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Environmental Accounting Using Emergy: Evaluation of Minnesota

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NOTICE

This report is contribution number AED-08-006 of the Atlantic Ecology Division (AED), National Health and Environmental Effects Research Laboratory (NHEERL), Office of Research and Development (ORD). The research described here has been funded wholly (or in part) by the U.S. Environmental Protection Agency and the document has been subjected to the USEPA's peer review process and has been approved for publication. However, we note that the opinions expressed in this report are those of the authors and they are not necessarily those of the U.S. Environmental Protection Agency. In addition, the methodology used in this report is not completely developed and the approach itself is not accepted by everyone in the scientific community. Therefore, caution should be employed in using the data and conclusions provided here. The data, calculations and conclusions reported herein have not been subjected to formal analyses of their uncertainties, and therefore should be viewed with extreme caution; no claims to their accuracy and veracity can be made at this time. Technical issues preventing the complete application of these methods include better methods to document far-field environmental liabilities such as disturbance to natural carbon, nitrogen, and sulfur budgets of regions. Finally, the mention of trade names or commercial products does not constitute endorsement or a recommendation for use.

ABSTRACT

Often questions related to environmental policy are difficult to resolve successfully, because robust solutions depend on accurately balancing the needs of both human and natural systems. To accomplish this end the socioeconomic and environmental effects of policies must be expressed in common terms so that both the contributions of the environment and the contributions of the economy to human well-being are valued fairly. Emergy is an accounting quantity that has the property of expressing all forms of energy in terms of their equivalent ability to do work when used in the system of which they are a part. Based on past studies and a previous report in this series, environmental accounting using emergy has proved to be a method that can be used to objectively value the work of the environment, economy and society by using an energy-based unit, the solar emjoule (sej) and a combined emergy-monetary unit the emdollar (Em$). Emergy tabulates the available energy of one kind required for the production of a product or service *i.e.*, the solar joules used up both directly and indirectly in the past to make the product or service. The unit of emergy is the emjoule, which denotes that the energy has been used in the past in contrast to a joule of available energy that is an energy potential that can be used in the present. What something can do when used within its network is represented by its emergy and not its energy. Thus, energy alone is not a sufficient basis for making policy decisions.

This USEPA Project Report contains an emergy evaluation of the State of Minnesota and it includes a guide to the Emergy Analysis methods used to characterize a state within the larger context of its region and nation. A summary of the results of this analysis based on the values of emergy indices calculated for the State and their interpretation follows: (1) Twenty-one percent of the emergy used in the State in 1997 was derived from home sources, which indicates a moderate potential for self-sufficiency. (2) The emergy use per person was 1.53E+17 sej/person. This index showed that Minnesotans have a high overall standard of living compared to the national average. (3) The import/export emergy ratio showed 1.33 times as much emergy leaving the State in exports as is received in imports, which indicates a slight imbalance in the exchange of real wealth with the Nation. However, when iron ore (taconite) is removed from the import-export balance, the emergy of exports is only 10% larger than that of the imports. (4) The emergy used per square meter (3.23E+12 sej/m^2) indicates that an average location in the State is developed relative to an average place in the Nation. (5) The emergy to dollar ratio was 4.66 E+12 sej/$, thus the purchasing power of a dollar in Minnesota in 1997 was 1.82 times that of an average place in the United States. This ratio had fallen to 1.69 times the national purchasing power of a dollar by 2000. (6) The investment ratio was 3.81:1, which indicates a relatively low intensity of matching between purchased economic emergy invested from outside the State and the emergy of renewable and nonrenewable environmental resources within the State. This index suggests that Minnesota is still an attractive place for further economic investment. (7) The environmental loading ratio was

37.1:1, indicating a more intense matching of purchased inputs with renewable energy from the environment than was found for West Virginia (20.4:1) or the Nation as a whole (19.6:1). Higher environmental loading ratios potentially result in higher stress on ecosystems and a heavier “load” on the waste processing capacity of the environment. (8) Minnesota can support 2.6% of the present population at the 1997 standard of living using its renewable resources alone in their current state of development compared to 3.0% for West Virginia and 4.9% for the Nation.

Minnesota is a state with large regional differences. The Northeastern region appears to be a hinterland exporting vast quantities of emergy in its natural resources. For example, the iron mining sector has a balanced monetary exchange but the emergy exchange shows a 42:1 advantage in favor of the buyer. The agricultural and industrial regions in the remainder of the State export value added products that command a premium over the average skill level used to produce the products imported. This premium paid for the services of Minnesota workers is the main reason for the State’s high standard of living relative to other states. Minnesota’s pool of highly educated and skilled labor can be attributed to an early and continuing interest in and support for education in the State. Based on this evidence the best thing that the State can do to ensure a prosperous future is to continue to educate forward-thinking, highly-skilled individuals through further developing and maintaining its school systems.

Keywords: emergy analysis, environmental accounting, Minnesota, renewable resources, nonrenewable resources, sustainability, quality of life, import-export balance

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Preface

PURPOSE OF THE REPORT

This USEPA Project Report has several purposes. The first purpose is to provide a second peer-reviewed report on a state for comparison with the results of our original report on West Virginia. The Minnesota and West Virginia reports are two analyses in a comparative analysis of eight states that were evaluated for the years 1997 and 2000. In addition, this report serves as a further guide to Emergy Analysis with particular emphasis on those methods used to characterize a state within the United States and the data needs for performing emergy analyses on all scales, including an expanded section on transformities with many new calculations. This report also provides emergy indices for the State of Minnesota that are needed to perform a proposed regional analysis of sustainability of the Arrowhead Region of Northern Minnesota. In this report we applied the results of our study to gain an energy systems perspective on some current policy questions facing the people of Minnesota.

SIGNIFICANCE OF THE REPORT

Many people struggle to understand the concept of emergy and why we go to so much trouble to document economic and ecological flows and storages in these terms. The practical answer is that the accounts for environmental systems cannot be kept in dollars alone, because environmental systems are based on both the work of humanity, which is paid for by a counter flow of dollars, and the work of ecosystems, for which no money is paid. An accurate picture of environmental systems requires that we account for the flows and storages of energy, matter, and information that are responsible for supporting economic and social activities and that may not be accompanied by flows of money. Energy can be used as a common denominator for quantifying all these flows. Converting flows of energy to emergy puts the work done by the economy and the environment on the same basis, so that economic and environmental flows are directly comparable. While it is true that dollar values are directly comparable, it is also true that economic markets only value a subset of the products and processes that are important in environmental systems. The key synthesis produced by Emergy Analysis is an accounting of social, economic and environmental flows in common terms on an objective basis. Thus, for the first time, what is removed from Minnesota is shown in true relationship to what is received in return. For example, it is true that everyone in Minnesota realizes that farming, mining, manufacturing, and timber are important sectors in the economy, but this is the first time the numbers have been calculated to show the relationship of the real wealth (emergy) in natural and human capital that supports the flows of emergy and the counter current of money moving through these sectors annually. The exchange of real wealth between Minnesota and the Nation is quantified for the first time and contrasted with those of another resource rich state, West Virginia. The importance of recognizing the true nature of value in exchanges is easily illustrated by the inequitable barter between Europeans and Native Americans in which ecological resources, *e.g.*, animal skins and land of great value, were exchanged for relatively less valuable items of industrial society. Emergy accounting can potentially give environmental managers tools similar to those regularly used by financial analysts to make business decisions. However, we are far from this point at present and there is much work left to be done by those who thoughtfully read this report. Further development of the emergy analysis methods and tools presented in this report and closer coordination with existing methods of environmental impact assessment, *e.g.*, life cycle assessment, will make it possible for managers to first examine complete and commensurate economic and environmental accounting data before making policy decisions about environmental systems.

The State of Minnesota and its relationships with its region and the Nation are characterized in the case study presented in this report. Insights from this study may be useful in establishing a context for determining policies for the State as a whole, but finer scale analyses must be performed to address more specific environmental management problems, such as what is sustainable for a region within the State. In addition, the analysis methods described here can be used as a guide to creating emergy accounts for any state in the United States.

STRUCTURE OF THE REPORT

This technical report gives an overview of the emergy accounting and analysis methodology, which can be used to evaluate environmental systems on any scale of organization (Odum 1996). However, it is impossible to condense the methods and insights of a comprehensive methodology in a single, relatively short document. For this reason, Section 2 (Methods) of this paper focuses on methods, calculations and data sources needed to evaluate a state within the United States of America. Even with this restriction, the task is daunting because there are 50 states and each one will present the researcher with new problems to solve. So far we have begun work on 10 of the 50 states, and as expected, almost without exception each one has presented a new theoretical or technical challenge. In Campbell *et al.* (2005) we made the task somewhat easier through the development of a method for determining the imports to and exports from any state using readily available data from the U.S. Census Bureau's Commodity Flow Survey that is performed every 5 years, most recently in 1997, 2002, and 2007. Application of the emergy analysis method is demonstrated through reporting a case study of the State of Minnesota (Section 3), which is presented in lieu of a Results section. This section of the report is written so that it can stand alone as a final report on the Emergy Analysis of Minnesota. Those readers who are primarily interested in the results of this study can go directly to Section 3.

The emergy analysis and environmental accounts for the State of Minnesota given in the case study include the following eight elements that we used to characterize any state: (1) a narrative history, (2) a detailed energy systems diagram of the state as an environmental system with supporting tables, (3) the Emergy Income Statement showing annual emergy and dollar flows of renewable and nonrenewable resources, production, consumption, imports and exports, (4) the Emergy Balance Sheet showing some of the stored assets in the state, (5) an aggregate diagram giving a macroscopic overview of the energy resource base for the state's economy and a summary table from which indices were calculated, (6) emergy indices of system structure and function, (7) the emergy signature for the state, and (8) the examination of several issues of concern for the well-being of Minnesota and its people in the future.

Following the Emergy Analysis of Minnesota, there is a Discussion (Section 4) which examines (1) some unique problems in the analysis of Minnesota and the solutions employed, (2) quality assurance, the reliability of the data, and areas of uncertainty in the analysis, and (3) the use of emergy accounting data for environmental decision-making and planning for the future. References are given in Section 5 and the data sources used along with their Worldwide Web addresses can be found in Section 6. Extensive data and documentation to support the method and the case study are given in the appendices found in Section 7. These appendices are as follows: the Energy Systems Language (Appendix A), information on the transformities used in this report (Appendix B), notes documenting the energy and emergy calculations (Appendix C), import-export calculation methods (Appendix D), and emergy analysis tables for Minnesota in 2000 (Appendix E). Supplemental information on this analysis and errata are posted at http://www.epa.gov/aed/research/desupp5.html.

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Section 1

Introduction

Accurate accounting of the inflows, outflows and storages of energy, materials, and information is necessary to understand and manage environmental systems at all levels of hierarchical organization. The accounting tools*, i.e.*, the emergy income statement, emergy balance sheet, and emergy indices described in this document can be used to analyze and understand systems defined for any arbitrary set of boundaries. Boundaries of concern to us define an environmental system containing both ecological and socioeconomic components. The research or management questions asked at each level of organization will be somewhat different but the most important questions that are concerned with the overall condition of the system will be illuminated by information and indices related to the system's inflows, outflows and to the storages of energy, matter, and information in the system. In this report we present the methods of environmental accounting using emergy and apply them to analyze the State of Minnesota. Therefore, the particular sources of data and methods presented here will relate to the calculation of the important flows and storages for states within the United States.

At present, records for the environment are kept in terms of physical units such as pounds of chemical pollutants discharged, miles of degraded streams, or the number of endangered species present in a given area, while the accounts of human activities are for the most part kept in dollars. Neither accounting mechanism is able to address the credits and debits of the other, thus there is often a gap in the scientific assessment information given to managers faced with solving complex environmental problems that have social, economic and ecological consequences. To keep accurate accounts for the environment, the economy, and for society we need a system capable of expressing the debits and credits (costs and benefits) that accrue to each in common terms. For more than 100 years, physical and social scientists have struggled with this problem, *i.e.*, how to incorporate resource limitations and contributions into the formulations of economics (Martinez-Alier, 1987). Land, labor, energy and other physical quantities have been tried without much success. Often these efforts centered on available energy, *i.e.,* energy with the potential to do work, as a potentially unifying common denominator for accounting purposes, because it is both required for all production processes and incorporated in all products of production. These early efforts failed largely because none of the proposed energy-based accounting methods considered differences in the ability to do work among energies of different kinds (Odum 1996).

In the 1980s, H.T. Odum and his colleagues solved this problem through the development of the concepts of emergy and transformity (Odum 1986, 1988, Scienceman 1987). *Emergy* is the available energy of one kind previously used up directly and indirectly to make a product or service. The unit of emergy is the *emjoule*, which connotes the past use of energy that was required to create the present product or service. *Transformity* is the emergy required to make a unit of available energy of the product or service. Most often, emergy accounts for the environment and the economy are kept using the solar joule as a base unit. In this case solar transformities are expressed as *solar emjoules* (sej) per joule (J). *Empower* is the flow of emergy (sej) per unit time. Emergy is related to the system of economic value through the emergy to money ratio. The *emdollar* (Em$) value of a flow or storage is its emergy divided by the emergy to money ratio for an economy in that year (Odum 1996). Odum's innovative definition of emergy established a medium for environmental accounting that for the first time made it possible to express economic commodities, services, and environmental work of all kinds on a common basis as solar emjoules. In this report we use the methods of emergy accounting to demonstrate how keeping the books on environmental systems can help us identify problems and seek solutions at the macroscopic level of a state economy. In our previous study of West Virginia (Campbell *et al.* 2005a); we began to adapt two standard accounting tools, the income statement and the balance sheet for use with emergy. Respectively, these tools allowed us to characterize state annual activities and long-term assets. We propose that creating combined emergy and monetary accounts for environmental, economic, and social systems is a method that will allow us to bridge the gap between economic and ecological analyses of natural capital and processes in a plausible and integrated manner, thereby leading to more accurate and comprehensive evaluations of the effects of environmental policies.

Section 2

Methods

Emergy evaluations of the macroscopic features of an environmental system such as a state, region, or nation are carried out in the same manner for each system regardless of its size or level in the hierarchy of organization, *e.g.*, county, state, nation, 1st, 2nd, … 6th order watersheds, *etc*. Emergy analyses like other assessment methods are guided by research or management questions. In general, the hierarchical organization of ecological and economic systems requires that emergy accounts be created for more than one level of organization to obtain accurate answers to questions about a system at any particular level of organization. Multiple levels of organization are examined because large-scale patterns within a system are often determined by energy inflows from the next larger system, whereas, internal system dynamics may be affected by policy changes in the management of important subsystems. The examination of multiple levels of organization is also recommended because environmental policies often have different consequences at different levels of system organization (Odum and Arding 1991). The general rule is that analyses at three levels of organization (the system, its subsystems, and the next larger system) are the minimum required for a thorough understanding of a particular system. Because of time and labor constraints the emergy analysis presented in this report varies from this standard because (1) it does not include an examination of important subsystems within the state, *e.g.*, the rapidly growing corn ethanol industry, and (2) international trade between the United States and Canada is not explicitly considered; therefore, it is only the first step in a complete emergy analysis of the state.

2.1 Understanding the System

Effective models and analyses depend on the degree to which the investigators understand the system that they have chosen to analyze. For this reason, a thorough study of the system to be analyzed and its relationship to the next larger system, which determines long-term trends, is a prerequisite for successful analysis. Before performing emergy analyses of states or other systems, we recommend that investigators review existing studies containing current and historic information on the state with a view toward characterizing it as an environmental system. Environmental systems include the economic and social infrastructure and activities of humanity as well as the storages, flows and processes of ecosystems. In the method presented here and illustrated in the Results section, the knowledge gained through this review is captured in the narrative history of the state. The narrative history is a vehicle for understanding how renewable and nonrenewable resources have shaped the current economy in the state. Setting down the history of the state helps trace causal pathways from the past to the present and establishes the historical context of changing relationships between the state and the nation. The knowledge gained through this review serves as a basis for creating a detailed energy systems diagram of the state as discussed below.

2.2 Overview of Emergy Analysis Methods

There are five main steps required to complete an emergy evaluation. First, a detailed systems diagram is completed. The second step is to translate this knowledge into an aggregated diagram of the system addressing specific questions. Third, descriptions of the pathways in the aggregated diagram are transferred to emergy analysis tables where the calculations needed to quantitatively evaluate these pathways are compiled. The fourth step in the method is to gather the raw data needed to complete the emergy analysis tables along with the conversion factors (energy contents, transformities, *etc*.) needed to change the raw data into emergy units. Finally, after the raw data has been converted into emergy units, indices are defined using an aggregate diagram (Odum 1996, Lu *et al.* 2007) and calculated using the appropriate data. These five steps are discussed in more detail in the following sections.

2.2.1 *Diagramming and Models*

First, a detailed energy system diagram is constructed representing all interactions between human and natural components of the system that have been identified as relevant (Fig. 1). The Energy Systems Language symbols and their intrinsic mathematics (see

Appendix A, Fig A1 and Odum 1994) are used to develop models of ecological and socio-economic interactions and components representative of the functions and structures within the system or process of interest. In an energy systems diagram, structure encompasses the system components and their arrangement, and function includes pathways of energy flow and interactions. Components can be both physical entities and properties such as information or aesthetics that are usually considered as intangible, but require small energies for their storage and operation. The pathways and interactions can be both physical flows such as electricity or raw materials as well as control mechanisms, *e.g*., logic programs controlling animal migrations or management decisions.

It is important to include all known connections between system components in the draft diagram to ensure completeness of the evaluation. A diagram like this is a useful tool for defining data needs. Once the exercise of defining all known interactions that affect the system components is completed, there is usually enough information to construct working hypotheses about the mathematical expressions that govern these processes. This in turn points to the appropriate factors that need to be measured when field work is required.

Variables in the detailed model are then aggregated, according to similarity of function, into variables considered important in controlling the system behavior that is relevant to specific research or management questions. Preliminary evaluations of the emergy in system storages and flows helps in determining the dominant components and processes of the system that should be included in the aggregate diagram. Aggregating does not mean removing any component from the system. It refers to combining components and using either averaged data or data from the dominant entity to evaluate the component or process. For example, data on a biological component can be weighted for population percentages. The goal of aggregation is to obtain the simplest possible system that still allows the original research or management question to be answered.

Committing our understanding of the energy and material flows, storages and connections within an ecosystem to paper invites review of the completeness and accuracy of the conceptual thinking. It is not necessary to include all known details in a diagram. In the emergy accounting procedure presented in this document, the pathways of primary interest are those crossing the boundaries, both as inputs and as outputs. At this scale, the focus is on the external flows supporting the environmental system. The only internal interactions of interest are the extractions of natural resource storages for economic use, *e.g*., minerals or soil erosion. Other internal pathways are drawn, but much of the detail concerning the workings of each component can be omitted.

2.2.1.1 *The Energy Systems Language*

The tools and methods for constructing an energy systems diagram are discussed extensively in Ecological and General Systems (Odum, 1994). The Energy Systems Language is a visual mathematics because each symbol is mathematically defined. A network of these symbols translates directly into a set of simultaneous 1st order differential equations. Energy Systems diagrams represent both kinetics and energetics in a single diagram and they demonstrate and obey the 1st and 2nd laws of thermodynamics in their structure (Odum 1994). The commonly used symbols and conventions of the language are briefly described below to assist the reader in understanding the energy systems diagrams used in this document (Figure A1).

System boundary A rectangular box represents the system boundaries. This is an arbitrary decision and boundaries are often chosen to address an issue or question being evaluated. Determining the boundary requires specifying the spatial and temporal scale of the analysis.

Forcing functions Any input that crosses the boundary is an energy source for the system. Such inflows include energy flows, materials, information, genes of living organisms, services, as well as inputs that are destructive, such as wastes and toxicants. External inputs are represented with a circular symbol and are arranged around the outside border from left to right in order of increasing transformity with sunlight on the left and information and human services on the right.

Pathway lines Flows are represented by lines and include energy, materials, and information. Money is shown with dashed lines and always flows in the opposite direction to the material or energy flow with which it is coupled. Lines without arrowheads flow in proportion to the difference between two forces and represent a reversible flow that follows the concentration gradients.

Outflows Any outflow that still has available energy, *e.g.*, materials more concentrated than the environment or usable information, is shown as a pathway exiting from any of the three upper system borders, but not from the lower border. Degraded or dispersed energy, with insufficient ability to do work in the system, is shown with gray lines leaving at the bottom of the diagram through a single arrow going to the heat sink.

Adding pathways Pathways add their flows when they join and when they enter the same storage. Every flow in or out of a storage must be of the same type and is measured in the same units.

State variables Storages of material, energy and information are shown as tanks, which may occur alone or within system compartments. Changes in the system can be recorded as fluctuating accumulations within each tank. In system diagrams using group symbols, the actual simulation details, such as tanks and complex interactions flowing into and out of each tank, are not presented. However, a state variable is always implied for every compartment within the diagram whether it is shown or not.

