor	J	8.72E+09	2.00E+06	17.44	0.58
	Sum of purchased inputs				388.66	12.96
	Sum of total inputs				897.28	29.91
PRODUCTS						
15	Milk	l	2.98E+06	3.02E+11	897.28	29.91
16	Manure	g	7.95E+09	1.13E+08	897.28	29.91
17	Methane	J	3.62E+12	2.48E+05	897.28	29.91
18	Electricity	J	7.56E+11	1.19E+06	897.28	29.91

Data from: D.S. Sasscer and T.O. Morgan "Energy Integrated Dairy Farm System in Puerto Rico" Center for Energy and Environmental Research, University of Porto Rico, 1986.

Notes to Table A.2

1 Sunlight - 3.83 E3 Kcal/m^2/day
(3.83 E3 Kcal/m^2/day)(365)(1800 acres)
(4047 m^2/acre)(70% albedo)(4186 J/Kcal) =
2.98E+16 J/yr
2 Wind - 712 J/m^2/day
(712 J/m^2/day)(365 days/yr)(1800acres)(4047 m^2/acre) =
1.89E+12 J/yr
3 Rain - 0.89 m/yr
(0.89 m/yr)(1-.25 runoff)(1800 acre)(4047 m^2/acre)(1000kg/m^3)(4.94 E3 J/kg)
2.40E+13 J/yr.
4 Ground water - (22800 l/day for dilution) + (2000 l/day for the cows)
(24800 l/day)(365 days/yr) (4.94 J/g)(1000g/kg)+
4.47E+10 J/yr
5 Agricultural Water - 54 in/yr
(54 in/yr)(.0254 m/in)(95 acre)(4047 m^2/acre)(1E6 g/m^3)(4.94 J/g) =
2.61E+12 J/yr
6 Seeds - 2.25 g/m^2/yr
(2.25 g/m^2)(90 acres)(4047m^2/acre)(3.345 kcal/g)(4186 J/kcal)=
1.15E+10 J
7 Fertilizer N (purchased) - 6.48 E6 g/yr
6.48E+06 g/yr
8 Forage (purchased) - 13.5 E5 Kg/yr
(13.5 E5 Kg/yr) (7.25 kcal/kg)(4186 J/kcal)=
4.10E+10 J/yr
9 Concrete - 850 m^3 for Loafing Barns + 100 m^3 for the methane production system
(950 m^3)(1.5 E3 kg/m^3)(1000 g/kg) =
2.85E+07 g/yr
10 Machinery - 10 E3 kg. (10 years of use)
Assumption: 60% for crops and milk production, 30%
for methane prod. and 10% for electricity prod.
1.00E+06 g/yr
11 Services = {1.45 E5 (for Agriculture) + 5.5 E4 (for Electrical Power) + 2.79 E5
(for Manure Management)}/20years + 4400+6400+4482 (Maintainance)
{(145,000+55,000+279,400)$/20 yr} + (4400+6400+4482 $/yr) =
3.93E+04 $/yr
12 Fuel - 55900 l/yr of gasoline
(55.9 E3 l)(2.79 E7 J/l) =
1.56E+12 J/yr
13 Electricity - 140,000 for milk production + 19915 for methane production
(159915 kWh)(3.6 E+6 J/kWh) =
5.76E+11 J/yr.

14 Human Labor - 40 E3 $/yr

Total man-hours=4 E4 $/6 $/hr=6666.67
Man-days = Total hours/8 hours per person per day = 833.33
Daily metabolic energy = 2.5 E3 kcal/day per person
(Total man-days)(Daily metabolic energy) (4186 J/kcal) =
8.72E+09 J/yr

15 Milk - 8500 l/day

(8500 l/day)(350 days/yr) =
2.98E+06 l/yr

16 Manure -22.7 E6 g/day

(22.7 E6 g/day)(350 days/yr) =
7.95E+09

17 Methane - 19600 ft^3/day

(19600 ft^3/day)(350 days/year)(500 Btu/ft^3) (1055 J/Btu) =
3.62E+12 J/yr

18 Electricity (produced) - 2.1 E5 kWh/year

(2.1 E5 kWh/yr)(3.6 E6 J/kWh) =
7.56E+11 J/yr

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Total EMergy for the farm (without methane production)	753.65
Total EMergy purchased by the farm	245.02
Net Emergy ratio for the dairy farm:	3.08
Total Emergy with Milk-Methane production	868.95
Total EMergy purchased with the methane production	360.32
Net Emergy Ratio for Milk or Methane production	2.41
Total Emergy with Milk-Electricity production	897.28
TotalEmergy purchased with electricity production	388.66
Net Emergy Ratio for Milk or Electricity production	2.31
Total Emergy if the Electricity is fed back	782.15
Total Emergy purchased if the electricity is fed back	273.52
Net Emergy Ratio for Milk or Electricity production (electricity fed back for internal use)	2.86

APPENDIX B

Emergy Evaluation of Dade County's MetroRail

By

M. T. Brown

Emergy Evaluation of Dade County's MetroRail

By

M.T. Brown

Table B-1 is an emergy evaluation of Metro-Rail in Dade County, Florida, an above ground mass transit system. Data were obtained directly from MetroDade Transit Authority. Data are based on a 21 mile segment of the rail, with cars having a useful life of 30 years and the rail, itself, having a useful life of 50 years.

Total emergy invested in the mass transit system is divided into materials in cars, materials in the rail system, and operation and maintenance. Total emergy of materials in cars is 0.82 E18 sej, while the emergy in the rail system is 54.7 E18 sej. The largest input to the rail system is the emergy in steel (37.8 E18 sej or about 69% of the total inputs. Services "embodied" in both cars and the rail system amount to 15.24 E18 sej or about 28% of the total inputs to the car and rail system.

Total emergy inputs to the mass transit system are equal to 121.7 E18 sej. Opperation and maintenance inputs total 66.2 E18 sej, or about 54% of the total. The emergy in structure equals about 46% of the total.

For comparison with other forms of transportation, the emergy costs are expressed as emergy per passenger-mile. The total number of riders per year was 1.49 E7 and the average trip length was 8.0 miles. Thus the emergy per passenger mile was calculated as 1.02 E12 sej/pass.-mi. (6.35 E11 sej/pass.-km)

Table B.1. EMERGY ANALYSIS OF MASS TRANSIT: Metro-Rail

Note	Item	Raw Units (J,Kg,$)	Transformity (sej/unit)	Solar Emergy (E18 sej)
DIRECT RENEWABLE ENERGY				
1.	Sun	1.32E+14 J	1	0.00
2.	Rain	8.57E+10 J	15444	0.00
MATERIALS IN CARS				
3.	Steel	8.55E+04 Kg	2.6E+12	0.23
4.	Iron	1.27E+04 Kg	9.3E+11	0.01
5.	Aluminum	1.90E+04 Kg	1.6E+13	0.31
6.	Plastics	1.43E+04 Kg	3.7E+11	0.01
7.	Other	2.69E+04 Kg	9.9E+12	0.27
	Subtotal	1.58E+05 Kg		0.82
MATERIALS IN RAIL SYSTEM				
8.	Concrete	1.77E+07 Kg	9.3E+10	1.64
9.	Steel	1.45E+07 Kg	2.6E+12	37.82
10.	Services	1.27E+07 $	1.2E+12	15.24
	Subtotal			54.70
OPERATION AND MAINTENANCE				
11.	Electricity	2.23E+13 J	1.6E+05	3.55
12.	Services	5.22E+07 $	1.2E+12	62.64
	Subtotal			66.19
TOTAL INPUTS				121.70
OUTPUTS				
13.	Emergy per passenger- mile		1.02E+12 sej/ pass.-mi	
14.	Emergy per passenger-kilometer		6.35E+11 sej/pass.-km	

Notes to Table B.1.

All data from MDTA except where indicated

1. Renewable energy: Sun

Length = 33950 m
Width = 7 m
Insolation = 133 Cal/cm^2/yr (Vishner, 1954)
Albedo = 0.90 (estimate)
Energy (J) = Length of rail * width * Insolation*(1-albedo)
= 1.32E+14

2. Renewable energy: Rain

Length = 33950 m
Width = 7 m
Rainfall = 1.46 m/yr (UFBEBR, 1991)
Runoff = 0.95 % (estimate)
Energy (J) = Length * width * Rainfall*(1-runoff)*(energy/kg)
= 8.57E+10

3-7. Materials in Cars (usefull life = 30 years)

Number of cars = 136 cars
Weight per car = 77000 #
Composition : (estimate)
Steel = 54%
Iron = 8%
Aluminum = 12%
Plastics = 9%
Other = 17%
Mass (Kg) = (No. of Cars*weight per car*% composition)/30 years

8. Materials in rail system: Concrete (useful life = 50 years)

Length = 21 mi
Volume/unit length = 22880 yds^3/mi (estimate)
Weight/unit = 4050 #/yd^3
Mass (Kg) = (Length*Vol/length*weight*0.4536 kg/lb)/50 yrs
= 1.77E+07

9. Materials in rail system: Steel (useful life = 50 years)

Length = 21 mi
Volume/unit length = 5720 yds^3/mi (estimate)
Weight/unit = 13284 #/yd^3
Mass (Kg) = (Length*Vol/length*weight*0.4536 kg/lb)/50 yrs
= 1.45E+07

10. Materials in rail system: Services (useful life = 50 years)
Cost of conttruction = 6.35E+08 $
Useful life = 50 yrs (estimate)
= 1.27E+07 $/yr

11. Operation and maintenance: Electricity (per year)
Electricity = 6.20E+06 KWH
Energy (J) = Electricity * 860 Cal/KWH* 4187 J/Cal
= 2.23E+13

12. Operation and Maintenance: Services (per year)
Labor costs = 1.56E+07 $
Maintenance costs = 3.66E+07 $ (estimate based on labor costs)
Total costs = 5.22E+07

13. Outputs: Emergy per passenger -mile
No. of Riders = 1.49E+07 per year
Avg. trip length = 8.0 mi
Emergy/pass.-mi = Total emergy per year /(no. riders)*(trip length)
= 1.02E+12 sej/passenger-mi

14. Outputs: Emergy per passenger -kilometer
Emergy/pass.-km = (Emergy/pass.mi) / (1.609 km/mi)
= 6.35E+11 sej/passenger-kilometer

APPENDIX C

Notes to Tables 4.1, 4.2, 4.4, and 4.5
EMERGY Evaluation of Dade County and the Hurricane Impact Area

by
R. Woithe

APPENDIX C Notes to Tables 4.1, 4.2, 4.4, and 4.5

Abbreviations Used

FDC	Florida Department of Commerce
FLDEDR	Florida Legislature Division of Economic & Demographic Research
MDCPD	Metro-Dade County Planning Department
UFBEBR	University of Florida, Bureau of Economic & Business Research
USFWS	United States Fish and Wildlife Service

Notes to Table 4.1.

NOTE:

1 SUNLIGHT ABSORBED AT SURFACE:
Annual Energy = ((shelf area) m^2 + (land area) m^2 * (insolation) J/m^2-y * (1-albedo)
Continental shelf= 930000000 m^2 (estimated)
Land Area = 506400000 m^2 (UFBEBR, 1991)
Insolation = 690000000 J/m^2-y (Vishner, 1954)
Albedo = 0.14 (% given as decimal) (Odum et al., 1987)
Annual Energy = 3.5568E+19 J/y

2 WIND ABSORBED AT SURFACE:
Surface Wind = 6E+17 J/y (estimated from Odum et al. (In Preparation))

3 RAIN, GEOPOTENTIAL:
Annual Energy = (area) m^2 * (mean elevation) m * (runoff) m/y * (water density) kg/m^3 * (gravitational constant) m/s^2
Area = 506400000 m^2
Runoff = 0.25 m (Odum et al., 1987)
Avg elev. = 5 m
Grav. constant = 9.80 m/s^2
Water density = 1000 kg/m^3
Annual Energy = 6.253E+13 J/y

4 RAIN, CHEMICAL POTENTIAL:
Annual Energy = ((land area) m^2 * (land rainfall) m/y * (fraction evapotranspired) + (shelf area) m^2 * (shelf rainfall) m/y)) * (moles water * univ. gas constant * temp.) kcal/oK-g * (ln((fresh water conc.)/(sea water conc.)) * (rain water density) Kg/m^3
Land area = 506400000 m^2 (UFBEBR, 1991)
Continental shelf = 930000000 m^2 (estimated)
Rainfall = 1.46 m/yr (UFBEBR, 1991)
Rain over shelf = 1.46 m/yr
Evapotrans rate = 0.50 (percent given as decimal)
Fresh water conc. = 1000000 ppm (assumed)
Sea water conc. = 965000 ppm (assumed)
Moles * R * temp. = 5000 J/Kg
Water density = 1000 kg/m^3
Annual Energy = 9.1931E+16 J/y

5 WAVES BREAKING ON SHORELINES:
Annual Energy = (exposed shore length) cm * 1/8 * (sea water density) g/cm^3 * (gravitational constant) cm/s^2 * ((mean wave height)^2 cm^2 * (water depth @ wave gage) m)^1/2 * 1.0E-07 J/erg * 3.2e+07
Shore length = 8900000 cm (estimated)
Sea water density = 1.03 g/cm^3
Grav. constant = 980.00 cm/s^2
mean wave ht. = 65.00 cm
depth @ gage = 300.00 cm
Annual Energy = 8.0744E+15 J/y

6 TIDES:
Annual Energy = (shelf area) m^2 * 1/2 * (# tides/y) * (mean tidal range)^2 m^2 * (fraction of tide absorbed) * (sea water density) kg/m^3 * gravitational constant) m/s^2 * 1.0E-07 J/erg * 3.15+07 s/y * 100 cm/m
Continental Shelf= 9.3E+12 cm^2 (estimated)
Mean Tidal Range = 70.00 cm (Odum et al., 1987)
Number tides/yr = 730.00
Tide absorbed = 0.13 fraction (estimated)
Sea water density = 1.03 g/cm^3
Grav. constant = 980.00 cm/s^2
Annual Energy = 3.893E+16 J/y

INDIGENOUS RENEWABLES

7 AGRICULTURAL PRODUCTION:
1990 total crops = 1.1E+14 J/y (estimated from UFBEBR (1991), SFGO (1992), & Pianka (1983))
Used within area = 5.5E+12 J/y (assumed 5% of total used within Dade)

At < 1% of state's total (UFBEBR, 1991), livestock production assumed to be negligible

FISHERIES:
8 1990 Shellfish = 2E+12 J/y (from UFBEBER (1991)) (assumes all used within Dade)
9 1990 Finfish = 1.9E+12 J/y (from UFBEBER (1991)) (assumes all used within Dade)