Intersection/interaction Two or more flows that are different, but required for a process, are drawn entering an intersection symbol. The flows to an intersection are connected from left to right in order of their transformity, the lowest quality one connecting to the notched left margin and the higher quality flows connecting to the top of the interaction symbol. Photosynthesis is an example of a multiplicative interaction in which light, plant biomass, and nutrients are the inputs required to produce organic matter. However, any mathematical relationship can be used to define an interaction by making the appropriate symbol or notation on the interaction symbol. A flow of one entity cannot go from its tank to a tank with a different entity without passing through some interaction, *e.g.*, sunlight cannot flow into a tank containing phytoplankton carbon without first interacting with nutrients, phytoplankton biomass and other inputs to produce a flow of carbon in gross primary production. If hierarchical symbols are being used, *e.g.*, the producer, consumer or a rectangular box for a sub-system (Figure A1), disparate flows can enter the symbol without showing the interactions. However, the interactions are implied and are shown explicitly when the hierarchical symbol is completely specified (Odum and Odum 2000).

Counter-clockwise feedbacks High-quality outputs from consumers, such as information, controls, and scarce materials, are fed back from right to left in the diagram. Feedback from right to left also represents recycle or a loss of concentration, because of divergence, with the service usually being spread out to a larger area. Feedback control or recycle paths go from right to left over the top of all other components and pathways.

Sensor If the quantity of a component in some way affects a flow without using up the component, a small box (sensor) is placed at the top of the storage tank and information on the stored quantity is drawn from this point for use by another symbol, *e.g.* an interaction or logic program. For example, the emergy stored in the biodiversity of a National Park may attract tourists to visit the park, but it is not ordinarily diminished as a consequence.

Material balances Since all inflowing materials accumulate in system storages or flow out, each inflowing material such as water or money needs to have a budget determined.

2.2.1.2 *Simulation Models*

The characterizations of Minnesota given in this report are based on data from 1997 and 2000 and as such they are snapshots of a dynamically changing system. The dynamic system processes of the State are constantly changing under the influence of both external forcing functions, *e.g.*, climate change, fuel availability, *etc.*, as well as variations in the internal structure of the system, *e.g.*, the growth and development of alternative energy industries such as wind power and ethanol. Microcomputer simulation is the standard Energy Systems Analysis tool used to examine system dynamics. Simulation models are not used in this report, but they will be important in future studies of the sustainability of the State and its regions and in predicting the development and behavior of important subsystems such as the ethanol industry within the State. Simulation models are often helpful in considering alternative futures, investigating dynamic properties,

Table 1. Tabular Format for an Emergy Evaluation

Col. 1	Column 2	Col. 3	Column 4	Column 5	Column 6
Note	Item	Data J, g, $	Solar Emergy/Unit sej/J, sej/g, sej/$	Solar Emergy sej, sej/y	Em$ U.S. Em$

and making predictions. They act as a controlled experiment and allow the investigator to adjust one variable at a time and note the resulting changes to the system. In creating a simulation model, an evaluated diagram showing the initial conditions for all state variables and pathway flows is made. Storages and flows are determined from the literature or from field measurements of biomass, production rates, *etc*. The simulation model is translated into a set of simultaneous first order differential equations containing the mathematical functions governing rates and interactions that result in changes in the state variables under a given set of forcing functions. These differential equations are written as difference equations in a programming language and solved on the computer to predict the changes in each state variable as a function of time or space. More detail on the use of models and simulation in energy systems analysis can be found in Odum and Odum (2000).

2.2.2 *Emergy Tables*

Emergy analysis tables provide a template for the calculation of the emergy values for energy storages and flows. In the emergy tables, raw data on the mass of flows and storage reserves are converted to energy and then to emergy units and emdollars to aid in comparisons and to provide information for public policy decision-making. Emergy tables are used to create the accounts for the emergy income statement and emergy balance sheet.

The common format used to set up emergy tables is illustrated above. Each emergy evaluation table has six columns as shown in Table 1.The columns are defined as follows: Column 1: Note. The line number for the item evaluated is listed. Each line number corresponds to a footnote where raw data sources are cited and calculations shown. The footnotes referenced in this paper may be found in the appendices. Column 2: Item. The name of the item is listed. Column 3: Data. For each line item the raw data is given in joules, grams, dollars or some other appropriate unit. The source, derivation and characteristics of the data should be shown in the footnotes. Column 4: Solar Emergy per Unit. For many items the solar emergy per unit (transformity where the unit is energy) has already been calculated in previous studies. If it has not, the solar emjoules per unit can be calculated using one of the methods listed in Odum (1996). Transformities and other emergy per unit ratios including some new values, *e.g.*, snow, taconite, dolomite, are listed in Appendix B. Column 5: Solar Emergy. The solar emergy is given here and it is the product of columns three and four. It can be an emergy flow (sej y^{-1}) or emergy storage (sej). Column 6: Emdollars (Em$). This number is obtained by dividing the emergy in column 5 by the emergy/dollar ratio for the country in the selected year.

2.2.3 *Data Sources and Model Evaluation*

In general, government sources are the first priority for environmental and economic data acquisition. For the emergy analysis of a state, U.S. government sources are preferred. Government sources are most likely to provide detailed descriptions of assumptions and methods, and they often provide a quantitative estimate of error. Recorded data specific to the system both in time and space are preferred. However, data are rarely collected in a manner that can be directly inserted into an emergy evaluation table. For example, international trade exchanges are recorded annually by several Federal agencies, but domestic trade is evaluated only through surveys conducted five years apart. Furthermore, a great deal of economic information is recorded in terms of currency exchange, but because unit prices vary substantially, it is difficult to estimate the actual resource or environmental use involved. In these cases, broader based assumptions and accepted models, many of them models employed by economists, are used to convert the recorded data into estimates for a particular area or system.

The information needed for the emergy income statement is most often reported as annual flows of mass and/or dollars. Usually mass can be easily converted to energy because the energy content of many objects has been widely tabulated *(1)*. *Numbers in italics follow* *data sources mentioned in the text and refer to entries in the Data Sources section of this report.* The energy contents of many materials evaluated in this study are given in Appendix C. The *specific emergy* or the emergy per unit mass has also been calculated for many items and can be used to convert mass flows to emergy when it is convenient (see Appendix B). Dollar flows can be converted to the average emergy in the human services associated with the good or service purchased by multiplying the dollar amount by the appropriate emergy to dollar ratio (Odum 1996). However, the dollar value of something does not give an accurate estimate of its emergy except when the work of humans accounts for all but a small part of the emergy required to make the item.

2.2.4 *Transformities*

The energy content of many items has been tabulated; however, the information available on the solar transformities of those items is often more limited. Thus, the availability of data on solar transformities often determines the ease and accuracy with which emergy accounting studies can be performed. Many solar transformities have been calculated (see Appendix C in Odum, 1996 and Appendix B below, Brown and Bardi 2001, Odum 2002), but most studies require the calculation of new transformities or the updating of old transformities, when the average or general value for the transformity of an item is not appropriate to answer the management or research question. Although several methods for calculating transformities exist (Odum 1996), transformity calculations are commonly based on an analysis of the production process for a particular item, *e.g.*, see Bastianoni *et al.* (2005). Global production processes are used to determine the transformity of planetary products like the wind, rain, snow, and waves (Odum 1996, Odum 2000). The relevant production processes of environmental and economic subsystems are analyzed to determine the transformities for particular economic or ecological products and services. For example, the inputs to Florida agricultural production processes for different crops were evaluated to obtain transformities for soybeans, grain corn, potatoes, *etc*. (Brandt-Williams 2001). The transformities calculated for agricultural products by Brandt-Williams (2001) were updated in this study and several crops commonly grown in Minnesota (grain corn, spring wheat, and soybeans) were evaluated. Transformities for Minnesota crops were used in this study where appropriate.

Transformities are determined through the analysis of a production process or by other empirical means. All energy inputs required for the production of an item are documented and converted to solar joules (the available energy inputs are multiplied by the appropriate transformity). These emergy inputs to the process are summed and divided by the available energy in the product to obtain the transformity of that item in sej/J. When many production processes are evaluated, a distribution of values can be obtained for the transformity of any item. The thermodynamic limits on the efficiency of all production processes lead to the hypothesis that there will be a minimum attainable transformity, which results when the production process is operating at maximum power. This minimum transformity may approach an asymptote for a given product or service and this minimum value indicates the location of that item in the hierarchy of all natural processes. In practice, when a general value for a transformity is to be determined, a well-adapted (fast and efficient) production process is evaluated on the scale and in the setting under which the product is commonly formed (Bastianoni *et al.* 2005). For example, rain and wind are products of the global atmospheric heat engine and thus their transformities are determined through an analysis of their global production processes (Odum 2000). In any emergy analysis it is important to consider whether the energy and material inputs to the system can be considered to be of average transformity for that item. If so, the general value for the transformity for these items can be used. For example, electricity can be generated by many processes (using wood, water, coal, gas, tide, or solar voltaic cells, *etc.*) each with a different transformity (Odum 1996). An average value of 1.7 E5 sej/J was determined by Odum (1996), which is close to the transformity of electricity generated from coal-fired power plants. The use of a general transformity for an item is appropriate when (1) the item is representative of the mix of production processes that determine the mean, (2) the general value reflects the specific input, and (3) the transformity of the particular item is unknown or is undeterminable. It would not be reasonable to use the general transformity for an item when the system or process under evaluation is known to be dependent on an inflow of higher or lower transformity energy.

The earth receives energy from three primary energy sources, *i.e.*, solar radiation, the deep heat from the earth, and the gravitational attraction of the sun and moon. Odum (1996) and Campbell (2000a) developed methods to equate these three independent sources in terms of solar emergy resulting in the determination of a set of planetary solar emergy baselines that depend on how the equivalences between the independent sources are determined. All transformities are measured relative to a planetary solar emergy baseline and care should be taken to ensure that the transformities used in any particular analysis are all relative to the same baseline. However, all the past baselines can be easily related through multiplication by an appropriate factor and the results of an emergy analysis do not change by shifting the baseline (Odum *et al.* 2000). The baseline used in this study is from Campbell and Odum (1998) and Campbell (2000a), who calculated a revised solar transformity for tidal energy that resulted in a correction to the planetary baseline in Odum (1996) giving a new value of 9.26 E+24 solar emjoules per year. The transformities used in this report have either been calculated using the 9.26 baseline or multiplied by the appropriate factor to express them relative to this baseline. These factors and information on baselines are provided in Appendix B, Table B1.1, where transformities are also given relative to the 15.83 E+24 sej/y baseline calculated in Odum *et al.* (2000).

2.2.5 *Flow Summary and the Calculation of Indices*

The final step in creation and analysis of emergy accounts for a system is to combine the information from the income statement into summary variables that are used in the calculation of emergy indices. These summary variables are shown on the aggregate diagram discussed above and provide a macroscopic overview of emergy and dollar flows of the system. Other analysis methods and tools are used in Emergy Analysis (Odum 1996, Odum 1994) but they cannot be adequately discussed in a short report. Using the emergy analysis tables and the aggregated figures, emergy indices are calculated to compare systems, predict trends, and to suggest alternatives that deliver more emergy, reduce stress on the environment, are more efficient or more equitable.

2.3 Creating the Emergy Income Statement

The income statement includes the following tabular accounts: (1) renewable resources received and used within the system and the production based primarily on the use of those resources, (2) production and consumption of nonrenewable resources within the system, (3) imports into the system, and (4) exports from the system.

2.3.1. *Evaluating Renewable Resources*

Renewable resources are replenished on a regular basis as a result of the use of planetary emergy inflows in solar radiation, the deep heat of the earth and gravitational attraction of the sun and moon. These primary planetary emergy inflows and the continuously generated co-products of their interactions in the geobiosphere comprise the renewable resources of the earth. All renewable resources known to be important inputs to a system are evaluated and the emergy contributed to the system by each is determined. While all renewable energies known to be important are calculated and included in the table, not all of them are included in the emergy base for a system. If all the co-products of a single interconnected planetary system are counted, some of the emergy inflow will be counted twice; therefore, a general rule is that only the largest of any set of co-products is counted in the emergy base. This rule may be modified in certain cases by adjusting the base used for transformities of two or more inputs (Odum *et al.* 1987, Lu *et al.* 2007).

Rain delivers two kinds of energy to systems, the chemical potential energy that rainwater has by virtue of its purity relative to seawater and the geopotential energy of the rain at the elevation at which it falls, and both must be accounted for in an emergy analysis. Renewable energy also enters the state or other system through cross-border flows of energy and materials in rivers. Renewable energy inflows to the system can be determined at two points, (1) the point of entry and (2) the point of use. The first of these two flow measurements gives the emergy received by the system and the second gives the emergy absorbed or used in the system. For example, the incident solar radiation is received by the system and the incident solar radiation minus the surface albedo is absorbed. The geopotential energy of rain on land at the elevation it falls is the geopotential energy received by the system, whereas the geopotential energy of the runoff relative to the elevation at which it leaves the state is used on the landscape to create landforms. The chemical potential energy of the rain that falls on the land is received, but the water transpired is actually used by the vegetation to create living structures on the landscape. In some cases almost all the emergy received by the system is absorbed, *e.g*., almost all tidal energy received is dissipated in estuaries and on the continental shelf.

Long-term averages are used for the environmental inputs to the system. An economy develops over many years in response to the environmental energies available to support human activities in the system; therefore, a long-term average of environmental variables, *i.e*., 10 to 50 years depending on the available data, is used to calculate the average energy supplied to the system from renewable sources. Long-term averages for environmental data smooth temporal variations in the inputs of renewable energy, which might otherwise lead to variability in the emergy indices based on renewable inflows. Environmental data should be collected with comparable technologies. Sometimes, with long environmental data sets, the technology used to obtain the data will have changed during the period of record. In this case, we may try to reconcile the two data sets, or if this fails, we may use only the data recorded using the most recent instruments, since they are comparable. Representative averages in space and time are also important to characterize inputs accurately. Where there are substantial differences in environmental inputs in different regions of a state, the differences should be prorated by area to ensure that the most accurate estimate of the energy input to the state as a whole is obtained for any particular variable. For example, mountainous areas often have a different climate and rate of surface heat flux compared to coastal areas. More specific methods for determining the emergy of renewable resources are provided in Appendix C.

2.3.2. *Evaluating Nonrenewable Resources*

Nonrenewable resources are storages of raw materials that have been built-up over a long period of time by environmental processes, but that are being used by human activities at a rate much faster than they can be renewed. Iron ore mined from the Mesabi Range or ground water in the Southwestern United States, which is being withdrawn in excess of the recharge rate, are respectively, examples of flows of a nonrenewable resource and of a renewable resource that is being used in a nonrenewable manner. An emergy evaluation does not determine the contribution of a nonrenewable resource by the price paid for the raw material – a ton of iron for instance – because this is not the value of the iron itself. It is the price someone is willing to pay for the labor, machinery, and materials required to mine the iron. When evaluating iron as an emergy input to steel making, for example, it is important to evaluate or estimate the energy required by nature to make the iron as well as the human work done in its extraction and processing (Appendix B3.4 gives an emergy evaluation of taconite). The solar emergy required to make a joule of iron is its solar transformity measured in solar emjoules per joule. Material flows are multiplied by the specific emergy (sej/g) of the item or converted to energy and then multiplied by the transformity (sej/J) to obtain an emergy flow. All storages in the system that are being used faster than they are being replaced contribute to the nonrenewable emergy supporting the system. This includes storages that can be used renewably, *e.g*., soil, groundwater, timber.

2.3.3 *Evaluating Exports and Imports*

The data sources and methods used to evaluate imports and exports will vary depending on the system. The following methods are specific for the evaluation of imports and exports to and from a state in the United States. Emergy is imported and exported in three forms: (1) emergy in services separate from any material flows (consulting, data analysis, financial services, *etc*.), (2) emergy in materials entering and leaving the state, and (3) emergy in the human service associated with the material inflows and outflows (collecting, refining, manufacturing, distributing, shipping, and handling). Most of the data on the shipment of commodities between states is collected in terms of both the dollar value and tonnage shipped. Both kinds of data are needed to make estimates of emergy movements because goods have energy and emergy associated with their creation and concentration in nature that is separate from the contributions of human services that are measured in the economic value of the good. Generally for steady state conditions, the value, or the money paid for a material at the point of use reflects the service associated with that commodity. This dollar value can be multiplied by the national emergy to dollar ratio for the year of analysis to give a 1st order estimate of the average emergy of the human services accompanying the flow of imported goods. The fluxes of energy or mass in each material flow can be multiplied by the appropriate emergy per unit (excluding services) and the results summed to determine the total emergy in the import and export of the materials in goods.

Determining the emergy in goods and services imported to and exported from a state is a difficult problem because data on the exchange of goods and services is collected at different points, by different government agencies, using different methods of aggregation and estimation. Furthermore, while imports and exports are tracked at the national level using shipping labels that have explicit information, the domestic distribution of goods is determined by the statistical analysis of survey data and other economic modeling methods. Domestic energy shipments are the only commodities tracked on the basis of a nearly complete accounting of actual state-to-state movements of the commodity. Petroleum is an exception to this level of detailed accounting because its movements are only tracked among regions.

The detailed export profile estimates and the overall information on state-to-state movements of goods in the Commodity Flow Survey (CFS) *(2)* and it was the primary source used to determine both the exports from and the imports to a state by product category. In addition, other sources were consulted to get a more complete accounting of goods crossing the boundary and to check the CFS numbers wherever possible. All of these data are available on government websites (see Data Sources).

2.3.3.1 *Determining the Emergy in Materials*

Theoretically, determining the emergy in material inflows should be straightforward; however, the data reported are not complete. Although total dollar and tonnage values are given for inbound and outbound shipments in the CFS for each commodity class, some commodity classes are missing an estimate for tonnage, dollar value, or both. This situation occurs most commonly because shipments are too variable to make the average a useful parameter or because a value, if given, would reveal information about an individual firm. A price per ton can be estimated from the data wherever the dollar value and tonnage are provided. Often both dollar value and tonnage for commodities are available for the total shipments out of a state. If the tonnage data was missing for a commodity in the shipments to a particular state, the price (dollars per ton) from the total shipments was used to calculate the unknown tonnage. Where flows are present but both tonnages and dollar values are unreported a tonnage-weighted export profile of commodities based on their respective fraction of total shipments was used to estimate the missing tonnage and to bring the total for all commodities exported to the total reported in the CFS (see Appendix D).

The Energy Information Administration (EIA) data on energy movements of coal and natural gas were estimated using all sources larger than a certain minimum size; and therefore, these data were considered to be more accurate and complete than the CFS data, which are estimated from the results of a survey of shippers. The EIA data were used to check and replace, if needed, entries in the CFS. In addition, a category for natural gas data was added. Natural gas movements through existing pipelines can be determined as well as natural gas exports or imports from or to the state.

All materials that are prepared for shipment from a state are reported as exported in the CFS. However, some of these materials end up within the state of origin. The materials actually exported from a state are determined by subtracting the tonnage of shipments that begin and end in the state of origin from the total tonnage of shipments in each commodity class.

While the amount of goods imported into a state are not directly tracked in the 1997 CFS, the destination state for exports is reported, and consequently, the goods imported to a state can be determined by adding up the tonnage within each commodity class exported from the other 49 states to the state under analysis (Minnesota). If a state has a customs entry point, the U.S. Customs data on imports are tabulated for each commodity class. The interstate shipment of goods tracked by the CFS includes all the goods shipped from a state regardless of origin, therefore international imports need not be included separately even for states with ports of entry. Most of the goods coming in from abroad are passed on directly to other states and contribute to the nation as a whole and to the states of destination, but they contribute little to the state where entry occurs, if they are not used there. A preliminary analysis of the State of Maryland including the port of Baltimore showed that emergy inflows through a major international port may be an order of magnitude larger than the state-to-state emergy shipments. Thus, including these pass-through flows from the next larger system alters the emergy indices of the state to such a degree that they are no longer comparable to states without major ports of entry.

The 1997 Commodity Flow Survey reported commodities using a two-digit Standard Classification of Transported Goods (SCTG) code. This code is different from the Standard Industrial Classification (SIC) and the North American Industry Classification System (NAICS), both of which are used in U.S. economic data reports. Both import and export data are included in the CFS, but conversion is not necessary unless the state has a foreign customs entry point (Minnesota has customs entries at Duluth and along its northern border with Canada). Imports listed by NAICS categories were converted to SCTG categories using an approximate conversion scheme that we developed for several different industry classification codes (see Appendix D, Table D1.1). Foreign trade entering the State of Minnesota was not considered separate from the CFS survey of total shipments, because of the problems observed in the Maryland study.

The emergy in materials exported from or imported to a state is then determined by multiplying the mass or energy flow in each commodity class by the appropriate emergy per mass or transformity, respectively, based on an average of these ratios for the major material items moving in the class (Appendix B, Table B2.1). Outflows or inflows are then summed across all commodities to get the total emergy exported or imported.

Three key data sources for export/import calculations are the 1997 Commodity Flow Survey *(2)*, the Department of Energy's Energy Information Administration *(3)* and import data from the US Customs Office and the Office of International Trade *(4)*. In addition, data for natural gas and coal shipments came from Department of Energy (DOE) documents *(5, 6)*. A step-by-step method for completing tables to calculate exports and imports is given in Appendix D.

2.3.3.2 *Determining the Emergy in Services*

Services *per se* can be tracked along with goods and the services required for their production using total receipts for the different industry sectors along with sector employment. These numbers are recorded for both the United States as a whole and for each individual state using the same methods, but there is no distinction between goods and services that remain within the state and services that are transferred to other states. A variation of the economic base-nonbase method was used to estimate the emergy imported and exported in services. The information on the base-nonbase method used in this report can be found at the web address *(7)* given in Data Sources.