NONRENEWABLE SOURCES FROM WITHIN THE SYSTEM

10 GROUNDWATER WITHDRAWLS:
Annual Energy = (water withdrawn) m^3/y * (moles water * univ. gas constant * temp.) * kcal/oK-g * (ln((fresh water conc.)/(sea water conc.)) * (fresh water density) Kg/m^3
1990 withdrawl = 670000000 m^3/yr (UFBEBR, 1991)
Moles * R * temp. = 5000 J/Kg

APPENDIX C continued

Fresh water conc. = 1000000 ppm (assumed)
Sea water conc. = 965000 ppm (assumed)
Water density = 1000 kg/m^3
Annual Energy = 1.2161E+13 J/y

11 LIMESTONE:
1990 extraction = 9.4E+11 g/y (estimated from FDC (1991))
% used in Dade = 50.00 % (assumed)
Used in Dade = 4.7E+11 g/y (assumes 50% used in Dade County)

IMPORTS AND OUTSIDE SOURCES:

12 FUEL:
1990 gasoline use = 1.6E+17 J/y (estimated from UFBEBR (1991))

13 ELECTICITY:
1990 total use = 2.2E+17 J/y (estimated from UFBEBR (1991))

14 NET IMMIGRATION:
Immigration = 16000 people/y (from FDC (1991))
Average Age = ??? years
j/Ind = 320000000 j/indiv
Energy in immigrants = 5.12E+13 J/y

15 GOODS & SERVICES IN IMPORTS:
1990 total tourism input= 310000000 $/y (Estimated from FLDEDR (March, 1990 - February, 1991)
1990 net Federal input= 540000000 $/y (Estimated from UFBEBR (1991))
Net Federal Government input = (Funding, Spending, & Payments - Taxes)
1990 transfer paymnts= 420000000 $/y (UFBEBR (1991))
Total = 1.27E+10 $/y

EXPORTS

16 AGRICULTUAL PRODUCTS:
1990 exports = 1.045E+14 J/y (assumes 95% of total production exported (from note 7 above))

17 LIMESTONE:
1990 extraction = 4.7E+11 g/y (assumes 50.00 % export)

18 SERVICES IN EXPORTS
Services in other exports = (Ag Exports + Mineral Exports)
= 312000000 $/y (estimated from FDC (1991))

APPENDIX C continued

Notes to Table 4.2.

NOTE:

1 SUNLIGHT ABSORBED AT SURFACE:

Annual Energy = ((shelf area) m^2 + (land area) m^2 * (insolation) J/m^2-y * (1-albedo)
Continental shelf= 1.86E+09 m^2 (estimated)
Land Area = 3.40E+09 m^2 (UFBEBR, 1991)
Insolation = 6.90E+09 J/m^2-y (Vishner, 1954)
Albedo = 0.14 (% given as decimal) (Odum et al., 1987)
Annual Energy = 3.12E+19 J/y

2 WIND ABSORBED AT SURFACE:

Surface Wind = 4.00E+17 J/y (estimated from Odum et al. (In Preparation))

3 RAIN, GEOPOTENTIAL:

Annual Energy = (area) m^2 * (mean elevation) m * (runoff) m/y * (water density) kg/m^3 * (gravitational constant) m/s^2
Area = 3.40E+09 m^2
Runoff = 0.25 m (Odum et al., 1987)
Avg elev. = 2 m
Grav. constant = 9.80 m/s^2
Water density = 1.00E+03 kg/m^3
Annual Energy = 1.68E+13 J/y

4 RAIN, CHEMICAL POTENTIAL:

Annual Energy = ((land area) m^2 * (land rainfall) m/y * (fraction evapotranspired) + (shelf area) m^2 * (shelf rainfall) m/y)) * (moles water * univ. gas constant * temp.) kcal/oK-g * (ln((fresh water conc.)/(sea water conc.)) * (rain water density) Kg/m^3
Land area = 3.40E+09 m^2 (UFBEBR, 1991)
Continental shelf = 1.86E+09 m^2 (estimated)
Rainfall = 1.46 m/yr (UFBEBR, 1991)
Rain over shelf = 1.46 m/yr
Evapotrans rate = 0.50 (percent given as decimal)
Fresh water conc. = 1.00E+06 ppm (assumed)
Sea water conc. = 9.65E+05 ppm (assumed)
Moles * R * temp. = 5.00E+03 J/Kg
Water density = 1.00E+03 kg/m^3
Annual Energy = 9.45E+16 J/y

5 WAVES BREAKING ON SHORELINES:

Annual Energy = (exposed shore length) cm * 1/8 * (sea water density) g/cm^3 * (gravitational constant) cm/s^2 * ((mean wave height)^2 cm^2 * (water depth @ wave gage) m)^1/2 * 1.0E-07 J/erg * 3.2e+07
Shore length = 6.00E+06 cm (estimated)
Sea water density = 1.03 g/cm^3
Grav. constant = 980.00 cm/s^2
mean wave ht. = 65.00 cm
depth @ gage = 300.00 cm
Annual Energy = 5.44E+15 J/y

APPENDIX C continued

6 TIDES:
Annual Energy = (shelf area) m^2 * 1/2 * (# tides/y) * (mean tidal range)^2 m^2 * (fraction of tide absorbed) * (sea water density) kg/m^3 * gravitational constant) m/s^2 * 1.0E-07 J/erg * 3.15+07 s/y * 100 cm/m
Continental Shelf= 1.86E+13 cm^2 (estimated)
Mean Tidal Range = 70.00 cm (Odum et al., 1987)
Number tides/yr = 730.00
Tide absorbed = 0.13 fraction (estimated)
Sea water density = 1.03 g/cm^3
Grav. constant = 980.00 cm/s^2
Annual Energy = 7.79E+16 J/y

INDIGENOUS RENEWABLES

7 AGRICULTURAL PRODUCTION:
1990 total crops = 4.95E+13 J/y (estimated from UFBEBR (1991), SFGO (1992), & Pianka (1983))
Used within area = 2.48E+12 J/y (assumed 5% of total used within area)
At < 1% of state's total (UFBEBR, 1991), livestock production assumed to be negligible

FISHERIES:
8 1990 Shellfish = 5.62E+12 J/y (estimated from UFBEBER (1991))
used in area = 5.62E+11 J/y (assumes 10% used within area)
9 1990 Finfish = 2.07E+12 J/y (estimated from UFBEBER (1991))
used in area = 2.07E+11 J/y (assumes 10% used within area)

NONRENEWABLE SOURCES FROM WITHIN THE SYSTEM

10 GROUNDWATER WITHDRAWLS:
Annual Energy = (water withdrawn) m^3/y * (moles water * univ. gas constant * temp.) * kcal/oK-g * (ln((fresh water conc.)/(sea water conc.)) * (fresh water density) Kg/m^3
1990 withdrawl = 1.27E+08 m^3/yr (estimated from UFBEBR (1991) and MDCPD (1988))
Moles * R * temp. = 5.00E+03 J/Kg
Fresh water conc. = 1.00E+06 ppm (assumed)
Sea water conc. = 9.65E+05 ppm (assumed)
Water density = 1.00E+03 kg/m^3
Annual Energy = 2.31E+12 J/y

11 LIMESTONE:
1990 extraction = 2.35E+11 g/y (estimated from FDC (1991))
% used in area = 50.00 % (assumed)
Used in area = 1.18E+11 g/y (assumes 50% used in Dade County)

APPENDIX C continued

IMPORTS AND OUTSIDE SOURCES:

12 FUEL:
1990 gasoline use = 3.04E+16 J/y (estimated from UFBEBR (1991))

13 ELECTICITY:
1990 total use = 4.18E+16 J/y (estimated from UFBEBR (1991))

14 NET IMMIGRATION:
Immigration = 4000 people/y (estimated from FDC (1991))
Average Age = 25 years
j/Ind = 3.20E+09 j/indiv
Energy in immigrants =1.28E+13 J/y

15 GOODS & SERVICES IN IMPORTS:
1990 total tourism input= 5.89E+08 $/y (Estimated from FLDEDR (March, 1990 - February, 1991)
1990 net Federal input= 1.03E+09 $/y (Estimated from UFBEBR (1991))
Net Federal Government input = (Funding, Spending, & Payments - Taxes)
1990 transfer paymnts= 7.98E+08 $/y (UFBEBR (1991))
Total = 2.41E+09 $/y

EXPORTS

16 AGRICULTUAL PRODUCTS:
1990 exports = 4.70E+13 J/y (assumes 95% of total production exported (from note 7 above))

FISHERIES:
17 1990 Shellfish = 5.62E+12 J/y (estimated from UFBEBER (1991))
exported from area = 5.06E+12 J/y (assumes 90% exported area)
18 1990 Finfish = 2.07E+12 J/y (estimated from UFBEBER (1991))
exported from area = 1.86E+12 J/y (assumes 90% exported area)

19 LIMESTONE:
1990 extraction = 1.18E+11 g/y (assumes 50.00 % export (see note 11))

20 SERVICES IN EXPORTS
Services in other exports = (Ag Exports + Mineral Exports)
= 2.70E+08 $/y (estimated from FDC (1991))

APPENDIX C continued

Notes to Table 4.4.

NOTE:

1 Beaches, dunes & salt flats
1991 area = 1.4E+02 ha (estimated from Brown (1980))
biomass/area = 6.8E+08 J/ha (from Brown (1980))
total structure = 9.5E+10 J

2 Emerging systems
1991 area = 3.6E+02 ha (estimated from Brown (1980))
biomass/area = 8.4E+08 J/ha (from Brown (1980))
total structure = 3.0E+11 J

3 Scrub mangroves
1991 area = 5.4E+03 ha (estimated from Brown (1980))
biomass/area = 1.2E+09 J/ha (from Brown (1980))
total structure = 6.5E+12 J

4 Lakes and ponds
1991 area = 9.7E+02 ha (estimated from Brown (1980))
biomass/area = 1.3E+09 J/ha (from Brown (1980))
total structure = 1.3E+12 J

5 Urban parks
1991 area = 1.5E+03 ha (estimated from MDCDP (1988))
biomass/area = 4.2E+09 J/ha (from Brown (1980))
total structure = 6.3E+12 J

6 Wet prairie
1991 area = 4.4E+04 ha (estimated from USFWS (1985) and Stephens (1984))
biomass/area = 8.7E+09 J/ha (from Brown (1980))
total structure = 3.8E+14 J

7 Scrub cypress
1991 area = 5.2E+03 ha (estimated from Brown (1980) and USFWS (1985))
biomass/area = 1.0E+10 J/ha (from Brown (1980))
total structure = 5.2E+13 J

8 Pine uplands
1991 area = 1.1E+03 ha (estimated from Brown (1980) and MDCDP (1988))
biomass/area = 1.4E+10 J/ha (from Brown (1980))
total structure = 1.5E+13 J

10 Agriculture
1991 area = 1.6E+04 ha (estimated from MDCDP (1988))
biomass/area = 3.1E+10 J/ha (from Brown (1980))
total structure = 5.0E+14 J

APPENDIX C continued

11 Mangroves and salt marshes
1991 area = 6.0E+04 ha (estimated from Brown (1980) and USFWS (1985))
biomass/area = 3.4E+10 J/ha (from Brown (1980))
total structure = 2.0E+15 J

12 Cypress domes & strands
1991 area = 2.5E+04 ha (estimated from Brown (1980) and USFWS (1985))
biomass/area = 3.6E+10 J/ha (from Brown (1980))
total structure = 9.0E+14 J

13 Hardwood hammocks
1991 area = 4.1E+03 ha (estimated from Brown (1980))
biomass/area = 4.0E+10 J/ha (from Brown (1980))
total structure = 1.6E+14 J

14 Sawgrass marsh
1991 area = 1.1E+05 ha (estimated from USFWS (1985) and Stephens (1984))
biomass/area = .6E+10 J/ha (from Brown (1980))
total structure = 5.1E+15 J

15 Single-family residential
1991 area = 5.3E+04 ha (estimated from MDCDP (1988))
concrete/area = 1.6E+08 g/ha (Brown, 1980)
total concrete = 8.5E+12 g
wood/area = 9.1E+11 J/ha (Brown, 1980)
total wood = 4.8E+16 J

16 Transportation
1991 area = 6.8E+03 ha (estimated from MDCDP (1988))
asphalt/area = 9.6E+11 J/ha (from Brown (1980) & Shonka (1978))
total asphalt = 6.5E+15 J
subase rock/area = 5.9E+07 g/ha (Brown, 1980)
total subase rock = 4.0E+11 g

17 Multi-family residential
1991 area = 4.0E+03 ha (estimated from MDCDP (1988))
concrete/area = 6.4E+08 g/ha (Brown, 1980)
total concrete = 2.6E+12 g
wood/area = 3.5E+12 J/ha (Brown, 1980)
total wood = 1.4E+16 J

18 Commercial & industrial
1991 area = 4.2E+03 ha (estimated from MDCDP (1988))
concrete/area = 5.5E+08 g/ha (Brown, 1980)
total concrete = 2.3E+12 g

Notes to Table 4.5

1 Natural System Structure (biomass):

Based on the following areas and total standing stock:

	Area (ha)	Stock (J/ha)	
Upland forests	5.20E+03	3.40E+10	(Odum & Brown, 1976)
Cypress	2.50E+04	3.60E+10	(Odum & Brown, 1976)
Mangroves	6.00E+04	3.40E+10	(Odum & Brown, 1976)

Assume the following percent losses:

	Percent loss	Total loss	
Upland forests	10%	1.77E+13	(estimate)
Cypress	10%	9.00E+13	(estimate)
Mangrove	20%	4.08E+14	(estimate)
	Total	5.16E+14	

2 Natural System Productivity:

Based on the following areas and annual productivity:

	Area (ha)	Prod. (kg OM/ha/yr)	
Upland forests	5.20E+03	5.20E+04	(Odum & Brown, 1976)
Cypress	2.50E+04	4.40E+04	(Odum & Brown, 1976)
Mangroves	6.00E+04	9.13E+04	(Odum & Brown, 1976)

Assume the following time for recovery and 50% loss:

	Time (years)	Total loss	
Upland forests	2	2.70E+07	(estimate)
Cypress	3	1.65E+08	(estimate)
Mangrove	3	1.64E+09	(estimate)
	Total	1.83E+09	

Energy (J) = Prod. * energy content

2.28 E10 kg * 4000 Cal/kg*4187 Joules/Cal = 3.07E+16

3 Agricultural Bldgs and Equip:

Estimated value as: $9.65E+08 (Miami Herald 9/10/92)

4 Agricultural Structure (biomass):

based on the following areas and total standing stock:

	Area (ha)	Stock (kg/ha)	
Veg. crops	29746	5.00E+03	(Odum & Brown, 1976)
Ornm. Plants	2900	1.00E+04	(Odum & Brown, 1976)
Tropical Fruit	2630	8.00E+03	(Odum & Brown, 1976)

Assume the following percent losses:

	Percent loss	Total loss	
Veg. crops	10%	1.49E+07	(estimate)
Ornm. Plants	75%	2.18E+07	(ERS, 1993)
Tropical Fruit	69%	1.46E+07	(ERS,1993)
	Total	5.12E+07	

Energy (J) = Biomass * Energy Content

5.12 E7 * 4000 Cal/kg*4187 Joules/Cal = 8.57E+14

5 Agricultural Productivity:

based on the following areas and annual productivity:

	Area (ha)	Prod. (kg OM/ha/yr)	
Veg. crops	29746	5.94E+03	(Odum & Brown, 1976)
Ornm. Plants	2900	1.80E+04	(Odum & Brown, 1976)
Tropical Fruit	2630	4.50E+03	(Odum & Brown, 1976)

Assume the following time for recovery a:

	Time (years)	Total loss	
Veg. crops	1	1.77E+07	(estimate)
Ornm. Plants	3	1.17E+08	(estimate)
Tropical Fruit	3	2.46E+07	(estimate)
	Total	1.60E+08	

Energy (J) = Prod. * energy content
1.6 E8 kg * 4000 Cal/kg*4187 Joules/Cal = 2.67E+15

6 Urban Infrastructure:
Based on estimates as follows:

Dwellings destroyed (number)	1.20E+04	(Powers, 1993)
Dwellings having 25% damage	6.80E+04	(estimate, Powers, 1993)
Hom. Air Force Base (m^2)	6.31E+05	(ERS,1993)
Comm. structure destroyed (m^2.)	2.34E+06	(estimate, Powers, 1993)
Comm struct. w/ 25% damage(m^2)	7.00E+06	(estimate, Powers, 1993)

Assume the following materials per dwelling and per sqft commercial

	Dwellings (per unit)		Comm Structure (per m^2.)	
Wood	5.90E+06	(g)		
Concrete	1.54E+07	(g)	1.14E+06	(Odum et al 1978)
Organics	3.63E+05	(g)	2.02E+04	(Odum et al 1978)
Metal	1.36E+05	(g)	8.07E+03	(Odum et al 1978)
Plastics	2.27E+04	(g)	1.68E+03	(Odum et al 1978)

Total damage is sum of amount destroyed and damaged
in each catagory = wood (g) 1.71E+11
concrete (g) 5.83E+12

Services = $ 6.97E+09 (Powers, 1993)

7 Urban Productivity:
Based on amount of gross county product expected to be interrupted as a result of decreases in tourism, retail sales, etc.
Estimated loss in county productivity 3% for 3 years (WWR, 1993)
Emergy= 3%*67.25 E+21 sej/yr * 3 years = 6.05E+21

8 Electricity
Estimated loss of electricity at Turkey Point based on net generating capacity of 693 MW and down time as follows: (FP&L Pers. Comm.)

Days	Percent Oower
59	0.0%
3	15.0%
35	50.0%

Total lost generation = (down time* 693MW* 8.6 E 5 Ca//MWH*4187 J/Cal)
= 4.61E+15

APPENDIX C continued

9 Population Loss (people) 50000 (Powers, 1993)

10 Dollar Payments (ERS, 1993)

11 Human Population inflow
Temporary workers 100000 (estimate based on FEMA, 1993)

12 Productivity Increase
Permanent new jobs created as a result of the reconstruction
= 80000 (Miami Herald 9/27/93)

APPENDIX D

Tables of EMERGY Evaluations of Carrying Capacity in South Dade

By
S. Lopez

Table D.1. Water from rain available for human consumption at three recycling and non-recycling stages.

Note	Item	Annual supply cubic meters	Population
1	Rainfall	2320000000	
2	Evapotransp.	1740000000	
3	Req. runoff	558000000	
4	Available	23200000	
5	Consume per person	347	
6	People Sustainable		67032
7	To recycle	18600000	
8	Available	9300000	
9	People Sustainable		93845
10	Miami Sewage	345000000	
11	Available	86200000	
12	People Sustainable		342530

Foot notes to Table D.1

1 Rainfall in South Florida
Annual rainfall 1.45 meters
Study area 1600000000 Square meters
" (From shoreline to Everglades, south of Tamiami Trail)"
Total annual 2320000000 Cubic meters
"(Morin, O.J. 1987 Desalination in South Florida)"

2 Evapotranspiration
Percent in decimals 0.75

3 Required runoff to estuaries
Percent in decimals 0.24

4 Available to aquifer recharge or human use
Percent in decimals 0.01

5 Use of water per capita in Florida
Annual use per capita 347 Cubic meters
Average including agriculture.
(The Atlas of water resources of Florida.
and O.J. Morin: Desalination in South Florida).

6 People sustainable
Water available for humans divided by consumption per capita.

7 Water available to recycle after human use.
Percent of rainfall in decimals 0.008

8 Water available after Recycling
Percent of rainfall in decimals 0.004

9 Water available for humans divided by consumtion
per capita.

10 Water from Miami sewage.
Waste water from Miami: 345000000Cubic meters

11 Water available for human use after treatment.
25 % after treatment 86200000 Cubic meters

12 People sustainable
Water available for humans divided by consumption
per capita.

Table D.2.- Carrying capacity on land required for population sustained on local rainfall using three scenarios. (annual data).

Note	Parameter	Local No Recycl	Recycle	Wastewater	
1	Population	67000	93800	343000	Habs.
2	Emergy required	1.8E+21	2.52E+21	9.21E+21	Sej.
3	Renewable	2.06E+20	2.89E+20	1.05E+21	Sej.
4	Non renewable	1.6E+21	2.24E+21	8.16E+21	Sej.
5	Required area	1.90E+08	2.60E+08	7.64E+08	Sq. Meters

Foot notes to Table D.2

1 Population

Populations from Table D.1

a) No recycling	67000
b) Recycling	93800
c) Adding Wastewater	343000

2 Emergy required (annual data).

To match the emergy per capita of the state.

Required emergy per capita = 2.69E+16 Sej

Population levels as indicated.

Emergy required = Population * Emergy per capita.

Emergy Required in a)	1.8E+21	Sej
Emergy Required in b)	2.52E+21	Sej
Emergy Required in c)	9.21E+21	Sej

3 Renewable emergy required

Emergy required / (1 + Emergy Investment Ratio)

Investment Ratio of Florida	7.75	
Renewable Emergy in a)	2.06E+20	Sej
Renewable Emergy in b)	2.89E+20	Sej
Renewable Emergy in c)	1.05E+21	Sej

4 Non-Renewable Emergy

Non-renewable Emergy = Total Use - renewable emergy

Non-renewable Emergy a) = 1.6E+21 Sej

Non-renewable Emergy b) = 2.24E+21 Sej

Non-renewable Emergy c) = 8.16E+21 Sej

5 Required Area to get renewable emergy (annual data).

Area = Renewable emergy required / renewable emergy per square meter.