Economic base theory is usually employed to analyze the growth potential and stability of an economy in terms of its export industries *(7)*. In this method, economic sectors are designated as basic (exporting sectors that are largely dependent on areas external to the state or region for marketing their goods and services) or non-basic (sectors whose products and services are mainly used within the state or local region of analysis). Once the industry data have been gathered and the assumptions about sector behavior have been recorded, an estimation of exported and imported services can be made.

The underlying assumption behind the base-nonbase method of estimation is that the aggregate demand of the people in a nation will be satisfied by the total production of goods and services in all sectors of the national economy. Thus the ratio of workers in any sector to total employment for the nation indicates the level of economic production necessary to satisfy the average needs of the people. The number of workers in any given economic sector in a state as a fraction of the total workers in that state compared to a similar ratio for the nation is an indicator of the excess or deficit production capacity that may exist within that sector in the state's economy. This ratio is the location quotient (LQ) and it can be used to determine whether a given industry sector produces exports. If LQ is greater than one, at least some of the sector is basic (exporting). If it is equal to one, the sector production is assumed to just meet local demand and there is no excess to export. If the LQ is less than one, the local economic sector cannot satisfy the average demand and thus it is assumed that no net export will occur. In this study we view sectors with location quotients less than one as potential importers of goods and services. The formula to calculate the LQ for employment, S, in industry sector, i, within the economy of a state with total employment,

S_t, referenced to employment in the same industry sector of the national economy, N_i, with total employment, N_t, is given below.

$$LQ = \frac{S_i / S_t}{N_i / N_t} \tag{1}$$

The following equation was used to determine the number of basic jobs, B, in the export portion of an industry:

$$B = \left[\left(\frac{S_i}{N_i}\right) - \left(\frac{S_t}{N_t}\right)\right] \times N_i \tag{2}$$

The number of basic sector workers, B, times the productivity per worker in the state industry gives an estimate of the dollar value of exported services. Multiplication of this number by the emergy to dollar ratio for the nation gives an estimate of the average emergy exported from a sector. If both goods and services are exported from the sector, the dollar value of the goods exported must be subtracted from total sector exports to estimate services. Alternatively for sectors that export both goods and services, the above method can be applied to more detailed data from sub-sectors that are almost entirely services and the export determined based on these sector divisions.

An estimate of the potential import of services to a region can be obtained in a similar manner. Under the assumptions given above, the deficit in employment in an industry sector should indicate the amount of service that would need to be imported for the residents of a region to enjoy the same level of service from these sectors experienced by an average person in the nation. To estimate imported services from the calculated potential, states above the average per capita income in the nation are assumed to be able to fill all their need for services, whereas states below this level were assumed to be able to fill only part of their needs. For example, West Virginia is a state shown to be impoverished by many social and economic indicators, *e.g.*, in 1997 West Virginia ranked 49th among the 50 states in per capita income *(8)*. Following the assumption given above, we assumed that West Virginians could purchase services in proportion to the ratio of West Virginia's 1997 per capita income to the 1997 national average per capita income. In contrast, Minnesota ranked 10th in per capita income in 2000 and it is assumed to import all services needed to fill any deficit. This number is only an estimate and the actual value of services entering the state is unknown. Assumptions governing the export and import of services from different industry sectors might be expected to vary somewhat based on the particular economic circumstances of individual states. In using this method, it is important to ascertain the facts about a given state's economy and to make supportable assumptions about service import-export relationships based on those facts. Steps in the method to calculate services are given in Appendix C.

2.4 Creating the Emergy Balance Sheet

The emergy balance sheet is a table containing the evaluation of the emergy stored in the natural and economic assets of the system. A partial list of assets for Minnesota that emphasizes the storages of natural capital is presented in this paper. The determination of some stored assets on the balance sheet of a state or region requires knowledge of the emergy input over the average turnover time of the storage. For example, to determine the emergy required for a forest of trees that are on average 80 years-old, the average annual energy used to support an area of forest (chemical potential energy of the water evapotranspired) would be multiplied by its transformity and then that number multiplied by 80 to determine the emergy required to develop the standing crop of trees comprising the forest. In evaluating an economic production process, start-up or capital costs are prorated over the average lifetime of the facility carrying out a production process. If the energy or mass of storage present in the system is known, this quantity can be multiplied by its transformity or specific emergy to obtain the emergy of the stored asset. For example, the estimated recoverable iron reserves in grams could be multiplied by the Gibb's free energy J/g to get energy and then by the transformity of iron (sej/J) to find the emergy of the stored capital asset. In this study environmental liabilities (Campbell 2005) are only partially accounted for on the emergy income statement and thus are not placed on the balance sheet; however, methods to better document them are under development and we plan to include these accounts fully in future studies. Also, the data to quantify the economic infrastructure of a state in physical units is not commonly tabulated, and thus, we are looking for data sources and methods to easily quantify the economic infrastructure and assets of society present within state borders.

2.5 Constructing the Emergy-Economic Overview

Information from the completed emergy income statement tables is combined to create a Table of Summary Flows, which provides the quantities needed for the calculation of the emergy indices. These summary flows are also placed on the aggregated overview diagram of the system. The item name often is sufficient to identify a quantity, but where it is not, additional explanation is given in the Table notes along with how the quantity was derived. The evaluated energy systems diagram of the macroscopic economic and ecological features of the system shows important classes of flows, the details of emergy and money movements across system boundaries, and a limited number of flows within the state. The inflows of renewable and purchased emergy and the outflows of emergy in products and services are summarized in an even simpler “3-arm diagram” that shows only the inputs and outflows from the system.

2.5.1 *Summary Emergy and Dollar Flows*

The summary table includes information on all the important emergy and dollar flows of the system designated with a letter for each category of flow. Numerical subscripts after a letter or symbol denote a particular flow of a given type. The renewable energy inflow to the system is designated with the letter “R”. The letter “N” indicates nonrenewable energy sources and it includes “N_0”, which designates ordinarily renewable sources that are being used faster than they are replaced, *e.g.*, soil, timber, or groundwater. The letter “F” designates flows of fuels and minerals imported to and/or used within the state. The gross economic product of the state (GSP) is designated with the letter “X”. The letter “G” designates imported goods excluding fuels and minerals. The dollars paid for all imports are shown with the letter “I”, and subdivisions of this sum are given by subscripts. The dollars brought into the state as Federal transfer payments are listed with other dollar inflows. The letters “PI” designate the emergy flows in human service that have been purchased by the dollars paid for imported goods and services. Exported products are represented with the letter “B”. The dollars paid for exports are shown with the letter “E” whereas the emergy of the human service required to produce these exports is shown as “PE”. Other flows can be added, *e.g.*, immigration, when they represent major inflows of emergy in the annual budget.

Money entering the state does not bring emergy into the state unless it is spent on goods, fuels, or minerals from outside sources. However, when money from outside is spent in the state, this money generates internal emergy flows. For example, the emergy flows generated when tourist dollars are spent in the state are included as emergy exports. Campbell (1998) argued that tourists receive value from their recreational experience and that these experiences are virtual emergy exports, which require that unique emergy storages and flows exist within the system to attract tourists and their expenditures. Tourist’s expenditures within the state are taken as a first order estimator of the value of the recreational experience that they take home with them. Recreational experiences are classified as exports, because they would not be possible without the unique opportunities provided by the emergy stores and flows that are present in a given area.

One research question of interest is, “Are Federal transfer payments linked to the overall emergy received by the nation from a state?” If so, Federal transfer payments might be larger if the real value received by the Nation exceeds that expected from the monetary exchange, *i.e.*, the monetary exchange balances but the emergy exchange does not. This relationship has not been proven, but Federal outlays add emergy flows to the state when these monies are spent within the state, *i.e.*, at the state’s emergy to dollar ratio. In this latter view Federal outlays are imports and Federal taxes are exports because they represent a foregone opportunity to generate emergy flows within the state. In this paper we examine the question of Federal outlays and taxes more closely by analyzing the structure of Federal outlays and taxes in Minnesota and by comparing Minnesota to West Virginia.

2.5.2 *Determining the Renewable Emergy Base for a System*

The objective in determining the renewable emergy base for a given area of the earth is to evaluate the degree to which the earth’s renewable emergy sources have been concentrated in a given area. All significant inflows are identified and evaluated, but the items included in the renewable emergy base for the system are determined in a manner that avoids double counting, *i.e*., the base includes only the largest of the emergy sources entering the area when they are co-products of the same generating process. For example, rain and wind are co-products of the work done by the planetary heat engine (the latitudinal gradient of temperature over the world oceans); therefore, only the largest would be counted toward the renewable emergy base for a given area. If a system includes land and sea areas, the renewable emergy base can be determined for each area and the two inputs summed to obtain the renewable emergy base for the entire area.

Planetary processes are considered to be one interconnected system for the purpose of determining the transformities of global products, thus the entire emergy input to the earth is necessary for the formation of all global co-products, regardless of the baseline. As a result the rules to minimize double counting in determining the natural emergy base for a given area of the earth will be the same for all baselines. A simple rule to avoid double counting when using the 15.83 or the 9.26 baseline is to only count the largest inflowing emergy of all the co-products of the planetary system (including tide) as the emergy base for any given area of the earth. Under this rule different areas in the same system may count different single emergies as the direct base, *e.g.*, tide for a state's area of coastal ocean and the chemical potential energy of rain for the land area of the coastal state can be added together to get the renewable emergy received by the entire area of the state. The same spatial resolution for determining the emergy inflows must be used to ensure that bases are comparable. Where emergy inflows are concentrated in space, higher resolution of the inputs will result in a greater emergy base for the system. For example, at a resolution of 100 m, the zone of breaking waves would be resolved for a coastal system and the wave emergy absorbed might be added to the emergy base for the system after adjustment of the area of the other inputs, and if it is the largest input received over the area of the 100 m coastal strip. This dependence on spatial resolution requires that the emergy analyst consider differences in the emergy signature across the landscape where they exist, thus areas of different biogeographic characteristics are considered separately and the largest emergy inflows to each are combined to represent the total system (Campbell 2000a).

With regard to determining the emergy base for a system, the main purpose of the emergy accounting is to include all the emergy required for a system without double counting any input. The rule to only count the largest input among co-products is a crude way of ensuring that no double counting occurs; however, this method gives a conservative estimate of the emergy required for the system. In fact, co-products may have only partial dependencies and where the relationship between these inputs is known other solutions can be used (Odum *et al.* 1987, Lu *et al.* 2007). How to handle partial dependencies among system inputs is being investigated in current research on emergy methods.

(A) Renewable emergy received. For any area, use the largest of the energy sources supplied by the planetary processes (rain, wind, waves, earth cycle, tides, *etc*.) at the point that they enter the system and sum over the entire area to determine the renewable emergy received. For rivers that cross into a state or flow along its borders, the emergy received at the point the river enters the state is included in the emergy base. If the river flows along the border between two states, ½ of the emergy received is given to each state.

(B) Renewable emergy absorbed. Both the emergy in chemical potential energy (evapotranspiration) and the geopotential energy (runoff) of water doing work in the system are counted, because these two forms of energy carried by water interact across the elevation gradient from mountains to the sea to maximize empower on the landscape (Romitelli 1997). All tidal energy received is assumed to be used within the estuarine and continental shelf area and all wave energy is assumed to be used when waves break on the shore. The chemical potential and the geopotential energy of rivers used in the state is found by determining the chemical and geopotential energy at the point where the river leaves the state and subtracting this from the respective potentials at the point of entry. For example, a river enters the state 500 m above sea level and leaves at an elevation of 250 m, the difference in geopotential energy of the annual water flows at these two points is the geopotential energy used within the state.

2.6 Emergy Indices

Emergy indices are often helpful in characterizing the condition of a region and in determining the relationship between the region and its larger system.

The emergy indices are calculated by performing various mathematical operations with the quantities given in the Flow Summary Table. The indices used in the emergy evaluation of Minnesota are identified and explained below.

2.6.1 *The Emergy/Money Ratio*

The ratio of annual emergy flow to money flow is a useful index because it connects economic activity to the emergy flows that support the economy in a given year. An emergy to money ratio is obtained by dividing the total emergy used by a state or country in a given year by the gross economic product for that year. The result gives the average amount of emergy that is purchased by spending a dollar in a certain place (sej/$) at a given time. In other words the emergy/dollar ratio tells us the purchasing power of a dollar in terms of the real wealth (emergy) that it can buy. Money is used to purchase products such as food, fuels, clothing, housing, electricity, information, *etc*. according to their market price. Each of these products also has an emergy value. In addition, many products of nature contribute to these economic products but are not traded in the market and thus have no market value. Dividing the emergy of a product or service by the emergy to dollar ratio for its system gives the emdollar value of the item. The emdollar value of a product or service represents the portion of the total purchasing power in the system that is due to a particular product or service from the economy or from nature. The emergy to dollar ratio has another useful property. Since dollars are only paid to people for their services, the emergy to dollar ratio for a system can be used as an estimate of the average value of human services in that system. Thus, multiplying a dollar value of a product or service by the emergy to dollar ratio gives, on average, the emergy equivalent of human service required for an item.

2.6.2 *The Emergy Exchange Ratio*

The emergy exchange ratio (EER) is the ratio of emergy received to the emergy given in any economic transaction, *i.e*., a trade or sale. The trading partner that receives more emergy will receive greater real wealth, and therefore, greater economic stimulation due to the trade. Indices of equity in exchange between states and nations are determined by comparing the emergy in imports and exports. The difference between imports and exports indicates whether the state or region is a support area for other regions and/or the larger system. The ratio of exports to imports indicates the degree to which a system contributes emergy to or receives it from a trading partner or its larger system. When applied to individual products, the EER gives the emergy advantage to the buyer by determining the emergy of the exported product relative to the emergy that could be purchased with the buying power of the money received in exchange.

2.6.3 *The Investment Ratio*

The investment ratio is the ratio of the solar emergy purchased from outside the system to the solar emergy supplied by the renewable and nonrenewable energy sources from within the system. It shows the matching of economic investment to the indigenous resources of a state or region. Lower values of this ratio indicate that more of the indigenous environmental resources are available per unit of economic activity than the average, and therefore, environmental resources may be available locally and capable of stimulating investment and additional economic use. The ratio of purchased to free emergy is a variation of the investment ratio, which compares purchased emergy with the free contributions of renewable emergy (*e.g*., rain) and renewable emergy used in a nonrenewable manner *(e.g*., soil erosion). Empower density or the emergy flow per unit area is a related measure that indicates the spatial concentration of economic activity or the intensity of development in any unit area of a state or nation.

2.6.4 *The Environmental Loading Ratio*

The environmental loading ratio is the ratio of the emergy used from nonrenewable sources (including renewable sources being used in a nonrenewable manner) and the emergy imported in goods and services to the renewable emergy used (Odum 1996, Brown and Ulgiati 2001). It indicates the expected intensity of impacts that must be carried by the renewable emergy base of the system, and therefore, the probability that the system will have incurred significant environmental liabilities on the balance sheet.

2.6.5 *Indices of Self-Sufficiency and Dependence*

The emergy used from home sources as a fraction of total emergy use is a measure of the relative self-sufficiency of a state or region. Conversely, the fraction of total emergy use purchased from outside shows the dependence of a state or region on the larger economy of which it is a part. The fraction of use that enters as imported services indicates the relative dependence of the state on the service economy of the nation.

2.6.6 *Indices of Sustainable Use*

The fraction of use that is free and the fraction of use that is renewable are indicators of what is sustainable in the long run. If the difference between these two indicators is large, it shows that the long-term capacity of the renewable emergy sources to support life is being degraded. Truly sustainable use is based on renewable resources alone used in a renewable manner. A quick estimate of the renewable carrying capacity of a state at the current standard of living is obtained by multiplying the fraction of use that is renewable by the present population of the state. Sometimes the developed carrying capacity at the current standard of living is also estimated by multiplying the above number by 8, an average ratio of purchased to renewable emergy in developed countries from past studies (Odum 1996). Eventually, this number will be modified based on the current set of state studies.

2.6.7 *Indices of Quality of Life*

The annual emergy flow per person is hypothesized to be an index of the overall standard of living that includes environmental and economic contributions to the quality of life. This assumes that the people living in the system actually benefit from the energy used there. Quality of life is also indicated by the emergy in electricity use as a fraction of total use. This ratio is a measure of the relative importance of the higher transformity activities of people, and therefore, it should be correlated with the contributions of technology to higher standards of living. Other emergy indices of quality of life need to be developed that better capture the human-information aspect of well-being.

2.7 Energy and Emergy Signatures

Energy and emergy signatures of a system show the magnitude of environmental and economic processes as a synoptic plot that is useful in characterizing and classifying systems. The energy signature is a bar graph of energy flows with the magnitude and direction of the flow (in or out of the system) in joules per year shown on the ordinate and the type of energy flow identified on the abscissa listed in order of increasing transformity. A bar graph of the same flows converted to empower (sej/y) is the emergy signature of the system. Conversion of energy flows to empower shows the relative contributions of the various energy inputs in terms of equivalent ability to do work. If functionally distinct areas have different emergy signatures (Campbell 2000b) and similar areas exhibit similarities in their emergy signature, the emergy signature may be useful in classifying different environmental systems based on differences in their inputs (Odum *et al.* 1977).

Section 3

An Emergy Evaluation of Minnesota

An emergy analysis of the State of Minnesota is given in this section of the report. The application of emergy analysis methods in this state study shows how each of the techniques given in the methods section is performed. The assumptions, calculations and data sources used in each part of the analysis are documented and given in the Appendices. This section is written as a stand alone report that can be used by scientists and managers who are interested in the results and conclusions of this case study, "Emergy Evaluation of Minnesota."

3.1 Introduction

The economic productivity and well-being of Minnesotans are dependent on the health and vitality of their environment as well as the wealth of their stored natural resources. However, the environmental contributions to Minnesota's economy cannot be evaluated using market values alone. This is true because there is an inverse relationship between the contribution that a resource makes to the economy and its price (Odum 1996). For example, when timber is abundant, prices are lowest but the contribution of timber to society is greatest because it is used in great quantity and for many purposes. On the other hand, after extreme logging of a region, timber becomes scarce and the cost increases; timber contributes less to the economy, because it is no longer commonly used (Odum 1996). Economic studies evaluate wealth by what people are willing to pay for a commodity or service, but because money is not paid to the environment for its work, market values do not effectively assess environmental contributions to society (Odum, 1996). Emergy includes nature's work contributions to economic products and services. Emergy accounts can provide directly comparable estimates of the environmental, social and economic costs and benefits of alternative actions. Therefore, the creation and analysis of such accounts is needed to ensure that managers have all the information that they need to make decisions in the best interest of society.

At present, Minnesota is faced with the conflicting needs of its people and the nation. There is a national energy policy initiative for the United States to reduce its dependence on foreign sources of energy (National Energy Policy Development 2001). At the same time, there is a growing recognition of the need to establish a sustainable relationship between society, resource use, and the environment (National Research Council 1999). If a constant standard of living is to be maintained in the United States as global petroleum production declines, fuel autonomy implies an expansion of national energy production and economic growth for Minnesota and other states with a rich abundance of natural resources. However, there are thought to be large environmental and social impacts associated with the use of Minnesota farmland to produce biofuels such as corn-based ethanol (Pimentel 2003). Minnesota is currently subject to national legislation calling for the increase of ethanol production. The need to increase corn production to make ethanol will compete for arable land with other food crops and prices for both corn and the displaced crops will increase. Emergy analyses of ethanol production from various feed stocks and technologies will help clarify the consequences of greatly increasing ethanol production in Minnesota and in the Nation as a whole. Minnesota is also under internal pressures to increase economic prosperity through further developing its human and natural capital resources while also confronting the daunting task of preventing agricultural and industrial development from further damaging the health of human beings and the environment.

Human economic activities such as mining, timbering, farming, and changing patterns of urban and industrial growth are the primary forces causing environmental change in the State. Major environmental problems in Minnesota include point and non-point pollution from agricultural activities and urban development, *e.g.*, effluents from agricultural and industrial manufacturing facilities, sediment accumulation in streams, nitrogen in runoff from farm lands, as well as invasion of exotic species, forest fragmentation, and habitat loss that accompany these and other human activities *(9)*. Because of its many lakes and wetlands, the aquatic environment is of special concern to Minnesotans, especially the deposition of mercury and its accumulation in game fish (M. Bourdaghs, pers. com.). In this report, we examine the larger system that controls the environmental and socioeconomic characteristics of local systems within Minnesota. The results of this study can serve as the context for the analysis of the sustainability of regional and local systems. In addition, the emergy analysis methods used in this state-wide study can be applied to characterize environmental and socioeconomic problems at the local and regional scale and to evaluate alternative solutions for watershed restoration.

3.2 The Efficacy of Emergy Accounting in Answering Management Questions

People need accurate and complete financial information to answer questions about their fiscal condition, so that they can make better decisions. The kinds of questions that can be answered by keeping accurate financial accounts are many and depend on the particular system for which the accounts are being kept. For example, people ask and answer practical questions about their individual finances every day. Some of these questions relate to the amount of assets or income, *e.g*., "How much money do I have in the bank?" or "Are my monthly expenditures within my budget?" Other questions relate to the equity of exchange*, e.g*., "Is that used car really worth the money?" or "How much will the schools improve if my property taxes go up?" Still other questions are social in nature and relate to how we are doing compared to others, *e.g*., "Do we have a higher or lower standard of living than the neighbors?" When the questions relate to financial condition, dollars are sufficient to provide the answer. However, where resources in the public domain are being used, degraded, or developed, questions about environmental systems cannot be answered by considering monetary value alone. Yet the health of society depends on accurate answers to questions about the condition and use of environmental resources as surely as individual financial health depends on assessing personal savings and income.

Standard accounting tools, such as the income statement and balance sheet, are used to document the financial health of a firm. It is no less important that we develop similar tools to assess the condition of environmental systems. Emergy accounting provides the means to keep the accounts for the economy, society, and the environment on a single income statement and balance sheet. The questions that we can answer after performing an emergy analysis of a system are similar to those that we can answer as a result of doing a financial analysis of a business or of our own individual accounts. The following key questions to be answered from information on Minnesota's environmental accounts were derived from discussions with environmental managers from Region 3 and they are the same questions used in the West Virginia study: (1) "What is the current level of economic investment in relation to Minnesota's resource base, and is this level of investment sustainable?" (2) "What is the net exchange of real wealth between Minnesota and the nation?" (3) "What are the major causes for any observed imbalances?" (4) "What actions can be taken to address an imbalance, if it exists?" (5) "How does Minnesota's standard of living compare to other states and the Nation?" (6) "Who benefits most from the productive use of the state's resources?" (7) "How self-sufficient is the state based on its renewable and nonrenewable resources?" (8) "How can we manage the environment and economy of Minnesota to maximize the well-being of humanity and nature in the State and in the Nation?" The emergy accounts for Minnesota presented below will provide information and indicators that will help answer these questions.

3.3 Narrative History of the Land, People and Natural Resources of Minnesota

Before considering in detail the condition of the State of Minnesota in 1997 and 2000, we briefly review the history of the State. Environmental systems like Minnesota are composed of the land, the people, and natural resources and it is our understanding of the development of all aspects of the system that allows us to accurately interpret the present and plan for the future. The following section presents a brief narrative history of the land, people, and natural resources of Minnesota, which is manifested today in the structure of environmental, economic and social systems in the State.

The real wealth of Minnesota can be found in the hard work and ingenuity of its people and in the emergy stored in its abundant natural resources. We first consider the geological history of the State and the development of its landforms and mineral deposits. The entire geologic history of Minnesota is not entirely clear but it is apparent that Minnesota has not always been prairies, rolling hills, and vast forests. Many of the physical features of Minnesota as seen today took millions of years to form and the land that makes up Minnesota has gone through billions of years of change. At times it rested on the equator; it has been the host to great inland seas, and it has been subjected to several periods of glaciation. In the last 150 years geologists have pieced together a great deal of the State's past (Ojakangas and Matsch 1982).

Some of the oldest rocks in the world are found in Minnesota. Called gneisses, they are approximately 3.6 billion years old. The oldest gneisses on Earth are found in Greenland and Labrador and these were formed in the pre-Cambrian era only 200 million years before those of Minnesota. Mountains and volcanoes are not something that Minnesota is known for today, but there were several periods of volcanism in Minnesota's geologic history. All that is known of the ancient volcanism is found in gneissic super belts that formed around 2.7 billion years ago. Minnesota was covered with large mountains due to volcanism at two points, 2.7 and 1.8 billion years ago. There was another period of volcanism in the State around 1.1 billion years ago, but this did not have a dramatic effect on the landscape. After the volcanism the terrain was subject to a great deal of folding. Next, large bodies of granitic magma intruded into and metamorphosed the volcanic and sedimentary rocks. Upon solidification of the granite, faulting began, creating rifts in the old sheets of rock. This combination of folding, intrusion, and faulting was responsible for forming the mountains in northern Minnesota. Since then, the land of Minnesota has been stable and free of violent geologic events. Erosion wore down the land and the mountains in the Lake Superior region over millions of years. The State lies on the Laurentian Upland and Interior Lowland of North America, which are two stable areas of low relief that are perhaps responsible for this long period of stability and erosion in Minnesota (Ojakangas and Matsch 1982). Within the last billion years, the State has been repeatedly covered with oceans; proof of this lies in the many layers of sandstone, shale and limestone within the State and the marine fossils that are found in some deposits.

The large iron deposits found in the State are from the pre-Cambrian era and they were formed from sediment deposition in an ocean that covered the land around two billion years ago. The middle-pre-Cambrian was a time when massive iron deposits were laid down in many shallow seas around the world, presumably by the action of iron-fixing bacteria (Ojakangas and Matsch 1982). The great prevalence of iron deposition at this time has been attributed to the low oxygen atmosphere that is presumed to have existed, before photosynthetic organisms came to dominate the earth.

Around 250-550 million years ago during the Paleozoic era, a transcontinental arch ran through Minnesota creating an area that could not be submerged by most of the subsequent invading oceans. Therefore there was very little deposition in Minnesota during this time and none at all through the center of the State. Also, during the Mississippian and Pennsylvanian periods the equator ran through the area that is now Minnesota. About 100 million years ago, an ocean invaded western North America and its eastern shoreline passed through Minnesota. Life flourished through the State in the Cretaceous period and led to small deposits of coal, but nothing that can be mined economically today.

From 75,000 to 10,000 years ago, glaciers covered Minnesota with ice that was several kilometers thick in some places. These glaciers were responsible for creating much of Minnesota's current landscape. During one stage, the glaciers extended south as far as Kansas, which is evidenced by glacial, erratic boulders found there that match Minnesota's bedrock. As the glaciers finally receded, several glacial lakes formed over Minnesota with the largest being Lake Agassiz. This lake formed on the western edge of Minnesota and extended into the Dakotas and Canada. Before the glaciers melted enough for the lakes to drain to the north, the water had to flow south and eventually spilled over the moraine which formed the southern boundary of Lake Agassiz. This draining action wore away a valley creating the Glacial River Warren, while at the same time depositing sediment. Eventually the glaciers melted enough to allow water to drain to the north into Hudson Bay. As this happened, the Glacial River Warren ceased to flow south and the Minnesota River began to flow in the glacial river's broad valley. Because the Minnesota River is many times smaller than its predecessor, it was able to wear away a deep valley in the loose sediment that the Glacial River Warren had deposited. The Mississippi River formed in much the same manner from smaller glacial lakes draining south. The resulting feature is that both rivers have wide flood plains and fertile river valleys. In the north, oxygen poor water and cool temperatures allowed peat to form easily on the poorly drained lands that had been covered by Lake Agassiz and other glacial lakes until around 5,000 years ago.

Even though the land had been subject to geologic forces for billions of years, one of the greatest forces that would alter the landscape had yet to arrive. For several thousand years before the present time, people inhabited the area that became Minnesota; however, they lived a low impact existence relative to today's industrial civilization. Ever since white Americans and Europeans began to settle in Minnesota in large numbers during the mid-1800s, the land has been in constant change. Nearly all of Minnesota's forests have been clear-cut at least once, and less than one percent of the original prairie remains (Tester 1995).

The history of the people of the State is complex, but it behooves us to consider it, if we are to understand the basis for present social structures and mores. The following account of the history of the people of Minnesota draws heavily on Theodore C. Blegen's "Minnesota, A History of the State" written in 1963.

The northern and southern halves of the State were separated by a vast expanse of wilderness, and as a result, they have notably different histories. Europeans arrived by boat from the south, coming up the Mississippi River and from the north, they found their way to Minnesota by canoe crossing Lake Superior. The Europeans and white Americans who arrived using these different access routes had very different resource exploitation goals, and these goals determined the different course of development in the north and south.

For centuries prior to European settlement, Native American tribes lived in Minnesota. In the north, the Sioux and Chippewa constantly battled, contesting the boundaries of their lands. Then in the mid-1600s, the French arrived in the northern region in search of furs. The French sided with the Chippewa and aided them in their battle against the Sioux. Eventually, with guns and new tactics learned from the French, the Chippewa drove the Sioux out of the forests of northern Minnesota and onto the Great Plains of southwestern Minnesota and the Dakotas. The French entrenched themselves in the region when they annexed the entire Lake Superior region, including part of Minnesota. The French presence lasted until 1763 when northeastern Minnesota was given to the British through the Treaty of Paris at the end of the French and Indian War. During the American Revolution, British soldiers made a brief show of force in the region by arriving at Grand Portage in 1778. This was the only involvement of the region in any part of that war. After the war, Britain ceded control of all land south of the Boundary Waters Area. Despite the cession of this territory to the United States, the British maintained control until after the War of 1812.

The displacement of the Sioux in the north eventually created conflict with the advancing settlers as they began to occupy land in southern Minnesota. This desirable area included good farmland that lay along the Mississippi and Minnesota Rivers. In 1851, thirty-five Sioux Chiefs signed a contract with the Territorial Governor, Alexander Ramsey, giving a large portion of their land along the Minnesota River to the Americans but retaining small portions of land for themselves in the upper reaches of the Mississippi. The Americans were supposed to pay the Sioux a cash settlement, but that was given to investors assuming they would make money on their investments and with that buy food, medicine, and other necessities for the tribes. In 1861 and 1862, conditions on the reservations deteriorated because of the failure to deliver the promised food and supplies and conflict between the tribes broke out. As the situation worsened, Chief Little Crow, whom both Sioux and Americans respected, approached the agent in charge of the reservation to negotiate food and supplies. When the Chief was rebuffed by a trader, the tribes retaliated by murdering five white settlers and declaring war the next day. The Sioux Uprising of 1862 lasted for five weeks and was eventually put down by a force led by Henry Sibley from the Twin Cities. As many as 800 settlers and soldiers died in the uprising along with an uncounted number of Sioux. In the wake of the uprising, 300 Indians were sentenced to death. President Lincoln intervened and he pardoned all but 38 Sioux who were eventually hanged. As a result of this uprising, Minnesota exiled all remaining Sioux from the territory and forbade their return.

Exploration of the southern part of the State began in 1680 when Father Hennepin, a Franciscan priest entered Minnesota from the south. He was the first European on record to arrive at and name the Falls of St. Anthony, which are at the heart of Minneapolis. In 1805, Zebulon Pike on orders from the United States Government purchased land from the Native-American tribes around the falls of St. Anthony. Settlement in the territory by white men began in 1820 with the completion of Fort St. Anthony, now known as Fort Snelling. The settlement around Fort Snelling offered an oasis of American civilization in the wilderness to travelers and St. Anthony Falls became one of the best-known tourist attractions in the northern United States. The first mills were built along the banks of the Mississippi at the St. Anthony Falls from 1821 to 1823. This was the beginning of a long history of exploiting the waterfall for its power. This event also marked the beginning of grain and lumber milling industries that would form the basis of a thriving economy in Minnesota for the next hundred years.

Initially, the falls and the land surrounding them were in the hands of the military, but by the 1830s the potential for private use of the land was realized and the military used its right of ownership to expel the nearly 200 squatters that had made their home on land belonging to the Fort. The displaced squatters left the "Falls" area and made their home eight miles down stream on Pig's Eye Island, named after a well known whiskey seller of the time. This island eventually became the city of St. Paul. In 1837, the government negotiated a deal with the Chippewa and Sioux that opened up the entire area of land between the Mississippi and the St. Croix Rivers to settlement. As soon as the treaty had been ratified by Congress, Minnesota's first land rush began. One of the people awaiting the news of ratification was Franklin Steele. He was determined to gain control of the eastern half of St. Anthony Falls so he could claim half of the river's water power for himself. Along with his business partners he already owned a large portion of the St. Croix Falls. At this point, timber was being cut quickly along the St. Croix River; however, logging had not made its way to the rich stands of trees along the Mississippi. Steel knew that since he owned the land and half of the falls, he could make a fortune if he built mills. To do that he needed capital, so he found several wealthy politicians from Massachusetts to fund his venture. This led to the first civilian dam on the river and resulted in the construction of mills at the Falls of St. Anthony.

In 1848 President Polk initiated the first land sale in the Minnesota Territory. Steele purchased another 332 acres of land around the falls and strengthened his claim. Once people started moving to the area, Steele was able to establish the township he had been envisioning from the beginning. Because St. Anthony Falls was too long of a name to fit on a map, the settlement on the east bank of the Mississippi became St. Anthony.

The early 1850s ushered in the era of forest clear-cutting in the Mississippi watershed, creating a steady flow of timber down the river to the booming milling industry at St. Anthony Falls. Eighteen fifty-one also brought a glimpse of the future when the first grist and flour mill was built in the settlement. The era of commercial flour milling began with the erection of a commercial grinding mill in 1854.

At the same time, Minneapolis was becoming a city across the falls. For many years, the western side of the falls was the property of Fort Snelling and the potential of the western half of St. Anthony Falls was not realized. This changed when Robert Smith, a congressman from Illinois, petitioned the Department of War to lease the lumber and grist mills and the house that had been built in the 1820s to supply Fort Snelling. Despite never actually moving to Minnesota, Smith kept up the façade that he was living there and the Secretary of War believed him. Steele was also attempting to gain a foothold on the western side of the river. He managed this by constructing a ferry at the falls and having one of his former employees settle on the western shore. This became the first residence on the land that would become Minneapolis. In 1852 Congress passed a bill that would open up over 2/3 of the 34,000 acres included in Fort Snelling to private auction. Several years after the auction, the city of Minneapolis was born. The two cities of Minneapolis and St. Anthony worked together on many things including building the first suspension bridge across the river at the falls in 1855 and competing with

St. Paul, which had become a formidable rival as the head of navigation for the Mississippi. The rivalry can clearly be seen as early as 1850 when a resident of St. Anthony, Paul R. George quoted, “man made Saint Paul, but God made Saint Anthony.” Because all three cities relied on the river for their livelihood to a similar degree, their future was to be decided by the people who controlled the businesses of the area.

In the mid-1850s several corporations were formed around the falls. The first was the St. Anthony Falls Water Power Company, which was formed by Steele in St. Anthony. Another corporation was formed on the opposite bank by Smith, and was called the Minneapolis Mill Company. Working together these companies headed up the construction of the second dam over the falls. At over 2,200 feet long, this was a major project that changed the face of the falls forever. After the construction of the dam, mills were able to more efficiently harness the power of the water and businesses around the falls grew quickly. Over the next two decades, as Minnesota became a state, the area around the falls changed dramatically. The cities grew rapidly as did the number of mills that relied on waterpower. Until around 1870 lumber milling was Minneapolis and St. Anthony’s main industry, but second was flour milling and it was rapidly catching up. Between 1860 and 1869 flour production rose from 30,000 barrels to 256,100 barrels. It was bolstered by the increase in grain being grown in the southern and western parts of the State. At the same time, residents of the two cities began to realize that one city around the falls was ideal and Minneapolis and St. Anthony became one in 1872.

Minneapolis was quickly becoming one of the largest producers of flour in the world and in 1880 it surpassed St. Louis as the largest flour milling center in the country. The two main reasons for this were its abundant waterpower and newly constructed railroads that opened some of the finest land in the country for farmers to produce wheat. The largest of the mills that were built in Minneapolis was the Pillsbury A mill; this was also the largest mill in the world at the time. Though sawmilling fell behind as the leading industry in the city around this time, Minneapolis remained third in the Nation in total lumber production. To bolster flour production, the lawmakers began to pass laws giving flour millers an unfair advantage. Eventually this forced lumber mills out of the falls area and into north Minneapolis where they utilized steam instead of water for power. Minneapolis would hold on to the top flour production ranking for the next fifty years.

In the late 1800s, the waterpower of the falls began to be converted to hydroelectric power generation. This metamorphosis would last until 1960 when the last water wheel was taken down. Through this time, the resource of the falls was managed by an engineer named William De La Barre. He was primarily responsible for transitioning the use of waterpower from era to era as technology improved and needs changed. Before 1960, flour milling fell by the wayside and total production was a fraction of what it had been in its heyday. As milling moved away from the falls, the Hennepin Island hydroelectric power plant took over the newly opened waterway. Today, only the Pillsbury A Mill remains as a working mill. In 1963 the Army Corps of Engineers finished a lock and dam by-passing the Falls and opening the river above the falls to the sea for the first time. Since this time, Minneapolis has held its place as the largest city in Minnesota and as the cultural and commercial center for the upper Midwest.

In the late 1800s Minnesota began to transform through rapid development of agriculture, industry, and education. The emphasis on wheat growing shifted toward other crops such as barley, oats, and corn. Dairy farming increased along with milk, butter, and cheese production under the organizing influence of cooperative creameries. Livestock production increased in the State and St. Paul became an important terminal for shipping livestock and later a center for meat packing. During this time Minnesota society began to create supporting institutions such as the cooperative mutual insurance companies for farmers and dairy men that formed as early as 1867. The cooperatives began to take on other tasks such as advertising, and by the 1920s Land O’ Lakes Inc. had made the Minnesota Co-operative Dairies Association the largest marketer of butter in the world. The cooperative idea spread further extending into cooperatively run grain elevators and as far as consumer cooperatives. From its beginning the cooperative movement in Minnesota was allied with the interests of the working person (Blegen 1963). Cooperatives spread into many businesses including cooperative wholesalers, insurance companies, telephone, farm supplies, and credit unions.

Education played an important role in the transformation of Minnesota agriculture. County agents working within agricultural extension programs that were mandated by Federal law in 1914 publically disseminated new information to farmers that promoted modern farming methods and technological advances. As Minnesota farms became some of the most productive in the Nation, the food processing industry located canneries and freezing facilities throughout the agricultural regions of the State. In the years since 2000 the use of Minnesota corn for industrial production of ethanol has gained prominence and as of October 2007, Minnesota had 17 operating ethanol facilities with a production capacity of 675 million gallons per year *(10)*.

3.3.1 *Timber*

Initially, timber was the main resource that drew people to Minnesota in the 19th century. With the Mississippi and St. Croix rivers capable of floating large amounts of wood to mills in Minneapolis and Stillwater, the forests were soon clear-cut. By the 1870s the great coniferous forests of the north were being cut and Minnesota was supplying more timber to America than was any other state (Borchert 1959). The vast scale and wealth of Minnesota's timber resources elevated the social importance of the lumberjack and generated stories of a mythical hero of giant proportions, Paul Bunyan and his blue ox, Babe. Nevertheless, by the 1920s, large-scale logging was finished in Minnesota and the great forest of the North Country was called the "cutover" (Borchert 1959). Beginning in 1895, logging began in the boundary waters area. At that time, the target resource was lumber and mine supports for the booming mining industry in that the northeastern part of the State. Once all of the big pine had been cut, the industry shifted to logging for pulpwood. This lasted until 1978 when a state law was passed ending logging in the Boundary Waters Canoe Area. From 1870 to 1900 Minnesota timber built cities, towns and farms all across the treeless plains to the south and west as the prairie lands were settled and developed.

3.3.2 *Flour*

Flour milling was established to use the waterpower of St. Anthony's falls to grind wheat, which was the dominant crop, produced from Minnesota's rich farmland from the 1850s through the 1880s. Beginning in 1880, and for the next fifty years, Minneapolis was the largest flour producer in the United States and second in the world only to Budapest. Great innovations were made in the wheat milling industry during this time and Minnesota's patented spring wheat flour was generally acknowledged as the best bread-making flour in the world. The conglomeration of milling companies in Minneapolis centered on St. Anthony Falls until the advent of steam and electric power became more efficient and less expensive to use than water power.

3.3.3 *Surface Water*

Minnesota has an abundance of surface waters including over 15,000 lakes, ponds, and wetlands and several large rivers such as the Mississippi, the Minnesota and the St. Croix. Minnesota's rivers have been used for transportation and waterpower since the 1800s and today its lakes are host to many forms of recreation in all seasons. Lake Itasca, the headwaters of the Mississippi, is located in Minnesota. The Boundary Waters Canoe Area (BWCA) lies within the State and it has been protected since 1978. The BWCA along with its sister park, Quetico Provincial Park across the border in Canada and Voyageurs National Park contain more land area together than Yellowstone National Park, which is the largest U.S. National Park. This land contains the largest area of unlogged virgin forest in the eastern United States.

3.3.4 *Iron Ore*

Iron was first found in Minnesota as early as 1848; however, production did not start until 1884. At first, explorers assumed that all the iron in the State was low-grade magnetite due to the effect of the rock on their compasses. However, high-grade hematite was later found in pockets within the magnetite. There are three main iron ranges in the State: Vermillion, Mesabi, and Cuyuna. The Vermillion range no longer produces ore, but the Mesabi and Cuyuna still produce two-thirds of the Nation's iron ore. Up to 1980, Minnesota mines had produced over three billion metric tons of iron ore. At current rates of production, Minnesota has over two hundred years worth of economically retrievable reserves with the potential for more if lower grade taconite rock can be economically beneficiated.

3.3.5 *Taconite*

Taconite is one of the hardest minerals known, making it very difficult to mine. Mining of taconite was not possible until the advent of a drilling technique known as jet piercing. Recent advances in mining technology through the use of tungsten-carbide drill bits, has increased the feasibility of mining taconite. The process of beneficiating taconite rock was worked out over many years by E.W. Davis, a professor at the University of Minnesota, and his colleagues. To refine the taconite, large plants had to be built at a price of about 250 million dollars each. To refine taconite, it must be crushed to a very fine powder, then, using powerful magnets the magnetite is separated from undesirable byproducts. Next, the magnetite is mixed with bentonite clay and fired to create pellets of hematite that are around 65% iron. Due to the small size of the pellets, it is easy to mix them with coke and limestone in a blast furnace to produce steel. In the furnace, taconite pellets melt quickly increasing the productivity of the furnace by roughly doubling the amount of steel that can be produced in a given time. This increased efficiency keeps taconite mining competitive with lower cost sources of ore.