Renewable emergy per square meter = renewable emergy /area

Emergy in rainwater = Chemical energy in rain * transformity

Energy from rain for all impact area = (land area + shelf area)*(rain)*(evapotransp.) *(moles water*gas constant*temp.)*(water dens)*(Gibbs free energy)

Land area = 1600000000 Sqr. meters

Shelf area = 450[illegible]000 Sqr. meters

Rainfall =	1.45	meter/ yr
Evapotranspiration	0.75	% as decimal
Freshwater concentration	1000000	ppm
Sea water concentration	965000	ppm
Moles * R* temperature	139	J/g.
Water density	1000000	g/m3
Gibbs free energy	4.95	J/g
Chemical energy in rain	1.48E+16	J/yr
Transformity	15000	Sej/J
Emergy from rain	2.22E+20	Sej

Annual energy in tides = (shelf area)*(# tides/yr)*(mean tidal range)^2 *(fraction of tide absorved)*(sea water density)*(gravitational constant) *(1.0 E-7 Joules/erg)*(3.15 E+7 s/yr)

1/2 of Continental shelf	233000000	m^2
Mean tidal range	0.49	m^2
Number of tides a year	730	
Tides absorbed	0.1	fraction
Sea water density	1030000	g/m^3
Gravitational constant	9.81	m/s^2
Conversion factors	3.15	
Annual energy	8.4E+16	Joules
Transformity of tide	24000	Sej/J
Emergy in tides	2.02E+21	Sej
Total renewable emergy	2.24E+21	Sej
Area of captation	2070000000	Square meters
Renewable emergy per unit area	1.08E+12	Sej
Area required for a)	190000000	Square meter

Emergy added in recycled rainwater (annual):

Volume of water recycled	9300000	Cubic meters a year
Water density	1000000	g/m^3
Gibbs free energy	4.95	Joule/gram
Energy in water	4.6E+13	Joule
Transformity of water (river)	1000000	Sej/J
Emergy in recycled wastewater	4.6E+19	Sej
Area of rain captation	1600000000	Sq. meter
Added emergy per square mtr.	2.87E+10	Sej.
Total emergy per square meter	1.11E+12	Sej
Area required for b)	260000000	Square meters

Emergy added in wastewater from Miami (annual):

Volume of water recycled	86200000	m^3
Water density	1000000	g/m^3
Gibbs free energy	4.95	Joule/gram
Energy in water	4.26E+14	Joule
Transformity of water (river)	1000000	Sej/Joule
Emergy in recycled wastewater	4.26E+20	Sej
Area of rain captation	1600000000	Sq. meter
Added emergy per square mtr.	2.66E+11	Sej/Sq. meter
Total emergy per square meter	1.38E+12	Sej.
Area required for c)	764000000	Square meters

Table D.3.- Population, land area and land use for three city classes in South Dade, based on water crop with out recycle.

Note	Items	Distribution of population and land uses			
		Central city	2nd. Towns	3rd. Villages	Region
1	Required centers	1	2	10	
2	Population	22300	11200	2230	67000
3	Area of each city	63400000	31700000	6340000	190000000
4	Land use areas (Sqr. meters).				
	Open land	1650000	793000	152000	4760000
	Parks	38100000	19000000	3810000	114000000
	Agriculture	19900000	9940000	1990000	59700000
	Institutional	222000	114000	22200	672000
	Low med density	2410000	1250000	258000	7480000
	Transportation	888000	444000	88800	2660000
	Med high density	63400	25400	5080	165000
	Business / Ind.	254000	121000	22800	723000
5	Area of wetlands	2190000	1100000	219000	6580000

Foot notes to Table D.3

1 Urban centers

Number of urban centers per category in hierarchy

2 Population

Estimate population per each urban center. The distribution was made proportionally following the formula: $p = (P/n)/N$ Where p is the population of each town; P is the population of the entire region; n is the number of towns of each class; and N is the number of classes of cities used.

3 Area of each city

The area for each urban center is determined keeping the population density (people per unit area), of the region: $a=p*(P/A)$. " Where a is the area of each urban center; p is the population of the center; P is the population of the region; and A is the total area of the region.

4 Percent of land use

An average of the land use percentajes of Northeast and the original Southeast Florida was used to obtain the proposed distribution. An estimated increase in the proportion of land used for higher empower uses was added to the higher class cities, and a higher proportion" of low empower was applied for rural small towns.

Percentages used:

Land uses	Central city	Secondary	Tertiary Town
Open land	0.026	0.025	0.024
Parks	0.6	0.6	0.6
Agriculture	0.3135	0.3135	0.3135
Institutional	0.0035	0.0036	0.0035
Low density residential		0.038	0.03930.0406
Transportation	0.014	0.014	0.014
Medium density residential		0.001	0.00080.0008
Commercial and industrial		0.004	0.00380.0036
TOTAL	1	1	1

(Source: Brown 1980).

5 Areas of wetlands

Wetlands areas required for treatment of waste water are included as part of the area assigned to parks.

Wetlands are assumed to be able to process two inches of wastewater a week.

Wetlands area = (Wastewater produced)/(treatment capability)

Wastewater produced a year per capita (.75 of water use per capita)	260Cubic meters
Processing capability of wetlands (2 inches a week)	2.65Meters

Table D.4.- Population, land area and land use for three city classes in South Dade, based on water crop adding Miami waste water.

Note	Items	Distribution of land uses and population			
		Central city	2nd. Towns	3rd. Villages	Region
1	Required centers	1	2	10	
2	Population	114000	57100	11400	343000
3	Area of each city	255000000	127000000	25500000	764000000
4	Land use area (Sqr. meters)				
	Open land	6620000	3310000	662000	19900000
	Parks	153000000	76400000	15300000	459000000
	Agriculture	79900000	39900000	7990000	240000000
	Institutional	917000	446000	89200	2700000
	Low med density	8660000	4590000	968000	27500000
	Transportation	3820000	1780000	357000	11000000
	Med high density	1020000	382000	25500	2040000
	Business / Ind.	1020000	510000	96800	3010000
5	Area of wetlands	11200000	5600000	1120000	33600000

Foot notes to Table D.4

1 Urban centers

Number of urban centers per category in hierarchy

2 Population

Estimate population per each urban center. The distribution was made proportionally following the formula: $p = (P/n)/N$ Where p is the population of each town; P is the population of the entire region; n is the number of towns of each class; and N is the number of classes of cities used.

3 Area of each city

The area for each urban center is determined keeping the population density (people per unit area), of the region: $a=p*(P/A)$. "
Where a is the area of each urban center; p is the population of the center; P is the population of the region; and A is the total area of the region.

4 Percent of land use

An average of the land use percentajes of Northeast and the original Southeast Florida was used to obtain the proposed distribution.
An estimated increase in the proportion of land used for higher empower uses was added to the higher class cities, and a higher proportion" of low empower was applied for rural small towns.

Percentages used: (see Table D.3)

5 Area of Wetland: (see Table D.3)

Table D.5.- Emergy based carrying capacity in South Dade.

Note	Item	No water recycled		Miami wastewater	
	Dade	At Fla's Ratio	At Dade's Ratio	At Fla's Ratio	At Dade's Ratio
1	Renewable emergy	2.24E+21	2.24E+21	2.67E+21	2.67E+21
2	Non-renewable emergy	1.74E+22	4.03E+22	2.07E+22	4.8E+22
3	Total use	1.96E+22	4.25E+22	2.33E+22	5.06E+22
4	Emergy per person	2.69E+16	2.37E+16	2.69E+16	2.37E+16
5	I.R. carrying capacity	728000	1800000	867000	2140000
6	Renewable carrying capacity	83200	94500	99100	112000

Foot notes for Table D.5

1 Renewable emergy

Renewable emergy available in study area	2.24E+21	Sej
Emergy from rain, tide and 10 % of minor imputs."		
Surplus with emergy of recycled wastewater from Miami	2.67E+21	Sej

2 Non Renewable emergy

Non-renewable = (Renewable emergy)*(emergy investment ratio)

Emergy investment ratio for Florida	7.75	
Emergy investment ratio for Dade County	18	
Non-renewable emergy for a)	1.74E+22	Sej
Non-renewable emergy for b)	4.03E+22	sej
Non-renewable emergy for c)	2.07E+22	Sej
Non-renewable emergy for d)	4.8E+22	sej

3 Total emergy use

Total use = (renewable emergy)+(non-renewable emergy)

4 Emergy per person

Ratio for Florida	2.69E+16	Sej/person
Ratio for Dade County	2.37E+16	Sej/person

(Source: Odum et. al. 1993a and Odum et. al. 1993b respectively).