3.3.6 *Other Minerals*

Recently, a large deposit of copper-nickel ore has been found in the Duluth Complex in northeastern Minnesota. This deposit makes up 25% of U.S. copper reserves and 12% of the world's nickel reserves. In addition, due to the geology of Minnesota and high radioactivity of wells, reserves of uranium ore are thought to exist in the State. Lastly, in 1865 and 1866, Minnesota had a small gold rush. Since then, however, no deposits have been found. Exploration continues, but has yielded nothing but trace amounts of gold and silver.

3.3.7 *Peat*

Peat was created in the glacial lakes that covered a large portion of the State thousands of years ago. It lies under nearly one million acres within the State. Peat contains half of the thermal potential of anthracite coal and may become an important fuel source in the future.

3.3.8 *Agriculture*

Minnesota can be divided into four agricultural zones: the dairy region covering the lake and hill region in the center of the State, the corn belt on the rich prairie lands of the southwestern portion of the State, the cash crop region covering the bed of glacial Lake Agassiz in the northwestern portion of the State and the North country, which is primarily forested but contains a few farms (Borchert 1959). The primary crops and growing conditions vary across the State. Corn, soybeans and livestock are the primary crops of the Corn Belt. Crops like wheat, sugar beets, and canola that will tolerate colder conditions than corn are grown on large tracts of land in the cash crop region. Dairy cattle and corn are grown in the Dairy Region, which is interspersed with many lakes and wetlands and includes many small hills where plowing is difficult, but which are ideally suited for pasture. The soils in the North Country region are young and poor in most places and therefore they are not suitable for large scale agriculture. Agriculture occupies over 40% of the land area of the State and it is one of Minnesota's largest industries. In 2000, it employed over 100,000 people and had sales over eight billion dollars *(11)*. The largest crops are corn, soybeans, and wheat and the largest livestock sales come from turkeys, hogs, and cattle. The State is the number one producer of turkeys in the country.

3.3.9 *Education*

Minnesotans had an early interest in promoting education within the State and as a result the State has become known for its many fine institutions of higher learning. For example, the University of Minnesota was founded in 1851 before Minnesota achieved statehood and it was ranked 20th on a list of the top research universities the U.S. for 2004 (88). Many of the early settlers came to Minnesota from the northeastern United States bringing with them their knowledge and experience with long-established schools and colleges. In addition, the State received many immigrants from northern Europe, who brought with them a belief in the value of a good education and hard work. Minnesota has several private schools that are ranked among the top educational institutions of the Nation. Minnesota's emphasis on education is reflected in the knowledge and skill level of the labor force. This abundance of "know-how" is shown by the fact that Minnesotans have been innovators in many fields from flour milling and iron mining to manufacturing and medicine.

3.4 An Energy Systems Model of Minnesota

An energy systems model of Minnesota that shows the major economic and environmental forcing functions, components, and connections is presented in Fig. 1. It offers a conceptual guide to thinking about the State and provides the basis for developing emergy accounts. The environmental energy sources, as well as the fuels, goods, and services that help make Minnesota's economy productive, are shown as circles around the edge of the system boundary, *i.e.*, the box labeled "Minnesota, 2000". Purchased imports and exports generate monetary flows that cross the State borders in exchange for products and services. Tourists bring money into the State to spend on recreation and the Federal government generates both monetary inflow as outlay and outflows as taxes. The flows of energy, material, and information into, through, and out of the State are identified by the various pathways, each labeled with a subscripted k. The k's are listed and defined in Table 2, but in this paper they only identify the various pathways. In a simulation model, each k has a numerical value that determines the rate of flow of energy or materials along the pathway. The system components, *e.g.*, economic sectors, shown within the diagram are defined in Table 3. The external forcing functions for the State are listed below and they are used in developing the emergy income statement for Minnesota. External forcing functions are arranged around the edge of the box indicating the system's boundaries from left to right in order of increasing transformity. In the left hand corner, solar radiation enters the system followed by other natural energies, in the form of wind, rain and snow, rivers, and geologic processes such as uplift, subsidence and volcanism. Next, the energy of fossil fuel and minerals enters, followed by material goods and services, people, and higher social structures, such as government, markets and tourism.

The model components in Fig. 1 include aggregated systems for coniferous forests, deciduous forests, and agriculture, which together represent the natural production systems in the State. The lakes and rivers, soils, and ground water of the State are subdivided into the region in which they are found. In addition, special systems are assigned within their appropriate regions, such as "Bogs and Fens", which reside within the coniferous forest region (Fig. 1). Timber is distributed between the coniferous and deciduous forests regions, which would be reflected in the harvest of softwood and hard wood logs in the State. The agricultural region is further subdivided into cash crops and food crops with a storage of soil assigned to each area. In addition, livestock production is designated as a separate system. Reserves of nonrenewable environmental resources are important to Minnesota. They include iron, sand, gravel limestone, dolomite, peat, and a recently discovered large copper and nickel ore body that includes some platinum. Renewable resources are abundant and also of primary importance to the economy of the State. Renewable resources include soil, surface and ground water, timber and agricultural production. When a renewable resource is used faster than it is replaced by natural processes, it makes a nonrenewable emergy contribution to the State. The mining of nonrenewable resources supports a large industry to process, upgrade and ship these raw materials, especially iron to the steel mills outside the State. Electric power generation is carried out mostly using fuel and mineral resources shipped into the State. Agriculture is one of the most important sectors of Minnesota's economy and, as a result food processing has become a leading industry there. Minnesota food processing companies accounted for 20% of all shipments in 2001 and did over 30 billion dollars worth of business in 2003 *(11)*. In addition to food operations, Minnesota is a leader in manufacturing with prominence nationally and/or internationally in ethanol and biodiesel, plant polymers and fibers, paper and packaging, computer and electronic equipment, industrial equipment, medical and dental devices, and printing and publishing.

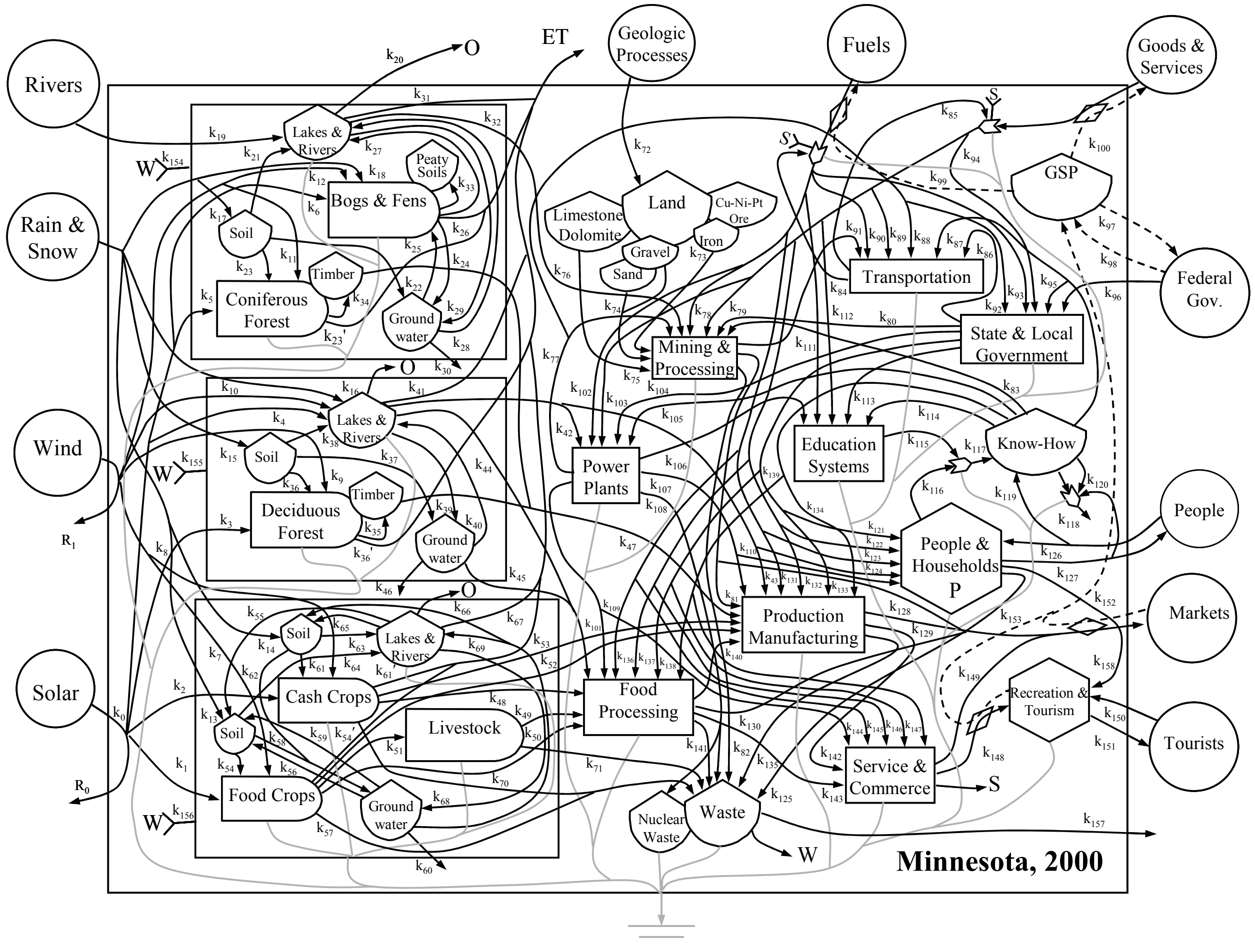

Figure 1. **A detailed energy systems model of Minnesota is shown (see Appendix A for symbol definitions and Tables 2 and 3 for the definition of sources, components and pathways). The large capital letters imply connections between sectors without using connecting lines.**

Table 2. Definition of pathway flows for the systems model of Minnesota's environment and economy shown in Figure 1.

Pathway	Definition of Flow
R_0	Albedo
R_1	Wind passing through the State
k_0	Solar radiation absorbed by the State
k_1	Solar radiation absorbed by food crops
k_2	Solar radiation absorbed by cash crops
k_3	Solar radiation absorbed by deciduous forests
k_4	Solar radiation absorbed by lakes and streams
k_5	Solar radiation absorbed by coniferous forests
k_6	Solar radiation absorbed by bogs and fens
k_7	Wind energy absorbed by food crops
k_8	Wind energy absorbed by cash crops
k_9	Wind energy absorbed by deciduous forests
k_{10}	Wind energy absorbed by lakes and streams
k_{11}	Wind energy absorbed by coniferous forests
k_{12}	Wind energy absorbed by bogs and fens
k_{13}	Rain and snow absorbed by food crops
k_{14}	Rain and snow absorbed by cash crops
k_{15}	Rain and snow absorbed by deciduous forests
k_{16}	Rain and snow absorbed by lakes and streams
k_{17}	Rain and snow absorbed by coniferous forests
k_{18}	Rain and snow absorbed by bogs and fens
k_{19}	River water flowing into the State
k_{20}	River water flowing out of the State
k_{21}	Runoff to lakes and rivers from the coniferous forest
k_{22}	Infiltration to ground water in the coniferous forest
k_{23}	Nutrient and water uptake by the coniferous forest
k_{23}'	Evapotranspiration by coniferous forest
k_{25}	Ground water supplied to bogs and fens
k_{26}	Evapotranspiration by vegetation in bogs and fens
k_{27}	Runoff to lakes and rivers from bogs and fens
k_{28}	Base flow to lakes and streams in the coniferous forest
k_{29}	Infiltration to ground water from lakes and rivers
k_{30}	Ground water outflow to regions outside the coniferous forest
k_{31}	Evaporation from lakes and rivers in the coniferous forest
k_{32}	Water use by the mining industry
k_{33}	Net production of peat
k_{34}	Net production of coniferous forest biomass
k_{35}	Net production of deciduous forest biomass
k_{36}	Nutrient and water uptake by deciduous forest
k_{36}'	Evapotranspiration by deciduous forest
k_{38}	Runoff to lakes and rivers from the deciduous forest
k_{39}	Infiltration to ground water from lakes and rivers

Table 2 continued

Pathway	**Definition of Flow**
k_{40}	Base flow from ground water to lakes and streams
k_{41}	Evaporation from lakes and rivers in the deciduous forest
k_{42}	Water use by power plants
k_{43}	Water use by production manufacturing
k_{44}	Surface water use in food processing
k_{45}	Ground water use in food processing
k_{46}	Ground water outflow to regions outside the deciduous forest
k_{47}	Soft and hard wood timber harvested for manufacturing
k_{48}	Cash crops processed
k_{49}	Livestock processed
k_{50}	Waste produced by livestock
k_{51}	Food crops used as livestock feed
k_{52}	Food crops used in production manufacturing
k_{53}	Cash crops used in production manufacturing
k_{54}	Water and nutrients taken up by food crops
k_{54}	Evapotranspiration by food crops
k_{56}	Ground water used for irrigation of food crops
k_{57}	Waste produced by food crops
k_{58}	Infiltration from food crop soil to ground water
k_{59}	Ground water resupply of soil water
k_{60}	Movement of ground water out of the cash and food crop regions
k_{61}	Water and nutrients taken up by cash crops
k_{61}	Evapotranspiration by cash crops
k_{63}	Runoff to lakes and rivers from cash crop soil
k_{64}	Runoff to lakes and rivers from food crop soil
k_{65}	Surface water used for irrigation of cash crops
k_{66}	Ground water used for irrigation of cash crops
k_{67}	Evaporation from lakes and rivers
k_{68}	Infiltration from lakes and rivers to ground water
k_{69}	Base flow of ground water to lakes and rivers
k_{70}	Waste produced by cash crops
k_{71}	Waste produced by livestock
k_{72}	Geologic processes building landform and mineral deposits
k_{73}	Iron ore mined and processed
k_{74}	Sand and gravel mined and processed
k_{75}	Dolomite and limestone mined and processed
k_{76}	Water used by the mining industry
k_{77}	Electricity used by the mining industry
k_{78}	Fuels used by the mining industry
k_{79}	Goods and services used by the mining industry
k_{80}	Government control of mining
k_{81}	Mining industry inputs to production and manufacturing
k_{82}	Waste produced by mining and processing ores

Table 2 continued

Pathway	Definition of Flow
k_{83}	Human knowledge and labor used in the mining sector
k_{84}	Transport of fuels into the State
k_{85}	Transport of goods and services into the State
k_{86}	Government regulation of transportation
k_{87}	Human knowledge and labor used in the transportation sector
k_{88}	Electricity used by the transportation sector
k_{89}	Goods and services input to the transportation sector
k_{90}	Fuels input to the transportation sector
k_{91}	Mining inputs to the transportation sector
k_{92}	Electricity use by the government sector
k_{93}	Fuels input to the government sector
k_{94}	Goods and services input to the government sector
k_{95}	Human knowledge and labor used in the government sector
k_{96}	Federal government regulations
k_{97}	Federal taxes
k_{98}	Federal outlays
k_{99}	Money spent on fuels
k_{100}	Money spent on goods and services
k_{101}	Electricity use by the food processing sector
k_{102}	Fuels input to the power plants
k_{103}	Goods and services input to power plants
k_{104}	Government regulation of power plants
k_{105}	Human knowledge and labor used by power plants
k_{106}	Electricity use by education systems
k_{107}	Electricity use by production and manufacturing
k_{108}	Waste produced by power plants (conventional and nuclear)
k_{109}	Electricity use by service and commerce
k_{110}	Electricity use by households
k_{111}	Fuels input to education systems
k_{112}	Goods and services input to education systems
k_{113}	Government regulation of education
k_{114}	Human knowledge and labor used in the schools
k_{115}	Teaching
k_{116}	Learning
k_{117}	Increase in human knowledge and skills
k_{118}	Loss of information (knowledge and skills)
k_{119}	Gain of knowledge and skills with immigrants
k_{120}	Loss of knowledge and skills with emigrants
k_{121}	Government regulation of people
k_{122}	Goods and services used by people and households
k_{123}	Fuels used by people and households
k_{124}	Water used by people and households
k_{125}	Waste produced by people and households
k_{126}	Immigration

Table 2 continued

Pathway	Definition of Flow
k_{127}	Emigration
k_{128}	Raw and processed ores exported
k_{129}	Manufactured products exported
k_{130}	Raw and processed food exported
k_{131}	Fuels used by production and manufacturing
k_{132}	Goods and services used by production and manufacturing
k_{133}	Government regulation of industry
k_{134}	Human knowledge and labor used in manufacturing
k_{135}	Waste produced by industry
k_{136}	Fuels used by food processing
k_{137}	Goods and services used by food processing
k_{138}	Government regulation of food processing industry
k_{139}	Human knowledge and labor used in food processing
k_{140}	Food processing inputs to manufacturing
k_{141}	Waste produced by food processing
k_{142}	Production and manufacturing inputs to service and commerce
k_{143}	Food processing inputs to service and commerce
k_{144}	Fuels used by service and commerce
k_{145}	Goods and services used by service and commerce
k_{146}	Government regulation of service and commerce
k_{147}	Human knowledge and labor used in service and commerce
k_{148}	Service and commerce used by tourists
k_{149}	Exports from the service and commerce sector
k_{150}	Tourists entering the State
k_{151}	Tourists leaving the State
k_{152}	Money gained from the sale of products and services
k_{153}	Money spent by tourists
k_{154}	Effects of wastes on coniferous
k_{155}	Effects of wastes on deciduous forests
k_{156}	Effects of wastes on agricultural lands
k_{157}	Wastes leaving the State
k_{158}	Minnesotans using recreation and cultural resources

Table 3 Definitions of the components for the systems model of Minnesota's environment and economy shown in Figure 1.

Component	Definition
Coniferous Forest	Land covered by coniferous forest.
Deciduous Forest	Land covered by deciduous forests.
Bogs and Fens	Peat forming wetland in the Coniferous Forest region.
Agriculture	Land devoted to food crops, cash crops, or livestock
Ground Water	The quantity of water held in aquifers in the State. Divided into ground water in the coniferous, deciduous and agricultural regions.
Lakes and Rivers	All surface water in the State including lakes, rivers, and Lake Superior divided into surface waters in coniferous, deciduous, and agricultural areas.
Soil	The storage of topsoil divided into soil underlying the coniferous and deciduous forests and cash crop and food crop agricultural lands.
Peaty Soils	Peat stored in the bogs and fens.
Timber	Tree biomass associated with the coniferous and deciduous forest lands.
Cash Crops	Sugar beets, wheat, rapeseed, *etc*. generally grown in the Red River Valley Region.
Food Crops	Corn, Soybeans, *etc*. usually grown in the southwest and central regions of the State.
Livestock	Cattle, hogs, turkeys, *etc*.
Land	Bedrock and surface materials.
Sand and Gravel	The reserves of sand and gravel within the State.
Limestone/Dolomite	The reserves of limestone and dolomite.
Iron	Reserves of iron ore in Minnesota.
Cu-Ni-Pt	Reserves of copper, nickel, and platinum.
Mining & Processing	All mining industries in the State including iron ore, taconite processing, copper, nickel, platinum, sand, gravel, peat, limestone, and dolomite.
Production and Manufacturing	All manufacturing of durable and non-durable goods including chemicals, pharmaceuticals, plastics, fabricated and primary metals, and glass, stone and clay products, Including the industrial use of farm products such as corn processed to ethanol.
Food Processing	Canning, freezing, meat packing and other processing of food crops, cash crops, and livestock.
Transportation,	All elements of transportation, including movement by truck, train, and river.
Power Plants	All fossil fuel, nuclear, and hydroelectric power plants.
Government	State and local government.

Table 3. continued

Component	**Definition**
Service and Commerce, S	Wholesale and retail trade, hotels, restaurants, banking, real estate, insurance and construction companies, repair shops; the transportation industry, communication and utilities; health, legal, social, personal, and repair services; waste treatment, hospitals, schools and other government services. The "S" leaving Service and Commerce connects to all the other sectors.
People and Households, P	The population of Minnesota and their assets (households).
Education Systems	Primary schools, secondary schools, colleges and universities.
Know-how	The knowledge and skill base of the people.
Recreation and Tourism	All cultural and recreational activities in the State, including sports, festivals, canoeing, boating, hiking, camping, and historical sites.
Waste, W	All solid, liquid, and gaseous waste created by people, industry, and agriculture and stored in the State.
GSP	Gross State Product

The mix of four nonrenewable energy sources used to generate electricity is primarily made up of coal, uranium, and natural gas. The use of wind power is increasing in the State and some electric power is also generated from water, oil, and wood. Waste is a by-product of all human activity and it most significantly affects the aquatic ecosystems of the State as drainage from agricultural lands, animal waste, human sewage, and industrial effluents. The service and commerce sector supports recreation and tourism, which generates a significant part of the gross state product, GSP. People and households in combination with their knowledge and skills (termed Know-how in the model) supply the labor that carries out and controls all the human activities in the State. The state population has been increasing linearly since 1850, but the rate of growth has shown signs of slowing during the past few years (1990-2006). The transportation sector is critical for the movement of goods and services into, out of, and within Minnesota. It connects Minnesota to the rest of the world through an international port at Duluth and through barge traffic down the Mississippi from the Twin Cities to New Orleans, LA. Good road and rail systems complete the linkages for the transport of goods and services within Minnesota and with Canada to the north and the contiguous states of Iowa to the south, North and South Dakota to the west and Wisconsin to the east.