5 Population

Total emergy use divided by emergy per person.

6 Population based on renewable emergy

Total renewable emergy in the study area divided by the emergy per person of the state and county respectively.

Table D.6.- Population, land area and land use for three city classes in South Dade based on carrying capacity without recycling water.
Florida's emergy per capita.

Note	Items	Distribution of land uses and population			
		Central city	2nd. Towns	3rd. Villages	Region
1	Required centers	1	2	10	
2	Population	243000	121000	24300	728000
3	Area of each city	534000000	267000000	53400000	1600000000
4	Land use area (Sqr. meters)				
	Open land	13900000	6950000	1390000	41700000
	Parks	321000000	160000000	32100000	962000000
	Agriculture	167000000	83800000	16800000	503000000
	Institutional	1920000	935000	187000	5660000
	Low med density	18200000	9620000	2030000	57700000
	Transportation	8020000	3740000	748000	23000000
	Med high density	2140000	802000	53400	4270000
	Business / Ind.	2140000	1070000	203000	6310000
5	Area of wetlands	23800000	11900000	2380000	71500000

Foot notes to Table D.6

1 Urban centers

Number of urban centers per category in hierarchy

2 Population

Estimate population per each urban center. The distribution was made proportionally following the formula: $p = (P/n)/N$
Where p is the population of each town; P is the population of the entire region; n is the number of towns of each class; and N is the number of classes of cities used.

3 Area of each city

The area for each urban center is determined keeping the population density (people per unit area), of the region: $a=p*(P/A)$. "
Where a is the area of each urban center; p is the population of the center; P is the population of the region; and A is the total area of the region.

4 Percent of land use

An average of the land use percentajes of Northeast and the original Southeast Florida was used to obtain the proposed distribution.
An estimated increase in the proportion of land used for higher empower uses was added to the higher class cities, and a higher proportion" of low empower was applied for rural small towns.

(2 inches a week) 2.65 Meters

Percentages used: (see Table D.3)

5 Area of Wetland: (see Table D.3)

Table D.7.- Population, land area and land use for three city classes in South Dade based on carrying capacity without recycling water.
Dade's emergy per capita.

Note	Items	Distribution of land uses and population			
		Central city	2nd. Towns	3rd. Village	Region
1	Required centers	1	2	10	
2	Population	598000	299000	59800	1800000
3	Area of each city	534000000	267000000	53400000	1600000000
4	Land use areas (Sqr. meters).				
	Open land	13900000	6950000	1390000	41700000
	Parks	321000000	160000000	32100000	962000000
	Agriculture	167000000	83800000	16800000	503000000
	Institutional	1920000	935000	187000	5660000
	Low med density	18200000	9620000	2030000	57700000
	Transportation	8020000	3740000	748000	23000000
	Med high density	2140000	802000	53400	4270000
	Business / Ind.	2140000	1070000	203000	6310000
5	Area of wetlands	58800000	29400000	5880000	176000000

Foot notes to Table D.7

1 Urban centers
Number of urban centers per category in hierarchy

2 Population
Estimate population per each urban center. The distribution was made proportionally following the formula: p = (P/n)/N
Where p is the population of each town; P is the population of the entire region; n is the number of towns of each class; and N is the number of classes of cities used.

3 Area of each city
The area for each urban center is determined keeping the population density (people per unit area), of the region: a=p*(P/A). "
Where a is the area of each urban center; p is the population of the center; P is the population of the region; and A is the total area of the region.

4 Percent of land use
An average of the land use percentajes of Northeast and the original Southeast Florida was used to obtain the proposed distribution.
An estimated increase in the proportion of land used for higher empower uses was added to the higher class cities, and a higher proportion" of low empower was applied for rural small towns.
Percentages used: (see Table D.3)

5 Area of Wetland: (see Table D.3)

Table D.8.- Population, land area and land use for three city classes in South Dade based on carrying capacity recycling Miami waste water.
Florida's emergy per capita.

Note	Items	Distribution of land uses and population			
		Central city	2nd. Towns	3rd. Villages	Region
1	Required centers	1	2	10	
2	Population	289000	145000	28900	867000
3	Area of each city	534000000	267000000	53400000	1600000000
4	Land use areas (Sqr. meters)				
	Open land	13900000	6950000	1390000	41700000
	Parks	321000000	160000000	32100000	962000000
	Agriculture	167000000	83800000	16800000	503000000
	Institutional	1920000	935000	187000	5660000
	Low med density	18200000	9620000	2030000	57700000
	Transportation	8020000	3740000	748000	23000000
	Med high density	2140000	802000	53400	4270000
	Business / Ind.	2140000	1070000	203000	6310000
5	Area of wetlands	28400000	14200000	2840000	85100000

Foot notes to Table D.8

1 Urban centers
Number of urban centers per category in hierarchy

2 Population
Estimate population per each urban center. The distribution was made proportionally following the formula: p = (P/n)/N
Where p is the population of each town; P is the population of the entire region; n is the number of towns of each class; and N is the number of classes of cities used.

3 Area of each city
The area for each urban center is determined keeping the population
" density (people per unit area), of the region: a=p*(P/A). "
Where a is the area of each urban center; p is the population of the center; P is the population of the region; and A is the total area of the region.

4 Percent of land use
An average of the land use percentajes of Northeast and the original Southeast Florida was used to obtain the proposed distribution.
An estimated increase in the proportion of land used for higher empower
" uses was added to the higher class cities, and a higher proportion"
of low empower was applied for rural small towns.
(2 inches a week) 2.65 Meters
Percentages used: (see Table D.3)
5 Area of Wetland: (see Table D.3)

Table D.9.- Population, land area and land use for three city classes in South Dade based on carrying capacity recycling wastewater of Miami.
Dade county emergy per capita.

Note	Items	Distribution of land uses and populations			
		Central city	2nd. Towns	3rd. Villages	Region
1	Required centers	1	2	10	
2	Population	712000	356000	71200	2140000
3	Area of each city	534000000	267000000	53400000	1600000000
4	Land use areas (Sqr. meters)				
	Open land	14600000	6950000	1390000	42400000
	Parks	321000000	160000000	32100000	962000000
	Agriculture	164000000	83700000	16800000	499000000
	Institutional	2460000	962000	187000	6250000
	Low med density	18700000	9080000	1920000	56100000
	Transportation	9080000	4010000	748000	24600000
	Med high density	2670000	1070000	160000	6410000
	Business / Ind.	2620000	1070000	214000	6890000
5	Area of wetlands	69900000	35000000	6990000	210000000

Foot notes to Table D.9

1 Urban centers

Number of urban centers per category in hierarchy

2 Population

Estimate population per each urban center. The distribution was made proportionally following the formula: p = (P/n)/N
Where p is the population of each town; P is the population of the entire region; n is the number of towns of each class; and N is the number of classes of cities used.

3 Area of each city

The area for each urban center is determined keeping the population " density (people per unit area), of the region: a=p*(P/A). "
Where a is the area of each urban center; p is the population of the center; P is the population of the region; and A is the total area of the region.