3.5 The Emergy Income Statement for Minnesota

The emergy income statement summarizes the major annual flows of emergy for the State. It consists of four accounts, renewable resources (Table 4), nonrenewable resources (Table 5), imports (Table 6), and exports (Table 7). Each account or table in the emergy income statement has six columns as defined in Table 1. The numbers in column one (labeled Note) refer to the listing of calculations and assumptions in Appendix C that document the values given in column three (Data).

The annual renewable resources and production for Minnesota in 1997 are shown in Table 4. There is a corresponding table of renewable natural resources and products for 2000 in Appendix E, Table E1. The wind energy absorbed is the largest renewable emergy source received by the State. The chemical potential energy of rain received by the State is the second largest emergy source entering the State, followed by the geopotential energy of rain and snow (the energy of water by virtue of its elevation relative to sea level). The largest source of renewable production in Minnesota is crop production, followed by livestock production, and timber harvested. The emergy of renewable crops produced in the State in 1997 was 157% of the emergy of iron ore mined in that year. The production and use of nonrenewable resources in Minnesota was evaluated for 1997 in Table 5 with a corresponding evaluation for 2000 in Appendix E, Table E2. Iron ore mined was the largest emergy from nonrenewable resources produced in the State followed by sand and gravel and then dolomite. Petroleum is the second largest nonrenewable emergy used in the State and it supplies 57% of the emergy of fossil fuels used, followed by coal (23%), and natural gas (20%).

In this study we took a small step toward a broader documentation of environmental liabilities by quantifying the emergy of some atmospheric pollutants deposited upon the ecosystems of the State. Nitrogen and the chloride ion were small compared to the renewable emergy of the State, 2.7 and 0.6%, respectively. However, the emergy of sulfur deposited was 43.7% of the renewable emergy base of the State, indicating that a substantial environmental liability is associated with this flow. We determined the transformity for sulfur using several methods and the calculations are given in Appendix B.

Minnesota's imports and exports for 1997 are shown in Tables 6 and 7. There are tables with the 2000 numbers in Appendix E, Tables E3 and E4. The largest emergy imported to Minnesota in 1997 was in the materials in goods entering the State. The second largest emergy inflow was in the services associated with those goods, followed by the emergy in petroleum. Federal government outlays may be spent outside the State to bring emergy into the State; however, these emergy inflows would be counted in our estimates of imported goods and services. In addition, Federal outlays will generate emergy flows in the State economy when they are spent there. Total outlays must be decreased by the amount of taxes paid to get the net effect of government expenditures on the State. If all Federal outlays are used to buy goods and services outside the State, the emergy purchased would be slightly more than the emergy imported in petroleum. However; if they are spent entirely in Minnesota, the emergy flow generated would be 1.88 times larger than the emergy imported in petroleum.

The value and pattern of imports by category in 2000 was similar to that observed in 1997. Differences between the two years are seen in a 33% decline in the amount of electricity imported accompanied by an 8.6% increase in coal emergy imported. Twenty-two percent of the decline in electricity imports was made up by a 35% increase in electricity from renewable sources. Natural gas imports increased by 2.3% and petroleum decreased by 3.3% in 2000 compared to 1997. Other notable changes are that tourist expenditures in the State increased by 25% and Federal government outlays by 13% during this time.

The dollars that tourists bring into the State are not accompanied by emergy *per se*; however, they generate flows of emergy in proportion to the State's emergy to dollar ratio when they are used to purchase products and services within the state economy. We hypothesize that the natural, historical, and aesthetic assets of the State deliver an experience to tourists that can be measured roughly by the emergy purchased through the dollars spent on tourism. This approximation gives a conservative value and the method is similar to the travel cost method used in economics. A more complete estimate might be obtained from a detailed analysis of the emergy required to support the assets that allow tourists to receive particular experiences. However, this work would require an evaluation of all aspects of tourism in the State, which is beyond the scope of this study. If all 1997 tourist dollars are spent at the Minnesota emergy to money ratio, they comprise 182% of the emergy that those dollars could purchase when spent at an average location in the United States.

Taconite pellets account for the largest amount (17%) of emergy exported from the State in a single product. Manufactured value-added products and the services required to produce them account for 82% of Minnesota exports. The overall pattern of emergy exports was similar in 1997 and 2000, primarily because we relied on the 1997 Commodity Flow Survey *(2)* for both estimates. However, there was a 25% increase in the emergy of the experiences tourists carried home with them as measured by the expenditure approximation and a 9.6% increase in Federal taxes between the two years.

3.6 The Emergy Balance Sheet for Minnesota

The emergy balance sheet, when fully developed, will provide the information needed to determine whether a human activity, institution, or system is sustainable (Campbell 2005). The balance sheets given in Table 8 and Appendix E, Table E5 summarize the important environmental assets of the State and they give a rough estimate of the skill and knowledge base of Minnesota's people. The balance sheet has the same six columns described for the income statement. The difference between the income tables and the balance sheet table is in the units of the items recorded. The balance sheet contains stored quantities of mass (g), energy (J), or emergy (sej), *etc*., whereas, the income statement contains annual flows of matter (g/y), energy (J/y), emergy (sej/y) and dollars ($/y).

Separate estimates for natural capital were not performed for 1997 and 2000 since these assets change relatively slowly. The social capital in the stored knowledge of people was determined in 1997 based on population estimates and using the methods in Odum (1996). A similar calculation was made for 2000 using census data. Many of the major storages of natural capital were estimated, but socioeconomic capital was not quantified in this study. Storages of natural, social, and economic capital that need to be evaluated to complete the balance sheet for this state are as follows: (1) the emergy in additional stores of natural capital including biodiversity, (2) the assets of society and culture, and (3) the economic infrastructure. In addition, the debts incurred through the loss of natural lands to urban and agricultural uses and the resulting diminishment of natural processes over the landscape need to be quantified and placed on the balance sheet, respectively, as environmental liabilities and as interest on the existing environmental debt. Campbell (2005) presented a theoretical basis for the definition and measurement of environmental liabilities and the use of emergy-monetary balance sheets to determine the true solvency of human endeavors and institutions. Currently, we are focused on developing the methods to document environmental liabilities through the completion of several example balance sheets.

The cumulative extent of the State of Minnesota's environmental liabilities is unknown; nevertheless, a partial balance sheet that includes its major natural capital assets (Table 8) contains useful information that documents the stored wealth available to the system. In Minnesota, the emergy of natural capital stored in accessible iron reserves is the largest actively used storage of natural wealth followed closely by sand and gravel aggregate. The large reserves of copper and nickel ore in Table 8 are in one ore body, which is not actively exploited at present. This ore body is not as well-known as the iron reserves, but permits to mine these resources have been submitted. The iron and gravel reserves are almost 7 times larger than soil, which is the third largest actively used storage of natural capital. The estimate of the amount of sand and gravel in the State was based on our extrapolation of Minnesota Department of Natural Resources estimates of the reserves for the 7 county region around Minneapolis and St. Paul and other assessed areas in the State. Complete coverage for the entire state was not available; therefore, it is more uncertain than the iron reserve estimate. The emergy in recently discovered reserves of copper and nickel ore may be, respectively, 11.1 and 2.3 times greater than the remaining iron reserves, but these numbers are highly uncertain. The rough estimates for the quantity of ore for both nickel and copper are the same, but copper is the richer deposit based on assessments available to us. Also, a small reserve of platinum, associated with the copper and nickel ore, is estimated to be about 0.2% of the mass and 6.7% of the emergy of the remaining iron ore.

The social capital stored in the education of Minnesota's people is the tenth largest storage of capital on the balance sheet. The emergy of the knowledge and skills of people is slightly less that that stored in peat and dolomite. This measure of social capital is about 2% of the emergy in iron ore reserves, but it is almost 700% of the storage of emergy in forest biomass. The population of Minnesota has continued to grow in a linear manner since about 1850, continuously adding to the knowledge and skills residing within the State.

Table 4 Annual Renewable Resources and Production for Minnesota in 1997.

Note*	Item	Data J, g, $, ind/yr	Units	Emergy/ Unit sej/unit	Emergy E+20 sej	1997 Emdollars E+6 Em$
Renewable Resources Within Minnesota						
1	Sun, Incident	1.07E+21	J	1	10.7	419.4
1	Sun, Absorbed	8.84E+20	J	1.21	10.7	419.4
2	Wind Kinetic Energy	1.26E+19	J	1467	185.5	7244.9
3	Earth Cycle Energy	2.80E+17	J	33700	94.3	3683.2
4	Rain, Chemical Potential Energy Received	7.07E+17	J	18100	127.9	4998.0
5	Evapotranspiration, Chemical Potential Absorbed	3.14E+17	J	28100	88.3	3449.3
6	Rain, Geo-Potential On Land	4.58E+17	J	10100	46.2	1805.7
6	Snow, Geopotential On Land	7.22E+16	J	101100	73	2852.4
7	Rain, Geo-Potential Of Runoff	2.55E+16	J	27200	6.9	270.7
7	Snow, Geo-Potential Of Runoff	4.67E+16	J	101100	47.2	1842.8
8	Wave Energy (Lake Superior)	1.55E+16	J	30000	4.7	181.9
9	Rivers Chemical Potential Received	9.15E+15	J	50100	4.6	179.1
9	Rivers Chemical Potential Absorbed	6.44E+12	J	50100	0.0	0.1
10	Rivers, Geo-Potential Energy Received	5.09E+15	J	27200	1.4	54.1
10	Rivers, Geo-Potential Energy Absorbed	1.51E+15	J	27200	0.4	16.0
11	NH4-N In Dry/Wet Deposition	1.55E+11	g	1.4E+09	2.2	84.1
11	NO3-N In Dry/Wet Deposition	4.44E+10	g	6.8E+09	3.0	118.6
11	Total N In Dry/Wet Deposition	2.00E+11	g	variable	5.2	202.7
12	S In Dry/Wet Deposition	5.26E+10	g	1.58E+11	83.2	3249.2
13	Cl In Dry/Wet Deposition	8.81E+09	g	1.31E+10	1.2	45.1
Renewable Production Within Minnesota						
14	Agricultural Products	7.00E+17	J	variable	2632.5	102833.7
15	Livestock	3.49E+16	J	variable	584.31	22824.5
16	Fish Production	1.32E+11	J	1961800	0.003	0.1
17	Hydroelectricity And Other Renewable	7.95E+15	J	1.20E+05	9.56	548.2
18	Net Timber Growth	1.28E+17	J	20600	26.43	1032.3
19	Timber Harvest	6.47E+16	J	68700	44.47	1737.2
20	Groundwater, Chemical Potential	4.61E+15	J	159100	7.33	286.4
21	Solid Waste, Recycled Or Recovered	4.55E+12	g	6.28E+09	286.10	140263.4

Table 5. Annual Production and Use of Nonrenewable Resources in 1997.

Note*	Item	Data J, g, $, ind/yr	Units	Emergy/ Unit sej/unit	Emergy E+20 sej	1997 Emdollars E+6 Em$
Fuels and Renewable Resources Used In A Nonrenewable Manner						
22	Coal Used In The State	5.09E+17	J	37800	192.5	16041.7
23	Natural Gas Used In The State	3.89E+17	J	43500	169.4	14115.8
24	Petroleum Used In The State	7.45E+17	J	64800	482.7	40228.6
25	Electricity Production	1.48E+17	J	170400	251.5	20958.3
26	Electricity Used In The State	2.00E+17	J	170400	341.3	28437.9
27	Nuclear Electricity	3.89E+16	J	170400	66.4	5530.8
28	Iron Ore Mined	4.79E+13	g	3.51E+09	1681.1	140094.6
29	Sand And Gravel	3.45E+13	g	1.31E+09	452.0	37662.5
30	Limestone	7.35E+12	g	9.81E+08	72.1	6008.0
31	Dolomite	3.08E+12	g	1.08E+10	332.1	27671.5
32	Peat	2.90E+10	g	3.53E+08	0.102	8.5
33	Soil Erosion	9.79E+16	J	72600	71.1	5921.1

* The notes for Table 5 can be found in Appendix C, Section C.2.

Table 6. Annual Imports to the Minnesota Economy in 1997.

Note*	Item	Data J, g, $, ind/yr	Units	Emergy/ Unit sej/unit	Emergy E+20 sej	1997 Emdollars E+6 Em$
34	Tourism (Money Imported)	7.20E+09	$	2.56E+12	184.3	7200.0
35	Electricity	4.48E+16	J	1.70E+05	76.3	2979.5
36	Uranium	2.94E+09	g	4.66E+11	13.7	535.5
37	Coal	5.09E+17	J	3.78E+04	192.5	7519.5
38	Petroleum	7.45E+17	J	6.48E+04	482.7	18857.2
39	Natural Gas	3.89E+17	J	4.35E+04	169.4	6616.8
40	Minerals	1.06E+13	g	Variable	106.0	4142.5
41	Goods (Materials)	3.92E+13	g	Variable	2747.9	107338.1
42	Goods (Services)	6.63E+10	$	2.56E+12	1698.0	66326.8
43	Fuels (Services)	5.51E+09	$	2.56E+12	141.0	5509.2
44	Minerals including Uranium (Services)	1.27E+08	$	2.56E+12	3.3	127.0
45	Electricity (Services)	6.22E+08	$	2.56E+12	15.9	621.7
46	Services	4.22E+09	$	2.56E+12	108.1	4221.5
47	Immigration	8.23E+03	ind.	variable	11.3	441.0
48	Federal Government Outlays (If Spent In US)	1.98E+10	$	2.56E+12	506.6	19789.3

* The notes for Table 6 can be found in Appendix C, Section C.3.

Table 7. **Annual Exports from the Minnesota Economy in 1997.**

Note*	Item	Data J, g, $, ind/yr	Units	Emergy/ Unit sej/unit	Emergy E+20 sej	1997 Emdollars E+6 Em$
49	Material Goods w/o Iron Ore and Fuels	7.37E+13	g	Variable	3854.9	150581.3
50	Iron Ore as Taconite	3.57E+13	g	3.61E+0	1290.4	50404.9
51	Services in Goods	9.46E+10	$	2.56E+1	2421.7	94597.0
52	Services	1.36E+09	$	2.56E+1	34.7	1356.7
53	Federal Government (Taxes)	2.60E+10	$	2.56E+1	665.7	26002.8
54	Tourists (Experiences Taken Home)	7.20E+09	$	4.66E+1	335.4	13100.2

* The notes for Table 7 can be found in Appendix C, Section C.4.

Table 8 Assets of Minnesota in 1997.

Note*	Item	Data J, g, $, ind/yr	Units	Emergy/ Unit sej/unit	Emergy E+20 sej	1997 Emdollars E+6 Em$
55	Forest Biomass Storage	6.26E+18	J	28200	1765.1	68949.7
56	Water (Lakes)	6.76E+17	J	18100	122.3	4778.9
57	Water (Lake Superior, MN share)	3.30E+17	J	240300	791.8	30928.5
58	Soils	9.42E+19	J	72600	68375.0	2670897.9
59	Iron	1.40E+16	g	3.51E+09	490324.4	19153297.6
60	Sand & Gravel	3.19E+16	g	1.31E+09	417826.0	16321326.7
61	Limestone	2.82E+15	g	9.81E+08	27661.4	1080522.7
62	Dolomite	1.32E+14	g	1.08E+10	14231.1	555900.5
63	Copper	4.50E+15	g	1.14E+11	5115002.3	199804775.6
64	Nickel	4.50E+15	g	2.55E+10	1147664.2	44830631.0
65	Peat	7.57E+19	J	1.86E+04	14100.0	550780.8
66	Platinum	2.90E+13	g	1.13E+11	32728.4	1278454.3
67	People	4.74E+06	Ind.	Various	12265.8	479134.7
	Preschool	317301	Ind.	3.34E+16	105.8	4134.1
	School	2312528	Ind.	9.22E+16	2132.3	83294.0
	College Grad	1812350	Ind.	2.75E+17	4977.8	194446.2
	Post-College	246293	Ind.	1.28E+18	3165.1	123638.3
	Public Status	47358	Ind.	3.85E+18	1875.8	71321.0
	Legacy	765	Ind.	7.70E+18	58.9	2301.0

* The notes for Table 8 can be found in Appendix C, Section C.5.

Finally, relatively small amounts of emergy are stored in forest biomass and surface waters.

3.7 Overview Models and Flow Summary

Figure 2 shows an aggregated model of the environment and economy of Minnesota in 1997. It provides an overview of the emergy and dollar flows across state boundaries and gives the various natural and economic sources of the flows. The pathways on the diagram show the interaction of renewable and nonrenewable resources within the system and the exchanges of emergy and dollars that drive the State's economy. Table 9 identifies the flows of emergy and dollars shown on Figure 2. The table that summarizes the flows of emergy and dollars for 2000 is found in Appendix E, Table E6. The pathway symbols and values in Table 9 are used in Table 10 to calculate indices. The number indicated in column one directs the reader to a description of the calculations used to obtain the summary flows, which are found in Appendix C6.

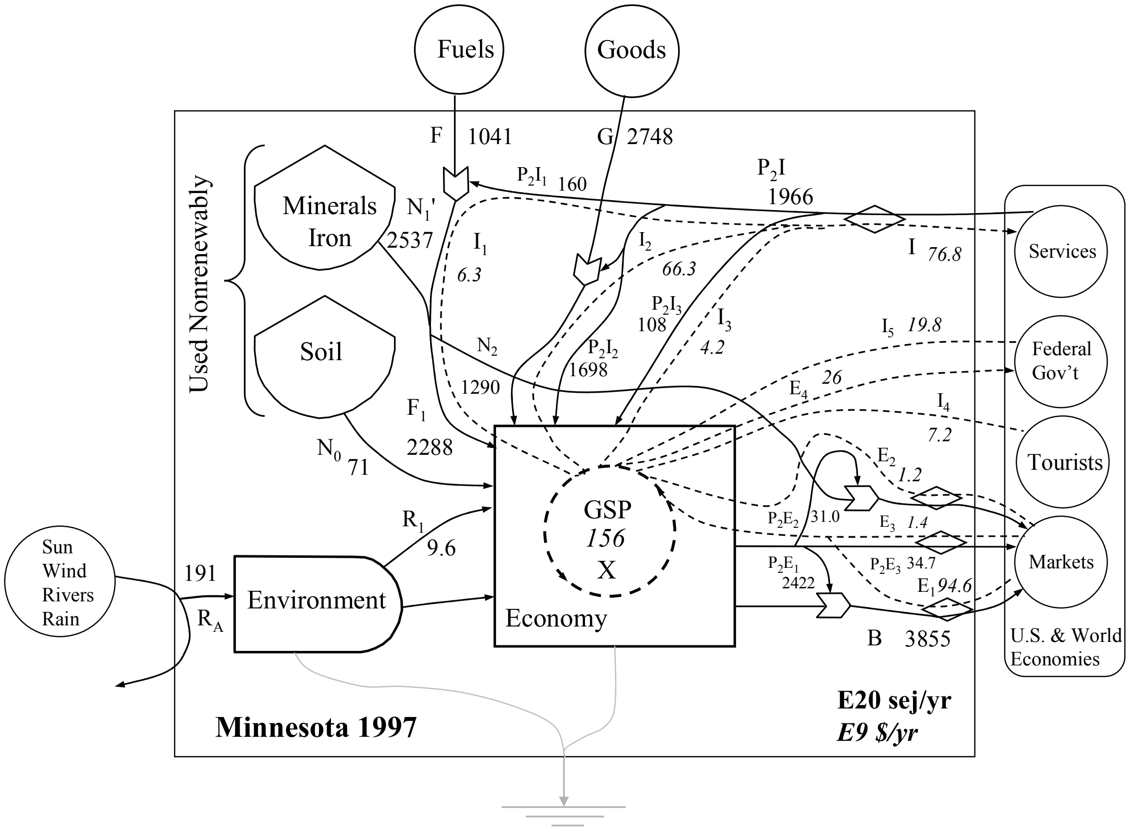

Figure 2: **Aggregated diagram of Minnesota's economy and emergy resource base used for the calculation of indices. Symbols are identified in Table 9. Emergy flows times E+20 sej/y; dollar flows times E+9 $/y.**

Table 9. Summary of Flows for Minnesota in 1997.