4 Percent of land use

An average of the land use percentajes of Northeast and the original Southeast Florida was used to obtain the proposed distribution.
An estimated increase in the proportion of land used for higher empower " uses was added to the higher class cities, and a higher proportion" of low empower was applied for rural small towns.

Percentages used: (see Table D.3)

5 Area of Wetland: (see Table D.3)

Table D.10.- Population, land area and land use for three city classes in South Dade based on carrying capacity without recycling water.
"Renewable carrying capacity, Florida's emergy per capita."

Note	Items	Distribution of land uses and population			
		Central city	2nd. Towns	3rd. Villages	Region
1	Required centers	1	2	10	
2	Population	27700	13900	2770	83200
3	Area of each city	534000000	30500000	6110000	1600000000
4	Land use areas (Sqr. meter).				
	Open land	13900000	763000	147000	16900000
	Parks	321000000	18300000	3660000	394000000
	Agriculture	168000000	9570000	1910000	206000000
	Institutional	1870000	110000	21400	2300000
	Low med density	20300000	1200000	248000	25200000
	Transportation	7480000	427000	85500	9190000
	Med high density	534000	24400	4890	632000
	Business / Ind.	2140000	116000	22000	2590000
5	Area of wetlands	2720000	1360000	272000	8170000

Foot notes to Table D.10

1 Urban centers

Number of urban centers per category in hierarchy

2 Population

Estimate population per each urban center. The distribution was made proportionally following the formula: $p = (P/n)/N$
Where p is the population of each town; P is the population of the entire region; n is the number of towns of each class; and N is the number of classes of cities used.

3 Area of each city

The area for each urban center is determined keeping the population " density (people per unit area), of the region: $a=p*(P/A)$. "
Where a is the area of each urban center; p is the population of the center; P is the population of the region; and A is the total area of the region.

4 Percent of land use

An average of the land use percentajes of Northeast and the original Southeast Florida was used to obtain the proposed distribution.
An estimated increase in the proportion of land used for higher empower " uses was added to the higher class cities, and a higher proportion" of low empower was applied for rural small towns.

Percentages used: (see Table D.3)

5 Area of Wetland: (see Table D.3)

Table D.11.- Population, land area and land use for three city classes in South Dade based on carrying capacity without water recycling.
"Renewable carrying capacity, Dade's emergy per capita."

Note	Items	Dsitribution of land uses and populations			
		Central city	2nd. Towns	3rd. Villages	Region
1	Required centers	1	2	10	
2	Population	31500	15700	3150	94500
3	Area of each city	534000000	267000000	53400000	1600000000
4	Land use areas (Sqr. meter).				
	Open land	13900000	6680000	1280000	40100000
	Parks	321000000	160000000	32100000	962000000
	Agriculture	168000000	83800000	16800000	503000000
	Institutional	1870000	962000	187000	5660000
	Low med density	20300000	10500000	2170000	63000000
	Transportation	7480000	3740000	748000	22400000
	Med high density	534000	214000	42700	1390000
	Business / Ind.	2140000	1020000	192000	6090000
5	Area of wetlands	3090000	1550000	309000	9280000

Foot notes to Table D.11

1 Urban centers
Number of urban centers per category in hierarchy

2 Population
Estimate population per each urban center. The distribution was made proportionally following the formula: $p = (P/n)/N$
Where p is the population of each town; P is the population of the entire region; n is the number of towns of each class; and N is the number of classes of cities used.

3 Area of each city
The area for each urban center is determined keeping the population " density (people per unit area), of the region: $a=p*(P/A)$. "
Where a is the area of each urban center; p is the population of the center; P is the population of the region; and A is the total area of the region.

4 Percent of land use
An average of the land use percentajes of Northeast and the original Southeast Florida was used to obtain the proposed distribution.
An estimated increase in the proportion of land used for higher empower " uses was added to the higher class cities, and a higher proportion" of low empower was applied for rural small towns.
Percentages used: (see Table D.3)

5 Area of Wetland: (see Table D.3)

Table D.12.- Population, land area and land use for three city classes in South Dade based on carrying capacity recycling wastewater from Miami.
"Renewable carrying capacity, Florida's emergy per capita."

Note	Items	Distribution of land uses and population			
		Central city	2nd. Towns	3rd. Villages	Region
1	Required centers	1	2	10	
2	Population	33000	16500	3300	99100
3	Area of each city	534000000	267000000	53400000	1600000000
4	Land use areas (Sqr. meters)				
	Open land	13900000	6680000	1280000	40100000
	Parks	321000000	160000000	32100000	962000000
	Agriculture	168000000	83800000	16800000	503000000
	Institutional	1870000	962000	187000	5660000
	Low med density	20300000	10500000	2170000	63000000
	Transportation	7480000	3740000	748000	22400000
	Med high density	534000	214000	42700	1390000
	Business / Ind.	2140000	1020000	192000	6090000
5	Area of wetlands	3240000	1620000	324000	9730000

Foot notes to Table D.12

1 Urban centers

Number of urban centers per category in hierarchy

2 Population

Estimate population per each urban center. The distribution was made proportionally following the formula: $p = (P/n)/N$ Where p is the population of each town; P is the population of the entire region; n is the number of towns of each class; and N is the number of classes of cities used.

3 Area of each city

The area for each urban center is determined keeping the population " density (people per unit area), of the region: $a=p*(P/A)$. " Where a is the area of each urban center; p is the population of the center; P is the population of the region; and A is the total area of the region.

4 Percent of land use

An average of the land use percentajes of Northeast and the original Southeast Florida was used to obtain the proposed distribution.
An estimated increase in the proportion of land used for higher empower " uses was added to the higher class cities, and a higher proportion" of low empower was applied for rural small towns.

Percentages used: (see Table D.3)

5 Area of Wetland: (see Table D.3)

Table D.13.- Population, land area and land use for three city classes in South Dade based on carrying capacity recycling wastewater from Miami.
"Renewable carrying capacity, Dade's emergy per capita."

Note	Items	Distribution of land uses and population			
		Central city	2nd. Towns	3rd. Villages	Region
1	Required centers	1	2	10	
2	Population	37500	18700	3750	112000
3	Area of each city	534000000	267000000	53400000	1600000000
4	Land use area (Sqr. meter)				
	Open land	13900000	6680000	1280000	40100000
	Parks	321000000	160000000	32100000	962000000
	Agriculture	168000000	83800000	16800000	503000000
	Institutional	1870000	962000	187000	5660000
	Low med density	20300000	10500000	2170000	63000000
	Transportation	7480000	3740000	748000	22400000
	Med high density	534000	214000	42700	1390000
	Business / Ind.	2140000	1020000	192000	6090000

Foot notes to Table D.13

1 Urban centers
Number of urban centers per category in hierarchy

2 Population
Estimate population per each urban center. The distribution was made proportionally following the formula: $p = (P/n)/N$
Where p is the population of each town; P is the population of the entire region; n is the number of towns of each class; and N is the number of classes of cities used.

3 Area of each city
The area for each urban center is determined keeping the population " density (people per unit area), of the region: $a=p*(P/A)$. "
Where a is the area of each urban center; p is the population of the center; P is the population of the region; and A is the total area of the region.

4 Percent of land use
An average of the land use percentajes of Northeast and the original Southeast Florida was used to obtain the proposed distribution.
An estimated increase in the proportion of land used for higher empower " uses was added to the higher class cities, and a higher proportion" of low empower was applied for rural small towns.

Percentages used: (see Table D.3)

5 Area of Wetland: (see Table D.3)