Note	Letter in Fig. 2	Item	Emergy E+20 sej	Dollars E+9 $/y	1997 Emdollars E+9 Em$/y
68	R_A	Renewable Sources Used	191		7.4
69	R_1	Renewable Electricity	9.6		0.4
70	N	Nonrenewable Source Flows	2608		104.9
71	N_1	Extracted Fuels and Minerals	2537		
72	N_0	Dispersed Rural Source	71		2.8
73	N_1	Conc. Use (Fuels, Minerals, Elec.)	1323		51.7
74	N_2	Exported without Full Use	1290		50.4
75	F	Imported Fuels (Fuels)	1041		40.7
76	F_1	Fuels, Minerals Used $(F+F_2)$	2288		89.4
77	F_2	In State Minerals Used $(N_1' - N_2)$	1247		48.7
78	G	Imported Goods (Materials)	2748		107.3
79	I	Dollars Paid for All Imports		76.8	
80	I_1	Dollars Paid for Service In Fuels		6.3	
81	I_2	Dollars Paid for Service In Goods		66.3	
82	I_3	Dollars Paid for Services		4.2	
83	I_4	Dollars Spent by Tourists		7.2	
84	I_5	Federal Transfer Payments		19.8	
85	P_2I	Imported Services, Total	1966		76.8
86	P_2I_1	Imported Services in Fuels	160		6.3
87	P_2I_2	Imported Services in Goods	1698		66.3
88	P_2I_3	Imported Services	108		4.2
89	P_1I_4	Emergy Purchased by Tourists	335		13.1
90	P_1I_5	Net Emergy Purchased by Fed. $	-289		-11.3
91	B	Exported Products w/o Taconite	3855		150.6
92	E	Dollars Paid for All Exports		97.1	
93	E_1	Dollars Paid for Goods		94.6	
94	E_2	Dollars Paid for Mineral Exports		1.2	
95	E_3	Dollars Paid for Services		1.4	
96	E_4	Federal Taxes Paid		26.0	
97	P_2E	Total Exported Services	2487		97.1
98	P_2E_1	Exported Services, Goods	2422		94.6
99	P_2E_2	Exported Services in Iron	31		1.2
100	P_2E_3	Exported Services	35		1.4
101	X	Gross State Product		155.9	
102	P_2	U.S. Emergy/ $ Ratio 1997 sej/$	2.56E+12		
103	P_1	MN Emergy/ $ Ratio 1997 sej/$	4.66E+12		

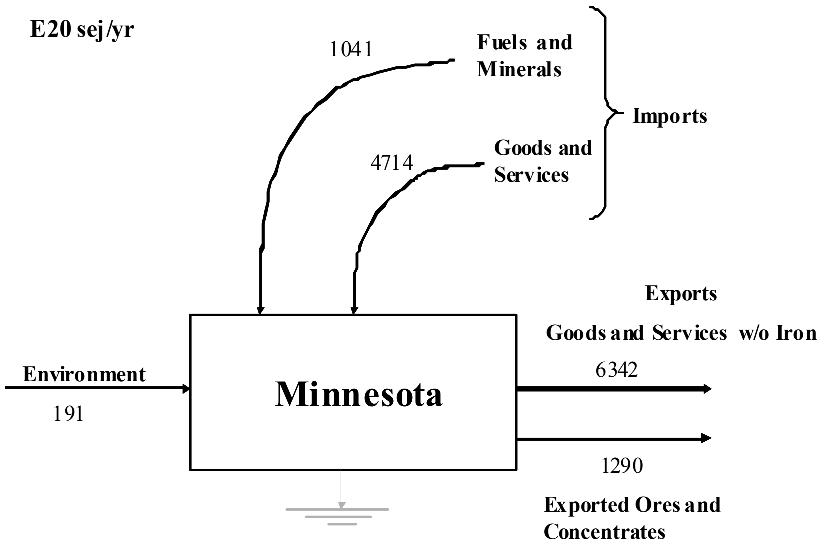

Figure 3. Summary of Minnesota's environmental and economic emergy flows.

The state system was further simplified using a "three-armed diagram" (Fig. 3). This diagram gives an overview of the renewable and nonrenewable emergy entering and leaving the State. Purchased imports and exports are shown with a single, simple visual image. Several key facts can be easily determined from this diagram: (1) in 1997, exported emergy was 1.33 times greater than the emergy imported (7632/5755); (2) the ratio of purchased to renewable environmental emergy was 30:1 (5755/191); (3) seventeen percent (1290/7632) of the emergy in exports was derived from the export of taconite pellets; (4) when the emergy of taconite pellets is removed from Minnesota exports, the emergy exported exceeds imported emergy by 10.2%.

3.8 Emergy Indices

Table 10 presents several emergy indices that help us gain a better understanding of the State of Minnesota in 1997. Similar indices for 2000 are shown in Appendix E, Table E7. The values of some important indices and their meaning follow: (1) Twenty-one percent of the emergy used in the State in 1997 was derived from home sources, which indicates a low potential for self-sufficiency compared to other states (see the comparison of states in Campbell *et al.* 2005a); (2) The emergy use per person was 1.53E+17 sej/ind., which shows that Minnesotans have a high overall standard of living (see Table 12 and Campbell *et al.* 2005a); (3) The import/export emergy ratio shows 1.33 times as much emergy leaving the State in exports as is received in imports, which indicates an imbalance in the exchange of real wealth with the Nation. (4) The emergy used per square meter (3.23E+12 sej/m^2) indicates that an average location in the State is developed relative to an average place in the Nation (Table 12); (5) The emergy to dollar ratio was 4.66 E+12 sej/$, thus the purchasing power of a dollar in Minnesota in 1997 was 1.82 times that of an average place in the United States. This ratio had fallen to 1.69 times the national purchasing power of a dollar by 2000; (6) The investment ratio was 3.81, which indicates a relatively low intensity of matching (Odum 1996) between purchased economic emergy invested from outside the State and the emergy of renewable and nonrenewable environmental resources within the State. This index suggests that Minnesota is still an attractive place for further economic investment; (7) The environmental loading ratio was 37.1:1, indicating a more intense matching of purchased inputs with renewable energy from the environment than found for West Virginia (20.4:1) or the Nation as a whole (19.6:1). Higher environmental loading ratios potentially result in higher stress on local ecosystems and a heavier "load" on the waste processing capacity of the environment.

3.9 The Emergy Signature for the State

The emergy signature for Minnesota in 1997 is shown in Fig. 4, which charts the significant emergy flows within the State as well as the major imports and exports. The large quantities of iron ore mined in Minnesota, and the taconite pellets exported indicate the strength of the connection between Minnesota's economy and the larger regional economies of the East coast, the Mid-West, and the world. The large emergy flows of materials in both exported and imported goods and services also show Minnesota's role in the larger system of the Nation and the strength of the State's economy in agriculture and manufacturing. The second largest pair of flows is also associated with import and export. These bars present on the right of the graph represent the services required for the production and transport of imported and exported goods. A second tier of smaller though still important flows includes energy and mineral, use, import, and export. Social emergy flows of comparable magnitude to petroleum use are generated by Federal outlays and expenditures for tourism. The emergy of Federal government outlays is fairly large, but once taxes are removed there is a net outflow of emergy from the State. Petroleum is the largest component in the energy consumption signature of the State, but overall the energy use pattern is fairly well-balanced with substantial inputs from natural gas, coal, and nuclear electricity balancing petroleum use. The generation of electricity from renewable sources was small in 1997, but has grown since then.

3.10 Analysis of Minnesota and Comparison with other States

The construction of emergy indices from the accounting data on storages and flows led to insights on the development and use of the State's natural resources. A comparison of these results with emergy analyses of other states and of the Nation will help put the Minnesota numbers in perspective. In this study, we compared Minnesota indices to West Virginia indices and selected national indices; all calculated using similar methods for documenting imports and exports. Many emergy analyses of states have been done in the past (Campbell *et al.* 2005a) and while the analysis method has not varied the accuracy with which imports have been determined has varied. Therefore, the results of many older analyses are only roughly comparable to those reported here. Comparisons can be made, but the investigator should be aware that the estimates of imported goods and services in older studies may be somewhat lower than the values that would be expected using the revised method first presented in Campbell *et al.* (2005a). The values of indices that include imported goods and services in there formulations should be compared with this caveat in mind.

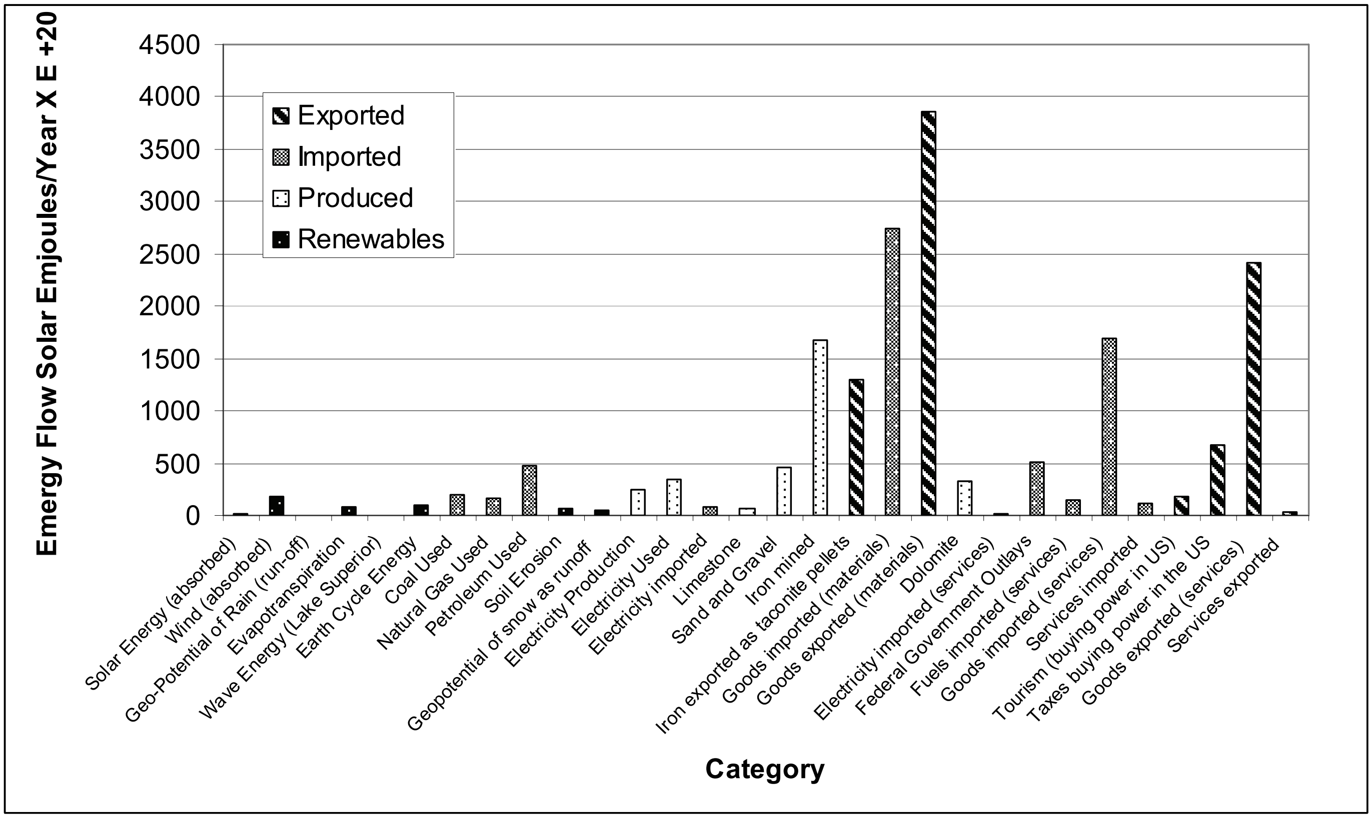

Figure 4. The emergy signature of the State of Minnesota in 1997 is shown. Items are arranged in order of increasing emergy per unit. Emergy flows shown to the right of dolomite are determined based on the emergy to dollar ratio (sej/\$) for the U.S. in 1997. Items from solar energy through electricity imported are arranged by transformity (sej/J) and those from limestone through dolomite are ordered according to their specific emergy (sej/g).

Table 10. Minnesota Emergy Indicators and Indices for 1997.

Item	Name of Index	Expression	Quantity	Units
104	Renewable Use	R_A	1.91E+22	sej y^{-1}
105	In State Non-Renewable Use	N_0+N_1	1.32E+23	sej y^{-1}
106	Imported Emergy	$F+G+P_2I$	5.75E+23	sej y^{-1}
107	Total Emergy Inflows	$R+F+G+P_2I$	5.95E+23	sej y^{-1}
108	Total Emergy Used	$U=(R_A+N_0+F_1+G+P_2I)$	7.26E+23	sej y^{-1}
109	Total Exported Emergy	$B+P_2E+N_2$	7.63E+23	sej y^{-1}
110	Emergy From Home Sources	$(N_0+F_2+R)/U$	0.21	
111	Imports-Exports	$(F+G+P_2I)-B+P_2E+N2)$	-1.88.E+23	sej y^{-1}
112	Ratio Of Export To Imports	$(B+P_1E+N_2)/ F+G+P_2I)$	1.33	
113	Fraction Used, Locally Renewable	R/U	0.026	
114	Fraction Of Use Purchased Outside	$(F+G+P_2I)/U$	0.792	
115	Fraction Used, Imported Service	P_2I/U	0.271	
116	Fraction Of Use That Is Free	$(R+N_0)/U$	0.036	
117	Ratio Of Purchased To Free	$(F_1+G+P_2I)/(R+N_0)$	26.77	

Table 10 continued. **Minnesota Emergy Indicators and Indices for 1997.**

Item	Name of Index	Expression	Quantity	Units
118	Environmental Loading Ratio	$(F_1+N_0+G+P_2I)/R$	37.12	
119	Investment Ratio	$(F+G+P_2I)/(R_A+N_0+F_2)$	3.81	
120	Use Per Unit Area	U/Area	3.23E+12	sej m^{-2}
121	Use Per Person	U/Population	1.53E+17	sej/ind.
122	Renewable Carrying Capacity	(R/U)*Population	124,235	people
123	Developed Carrying Capacity	8*(R/U)*Population	993,882	people
124	State Economic Product	GSP	1.6E+11	$/yr
125	MN Emergy Use To GSP	U/GSP	4.66E+12	sej/$
126	U.S. Emergy Use To GNP	U/GNP	2.56E+12	sej/$
127	Electricity Used/Emergy Use	El/U	0.047	
128	Electricity Produced/Emergy Use	Elp/U	0.035	
129	Emergy of Fuel Use per Person	Fuels/Population	1.78E+16	sej/ind.
130	Population		4.74E+06	people
131	Area		2.25E+11	m^2
132	Renewable Empower Density	R_A/Area	8.46E+10	sej m^{-2}

3.10.1 *Characteristics of Minnesota Based on Emergy Analysis*

The geopotential energy available in the State of Minnesota is governed by the fact that most of the State is covered by landforms that were deposited during the last glacial period (Tester 1995). The elevation of the land varies from the lowest point on the Lake Superior shore (183 m) to the highest point on Eagle Mountain (701 m). Minnesota is fairly unusual among the states that we have examined, because the largest emergy inflow to the State is in the wind energy absorbed, rather than the chemical potential energy of rainfall. The wind accounts for more than 97% of the largest emergy base for the State and waves on Lake Superior make up 2.44% with the remainder supplied by the chemical and geopotential energy of the St. Croix River that enters from Wisconsin and flows along the border.

Nonetheless, the renewable emergy supplied by water is the basis for many ecological processes in the State, *i.e.*, transpiration of forests and crops, and the emergy of these flows was also examined. The water budget of Minnesota is unique among the states that we have examined in that snow is a prominent feature of the annual geopotential energy flows. A new transformity for the geopotential energy of snow was determined in this study (Appendix B), and based on the global distribution of rain and snow fall, it was found to be about an order of magnitude greater than that of the geopotential energy of rain. In light of this fact, it is understandable that 32% of the renewable emergy of water used in the State is supplied by the geopotential energy of runoff generated by snow. Most of the remaining emergy of water (59%) is attributed to the chemical potential energy of rain transpired by vegetation. The geopotential of rain as runoff, waves on Lake Superior and the chemical and geopotential of the St. Croix River make up the remainder. The high transformity of the geopotential energy of snow relative to rain means that it should have special organizing powers not possessed by rainfall, *i.e.*, snow accumulates over many months and this stored geopotential energy is released in a pulse over a relatively short period of time during snowmelt in the spring. This highly concentrated delivery of geological work that is a property of the snow pack is consistent with the higher transformity of snow calculated on the basis of its global annual production.

Minnesota is richly endowed with mineral resources (principally iron, but see Table 8). The emergy density of actively exploited underground fuel and mineral resources in Minnesota is 4.28E+14 sej m^{-2}. This is about half of the emergy density of underground mineral reserves in West Virginia. However, if the vast reserves of copper and nickel predicted to be available in Minnesota are proven, the emergy density of minerals beneath Minnesota would be 3.6 times that of the coal beneath West Virginia. From this analysis we might predict that iron mining, beneficiation, and transport will dominate the emergy flows, and ostensibly the economic activities and environmental impacts in the northeastern region of the State; however a complete regional analysis needs to be performed to confirm this prediction. The emergy of iron produced in Minnesota in 1997 was equal to 23% of the total emergy used in the State. Most (75% or more) of the iron mined in Minnesota is exported *(2)*.

Emergy measures the power to create useful products and services in a system. The taconite produced in Minnesota provides a tremendous subsidy (1.29E+23 sej/y) of organizing power to the larger economies of the United States and the world. However, the actual subsidy would be 3 times greater, if geological processes did all the work of concentration. The transformity of taconite pellets was calculated as part of this study (Appendix B3.4). This transformity is based on the work of nature in creating iron ore (taconite rock, 20% Fe) and the energy and human service required to beneficiate low grade ores. E.W. Davis's technology to concentrate low grade ores results in a 22:1 emergy yield for every sej used in beneficiation (Appendix B3.4). However, when compared to the work that nature does in creating an ore of 63% iron, the magnification factor is 47:1. The taconite exported to steel mills in the east would require three times more emergy, if it was a natural iron ore with the same iron concentration. This calculation demonstrates how technology can increase the production efficiency of materials used by society, *i.e.*, taconite is like an ore containing 63% iron, which would take three times as much emergy to produce through the work of natural geological processes. Given the high net emergy yield of Minnesota's original rich iron deposits, it is not surprising that the mining of this ore during the 1890s led to the rapid expansion of the iron and steel industry in the United States and subsequent dominance of the U.S. in manufactured exports (Irwin 2003).

The emergy to money ratio for Minnesota in 1997 was 4.66E+12 sej/$ compared to 2.56E+12 sej/$ in the United States as a whole. This index means that in 1997, the power of a dollar to purchase emergy was 1.82 times greater at an average place in Minnesota than in an average place in the Nation. The consequences of this relationship can be better understood by considering an example such as Federal outlays and taxes. The United States contributed $19.8 billion dollars in Federal outlays to individuals and to state and local governments in Minnesota in 1997. Multiplying this value by the emergy to dollar ratio for Minnesota in 1997 shows that the combined expenditures of the Federal government could have generated an emergy flow of 9.22E+22 sej/y, if all the tax money had been spent in the State. This is 71% of the emergy in taconite pellets exported. However, if the money was spent at an average location in the United States it would only generate a flow of 5.07E+22 sej (45% less). Federal taxes amounting to $26 billion were collected from Minnesotans in 1997. Similarly, if this tax money had been spent in Minnesota it would have generated an emergy flow that was 1.82 times the flow when spent at an average location in the U.S. The difference between taxes and outlays in this year was 6.21 billion dollars or 23.9% of taxes and the emergy deficit assuming all money was spent in the Nation was also 23.9%. Table 11 analyzes several Federal outlay and tax scenarios for Minnesota depending on where tax dollars and Federal outlays are spent. As indicated by the relative values of the emergy to money ratio in Minnesota and the United States, more emergy flows when Federal dollars are spent in Minnesota. This fact is balanced by the need for tax dollars to support national structure and function that all the states rely upon for their well-being and the well-being of the Nation.

Emergy parity like monetary parity can be used as a benchmark to show relative advantage and disadvantage in a relationship. Scenarios B and C in Table 11, respectively, show the emergy balance when all Federal outlays are spent either in an average place in the United States or in Minnesota. At the same time tax dollars are removed to support the Nation; and therefore, they probably are not spent in Minnesota. The results for Scenario B, in which outlays are spent out-of-state, show that parity in emergy flows can be obtained by either increasing outlays or decreasing taxes with a much larger change in the dollar flow required, if outlays must be increased rather than taxes cut. Scenario C, in which outlays are spent in MN, gives the same result for decreasing taxes that would be found by seeking monetary parity in the tax-outlay relationship. However, a larger percentage increase (31% vs. 24%) in the dollar outlay is required compared to the tax dollar decrease to achieve both dollar and emdollar parity. Emergy or dollar parity *per se* may not result in the optimum relationship to promote maximum mutual benefit between a state and the nation of which it is a part. Energy Systems Theory (Odum 1994) postulates that maximizing empower at all levels of organization

Table 11. Analysis of Federal Outlay and Tax Relationships

	sej y^{-1} X 10^{20}	1997 Em$	$	% Change
Scenario A (Current)				
All Federal outlays spent in MN	921.8	3.60E+10	1.98E+10	
All Minnesota taxes spent in US	665.7	2.60E+10	2.60E+10	
Surplus for the US	256.1	1.00E+09	-6.21E+09	
Minnesota surplus over outlays spent in U.S.	415.2	1.62E+10		
Scenario B				
All Federal outlays spent in the US	506.6	1.98E+10	1.98E+10	
Federal taxes not spent in Minnesota	1211.2	4.73E+10	2.60E+10	
Emergy Deficit for Minnesota	-704.6	-2.75E+10	-6.21E+09	
Emergy Parity	704.6	2.75E+10		
Increase Federal outlays for parity			2.75E+10	139%
Decrease Minnesota taxes for parity			1.51E+10	58%
Scenario C				
Federal outlays spent in Minnesota	921.8	3.59E+10	1.98E+10	
Federal taxes not spent in Minnesota	1211.3	4.75E+10	2.60E+10	
Emergy Deficit for Minnesota	-289.4	-1.13E+10	-6.21E+09	
Emergy Parity	289.4	1.13E+10		
Increase Federal outlays for parity			6.21E+09	31%
Decrease Minnesota taxes for parity			6.21E+09	24%

simultaneously (Campbell 2000) is the goal function for successful systems. The current Federal outlay and tax situation for Minnesota is shown as Scenario A. Although we do not know that this scenario is maximizing empower in both systems, it has some interesting emergy flow advantages for both the state and nation. Using the extreme conditions that all Federal outlays are spent in Minnesota and that all taxes are spent elsewhere in the Nation, we found that the nation has an emergy surplus of 1.00E+10 Em$ which is 61% larger than the monetary surplus ($6.21E+9) under these conditions. This surplus emergy flow is derived primarily from the additional empower generated by spending outlays in Minnesota. In addition, Minnesota realizes a surplus under these conditions compared to what it would have if all Federal outlays had been spent out of the State. Determining the balance of taxes and outlays between states and the Nation is, of course, a political decision, but it is apparent that the Federal government gets good value for its tax dollars spent in Minnesota. Federal outlays increased 13.1% between 1997 and 2000, while taxes increased 9.6% during this time (Appendix E). These increases actually result in a lower Federal stimulus and tax burden for Minnesota, since the emergy to dollar ratio of the United States (Appendix B4.2) declined by about 15% over these years. State emergy flows appear to be more sensitive to tax decreases, whereas, the Federal surplus may be more closely tied to an increase in outlays spent in Minnesota. Spending more of Minnesota's tax dollars to support Federal functions located in the State or locating new Federal functions in the State may be win-win situations for both Minnesota and the Nation.

The largest storage of biological natural capital in the State is found in Minnesota's soils. The real wealth in Minnesota soils is 14% of the real wealth in its remaining iron ore reserves. With this large source of available energy, it should not be a surprise that Minnesota was 5th in the Nation in both agricultural receipts and exports in 2005 *(12)*. We used an emergy analysis of Florida agricultural crops (Brandt-Williams 2001) as a template to evaluate several Minnesota crops. The evaluations for Minnesota dairy, spring wheat, grain corn, and soybeans are reported in Appendix B3.7.2 and compared to similar crops grown in Florida and Arkansas (Appendix B3.7.1). The relative difference between transformities for the same or similar items is a measure of the relative efficiencies of the two production processes. Using this indicator we found that production of the three crops was much more efficient in Minnesota than in Florida or Arkansas. For grain corn almost all the inputs were lower and the yield was 3.76 times higher in MN than in FL. The transformity of grain corn grown in Minnesota was only 0.082 to 0.126 of that grown in Florida with and without services, respectively. A similar pattern was seen for soybeans for which yield was 2.32 times higher and most inputs were lower giving a ratio of transformities (MN/FL) that was 0.28 and 0.42 with and without services. Fertilizer inputs were markedly less in Minnesota compared to Florida as might be expected based on Minnesota's fertile soils. Energy and labor inputs varied by crop and location, but in general lower amounts of these inputs were required in Minnesota compared to Florida. One negative factor was soil erosion which was much greater in Minnesota. Soil erosion diminishes natural capital assets and would appear as a credit on the environmental liability account for agriculture in the State. The comparison of Minnesota spring wheat to wheat grown in Arkansas was less favorable. The yield per hectare was lower (82%), but required inputs were also lower, especially fertilizer and fuel. This resulted in a ratio of transformities (0.38 and 0.41) with and without services that made Minnesota the more efficient producer of wheat. Dairy production was also more efficient in Minnesota compared to Florida, but a full analysis of Minnesota inputs was not available so the exact difference is not known with confidence.

Since the time of these analyses, Minnesota has rapidly built up the capacity to exploit its endowment of renewable emergy and natural capital to meet the State's and the Nation's need for energy. The use of wind power in Minnesota increased from 1997 to 2000 and it has continued to increase up to the present. Renewable energy production in Minnesota other than from hydropower doubled from 2000 to 2006 *(3)* and most of this was wind power. Even with this increase the generation of electricity from renewable sources only accounted for 6.8% of the electric power generated in Minnesota in 2006. In 2008 the large natural capital stored in the deep, rich alluvial soils of Minnesota was not only being used to produce food, but also energy in the form of corn ethanol. We have seen earlier that Minnesota is a very efficient producer of corn, but emergy studies (Odum and Odum 1984, Lanzotti *et al.* 2000, Ortega *et al.* 2003, Felix and Tilley 2008) have shown that ethanol from both agricultural crops and biomass crops yields little net emergy (Emergy Yield Ratio, EYR, = 1.1-1.3). The energy sources that were economic from 1980 until 1994 had an EYR from 3 to 12 (Odum 1996) and in earlier times the Emergy Yield Ratios were even higher (Odum 1996). Thus, we can not expect ethanol to replace petroleum as an engine of growth for the United States, because growth requires a large net emergy yield. An emergy analysis of the corn ethanol industry in Minnesota should be performed evaluating its net emergy yield including any negative effects on the environment and food production in the assessment of costs and benefits.

3.10.2 *Comparison with other States*

Minnesota's status relative to other states and the Nation can be shown by comparing emergy indicators and indices. Indices that are related to system characteristics such as self-sufficiency, sustainability, and equity in the exchange of real wealth (emergy) are of particular interest to society because they are related to the well-being of environmental systems. Table 12 contains comparisons of indices calculated for Minnesota in 1997 and 2000 with those of West Virginia in the same two years and for the United States in 1997. The results reported in Table 12 are calculated using the same method that incorporated improvements presented in Campbell *et al.* (2005a). In addition, Campbell and Lu (manuscript) have recently recalculated the emergy to dollar ratio for the U.S. from 1900 to 2004, which allowed us to calculate the partial set of indices for the United States shown in Table 12. We will have a stronger basis for comparative analysis when studies of 6 additional states (VA, MD, PA, DE, NJ, and RI) for the base years 1997 and 2000 are completed.

The *import/export balance* of emergy flows shows the relationship between trading partners. In a system where trade is equitable, the emergy exchanged would be approximately equal, *i.e.*, there would be parity in emergy exchange.

Table 12. Comparison of Emergy Flows and Indices for Minnesota and West Virginia in 1997 and 2000 with selected indices for the United States in 1997. All flows times 10^{21} sej y^{-1} unless otherwise noted or expressed as ratios.

Index	Minnesota[1] 1997	Minnesota[1] 2000	W. Virginia[2] 1997	W. Virginia[2] 2000	US[1] 1997
Renewable Absorbed	19.1	19.1	6.6	6.6	1031
In State Non-renewable use	132	146	206	196	
Imported Emergy	575	570	159	157	
Total Emergy Inflows	595	589	169	169	
Total Emergy used	726	735	221	230	21240
Emergy used from home sources	0.21	0.21	0.28	0.31	
Exported emergy including fuels	763	759	305	288	
Imports-Exports	-188	-189	-147	-129	
Ratio of export to imports	1.33	1.33	1.92	1.81	
Fraction used, locally renewable	0.026	0.026	0.030	0.030	0.049
Fraction of use purchased outside	0.79	0.78	0.72	0.68	
Fraction of use that is imported services	0.27	0.27	0.17	0.15	
Fraction of use that is free	0.036	0.036	0.031	0.029	0.057
Ratio of purchased to free	26.8	26.7	19.7	20.6	3.5
Environmental Loading Ratio	37.1	37.1	20.4	21.3	19.6
Investment Ratio	3.81	3.67	2.39	2.11	
Area m^2	2.25E+11	2.25E+11	6.24E+10	6.24E+10	9.82E+12
Population, individuals	4,735,830	4,919,479	1,815,481	1,808,344	272,912,000
Use per unit area, sej m^{-2} y^{-1}	3.23E+12	3.26E+12	3.54E+12	3.70E+12	2.16E+12
Use per person, sej $ind.^{-1}$ y^{-1}	1.53E+17	1.49E+17	1.22E+17	1.27E+17	7.78E+16
Renewable Carrying Capacity, individuals	124,235	127,574	86,805	82,702	13,247,282
Developed Carrying Capacity, individuals	993,884	1,020,589	694,443	661,619	108,978,256
Gross State Product $	1.55E+11	1.85E+11	3.83E+10	3.97E+10	8.30E+12
Emergy to Money Ratio sej/$	4.66E+12	3.97E+12	5.76E+12	5.79E+12	2.56E+12
Ratio of Electricity to Emergy Use	0.047	0.047	0.073	0.073	0.095
Fuel Use per Person, sej/individual	1.78E+16	1.73E+16	4.50E+16	3.41E+16	1.65E+16
Renewable Empower Density sej m^{-2} y^{-1}	8.46E+10	8.46E+10	1.06E+11	1.06E+11	1.04 E+11

[1]This study, [2]Campbell *et al.* 2005).

However, a definitive determination of an equitable balance between partners would have to consider all aspects of their relationship, including factors that are difficult to evaluate such as the exchange of technical and cultural information and the provision of security. What is equitable in trade is also determined by the resource reserves and needs of the various states or regions and the needs of the Nation of which they are a part. Often a monetary balance does not mean that the emergy exchange is balanced and this leads to distinct advantages in the exchange of real wealth for either the buyer or seller (Brown 2003, Campbell *et al.* 2005a). The Energy Systems approach calls for analysis of systems on multiple scales to determine the net result of trade at several different levels of hierarchical organization, *e.g*., county, state, nation.

The results in Table 12 show that the emergy of exports exceeds imports for both Minnesota and West Virginia. In Minnesota the emergy deficit is caused primarily by the shipment of iron ores and concentrates out of the State, whereas in West Virginia the shipment of coal accounts for almost the entire emergy deficit. Strategic materials and energy are invariably concentrated in particular locations in a nation and the national system could not survive and prosper without using them broadly. Emergy accounting shows the real wealth in these resources in terms that are directly comparable to the real wealth in the purchasing power of the money received for them. The question that resource rich states, like West Virginia and Minnesota, and the Nation must answer is, “What is an equitable emergy feedback to compensate for the vast quantities of the work of nature that were required to generate nonrenewable fuels and minerals?” This question is complicated by the additional question, “Who owns the products of nature’s work?” and “Who has the right to benefit from this work?” In the case of Minnesota and West Virginia the whole nation benefits greatly from the imbalance in emergy exchange between these two states and the nation at-large. However, the social consequences of these deficits have been very different *(13)*. Minnesota is one of the richest states in the Nation (8th in per capita income in 2004), whereas West Virginia is one of the poorest (48th in per capita income in 2004). It is interesting that the poorest region of Minnesota, *i.e*., the Arrowhead Region, supplies the Nation with a rich emergy subsidy in ores and timber.

The emergy gain to the Nation from trade with Minnesota and West Virginia is evidenced by the *emergy exchange ratio* (EER) for iron and coal. Minnesota exported 1290E+20 sej of iron ores and concentrates in 1997 for which it received 1.2 billion dollars and West Virginia exported 1497 E+20 sej of coal in the same year, for which it received 3.92 billion dollars. The Emergy Exchange Ratios (EER) for Minnesota iron and West Virginia coal are as follows:

Minnesota Iron;
(1290 E+20 sej/y)/ [($1.2 E+9) (2.56 E+12 sej/$)] =
(1290 E+20 sej/y)/ (30.7 E+20 sej/y) = 42:1

West Virginia Coal;
(1497 E+20 sej/y)/ [($3.92 E+9) (2.56 E+12 sej/$)] =
(1497 E+20 sej/y)/ (100 E+20 sej/y) = 15:1

Thus, the buyer of Minnesota iron receives 42 times the benefit in real wealth compared to the emergy buying power of the money paid for the concentrates, if the money paid for the concentrates is then spent at an average location in the United States. In the case of WV coal, the net benefit is 15 times the buying power of the money received. If the money received for taconite pellets was spent in Minnesota, the advantage to the buyer would be 22:1. In either case, Minnesota iron and West Virginia coal provide large fluxes of real wealth to support growth in the regional, national and global economies that receive these raw materials.

The recent increase in oil prices on the international market provides and example of the limits to growth imposed when rising prices eliminate the emergy advantage to the buyer of natural resources. For example, Saudi Arabian oil at $100 per barrel when exchanged for 2004 US dollars has an emergy yield of 1.647:1 {(6.1E+9 joules per barrel) (54000 sej/J)/ [(2.0E+12 sej/$) ($100 per barrel]}. In 2004, $20 per barrel oil would have yielded 8.2:1 and oil at $164.70 per barrel oil would have no net yield to the United States. From this preliminary analysis we might guess that the long term equilibrium price for oil based on emergy parity of the exchange and the emergy to money ratio in the U.S. economy in 2004 would be around $165 per barrel. Above this price the U.S. infrastructure and functions that depend on oil for their maintenance would be forced to decline or find substitutes for petroleum. Of course, the parity price would rise in the future if the emergy to dollar ratio declines as a result of inflation, *i.e*., more dollars and/or less emergy flowing in the U.S. economy.

The empower density or the emergy use per unit area is indicative of the average intensity of development in a state. In 1997, the annual emergy use per square meter in Minnesota was 0.91 of that in West Virginia and 1.5 times that of the U.S. as a whole. Twenty-nine percent of the State's land area is covered by forests and 39% is used for agriculture. High empower densities are found in areas with emergy intensive activities, *e.g.*, iron mining. Also, major urban areas, such as Minneapolis-St. Paul, which is a metropolitan regional center with a diverse manufacturing base, and the port city of Duluth, which is the center of commerce in the resource rich northeast. The diverse economic base for Minnesota, which includes agriculture, mining, manufacturing, forestry and commerce, illustrates why its emergy flow density is 50% greater than the Nation as a whole. In the case of West Virginia, the intense industrial utilization of coal to generate electrical power for consumption outside the state and to support chemical manufacturing, steel production, and other export industries results in very high empower densities in certain areas within a state that is 79% forested. This tendency to spatially concentrate the industrial use of coal power is further magnified by the relatively small area of flat land in West Virginia. Thus industry is found to be heavily concentrated in narrow valleys, as in the Kanawha Valley and along the Ohio River, and the overall result is an average empower density 1.64 times that of the Nation.

The renewable emergy base for a state sets limits on the level of economic activity that is sustainable without subsidies from outside. Minnesota can support 2.6% of the present population at the 1997 standard of living using its renewable resources alone in their current state of development compared to 3.0% for West Virginia and 4.9% for the Nation. If the 1997 standard of living in West Virginia is adjusted by removing exported electricity from total emergy use, 5.8% of the population could be supported. By this measure, the sustainability of Minnesota at its 1997 standard of living was 47% lower than the national average and 55% lower than West Virginia. Minnesota's large storage of wealth in iron and mineral reserves will not help its energy sustainability except through trade for needed fuels. However, its large endowment of wind energy and waves and the stored wealth in soils and peat along with sustainable rotations for the management of forest biomass will provide a renewable energy base for Minnesotans, when fossil fuel energy sources decline.

The investment ratio is an indicator of the competitiveness of a state in attracting additional investments. Lower ratios are more attractive for future development. The investment ratio in Minnesota in 1997 was 3.73:1 compared to an average ratio of 2.39:1 for West Virginia and 7.0:1 for the United States as a whole (Odum 1996). In contrast, the environmental loading ratio, ELR, was 37.3:1, which is 86% higher than West Virginia (20.4) and the Nation (19.6). This ratio indicates that economic activities may be putting a large stress or load on the environment of Minnesota. These results may mean that the heavy nonpoint loads from agriculture in Minnesota are at least as important as intense point loads from mining and chemical manufacturing found in West Virginia, which of course are also present in parts of Minnesota.

The fraction of use from home sources for Minnesota was 0.21 in 1997. West Virginia was less dependent on the national economy with 28% of its emergy coming from sources within the State. Since the two numbers are complements, this fact was also evident from the fraction of total use that was purchased outside the State, 0.79, compared to 0.72 for West Virginia.

The emergy use per person is considered to be an indicator of the overall quality of life experienced by the people of a nation or state. The emergy use per person in Minnesota was 25% to 53% higher than in West Virginia depending on whether exported electricity is counted in the State's emergy use and 97% higher than for an average place in the Nation. This index shows that the quality of life experienced by Minnesotans is high. This includes not only their economic welfare, but also the wealth of their natural resources and society. At present social welfare is captured implicitly in overall emergy use. In the future we will develop methods to fully assess the social systems of the State, so that these values can be captured explicitly in our overall estimates of welfare.

In 1997, the emergy to dollar ratio for Minnesota was 81% of that for West Virginia and 182% that of the United States. This indicates that in 1997, a dollar spent in Minnesota purchased about 1.8 times the real wealth (emergy) in Minnesota products and services compared to a dollar spent at an average location in the United States. The emergy to dollar ratio indicates how much Minnesota loses or gains on average when it trades with various partners (see the emergy exchange ratio discussion above). Areas with a high emergy to dollar ratio can attract tourists and new businesses. The emergy to dollar ratio of Minnesota indicates that it is an attractive destination for tourists as indicated by the increase in tourist dollars spent in the State from 7.2 billion in 1997 to 9 billion in 2000. States with a high emergy to money ratio, *e.g.*, Maine (Campbell 1998) and West Virginia (Campbell *et al.* 2004), often have tourism as a major part of their economies. The difference between the emergy to money ratios in West Virginia and Minnesota indicates that Minnesotans would gain from vacationing in West Virginia, because a dollar spent in West Virginia buys more real wealth (emergy) than it does when spent in Minnesota. This is true because the free work of the environment contributes more to local products and services in states with a high emergy to money ratio. Brown and Ulgiati (2001) showed that problems can arise when tourists' dollars compete for limited natural resources in developing economies. Therefore, where the support capacity of the system is limited the effects of tourism on the price of local products consumed by residents should be carefully monitored.

The ratio of the emergy in the electricity and fuel used to total emergy use is an indicator of the high quality energy in people's lives. This indicator of the standard of living was 36% lower in Minnesota than in West Virginia and 50% lower than the national average. We are not sure why Minnesota's use of electricity is a lower fraction of total use than in West Virginia, but the emergy of electricity used per capita there is 81% of that used in West Virginia. This lower electricity use in a state with a high quality of life might be explained by a lower fraction of electricity being used for low quality purposes, *e.g.*, heating, in Minnesota. Fuel use per person in MN was about the same as in the Nation and about half of that used in West Virginia, where some coal mined in-state is used to produce electricity for export (Campbell *et al.* 2005a).

3.11 Summary of Findings as Related to the Management Questions

The findings of the Minnesota emergy evaluation provide understanding and data to shed light on the management questions presented above. Here each question is repeated and then relevant information from the analysis is presented.

(1) "What is the current level of economic investment in relation to Minnesota's resource base, and is this level of investment sustainable?" Minnesota's relatively low investment ratio 3.81:1 in 1997 and 3.67:1 in 2000 and relatively high environmental loading ratio (37.1:1) show that it is a state with enough renewable and nonrenewable resources to attract further economic development, while currently experiencing some degradation of its renewable resource base due to past and present economic activities. Even though environmental resources are being exploited by intense economic development in parts of the State, *e.g.*, the iron ranges, some agricultural and forest areas, and most industrial areas, Minnesota's stored wealth is so great that development pressures can be expected to continue and increase in the future. The pressure to further develop Minnesota's resources, as well as current point and nonpoint pollution produced by agriculture, industry and mining imply that Minnesota will need to continue to protect and restore the environment to ensure that the present high quality of life experienced by Minnesotans continues into the future.

Our estimate of carrying capacity indicates that only 2.6% of the Minnesota population in 2000 can be sustained at the 2000 standard of living using the emergy of renewable resources alone. If the intensity of resource use needed to support an average developed state in the world during the 1980s was to be maintained in the future in Minnesota, only one fifth of the 2000 population could be supported at their 2000 standard of living. These are conservative levels of support and technological change to harvest a greater fraction of renewable emergy inputs for human use may result in raising these low estimates somewhat. Today, Minnesotans and the people of the United States as a whole face serious challenges with regard to our choices about energy and the environment that will determine our future prosperity. This fact has become evident to many people and government and private entities are beginning to search for solutions.

(2) "What is the net exchange of real wealth (emergy) between Minnesota and the Nation?" Emergy accounting shows that Minnesota is a state with great real wealth in natural resources that supplies a large emergy subsidy to the Nation. Minnesota exports 33% more emergy than it receives in return. In 1997, this resulted in an imbalance of 1.88E+23 sej y^{-1}, which is about one-fourth of the annual emergy used in the State. If exported ores and concentrates are removed from the balance, exports exceed imports by about 10%. In

contrast, the monetary exchange between Minnesota and its trading partners shows a $20 billion surplus in 1997. The import (+) and export (-) of the emergy in materials (without considering taconite) is nearly balanced (-1.7%), but the exported services exceed imported services by 26.5%. The surplus in value added services goes directly to the bottom line in its effect on personal income and the welfare of the population. In contrast, imported services were slightly larger than exported services in West Virginia and personal income apparently suffered as a result. Both states are resource suppliers for the Nation, exporting large emergy surpluses in the environmental work used to create fuels and minerals.

(3) “What are the major causes for any observed imbalances?” The emergy of iron ores and concentrates exported without full use accounts for about two-thirds of the difference between emergy imports and exports in the State. Most of the remaining imbalance is accounted for by the work of human services incorporated in Minnesota agricultural, industrial, and informational products for export. The large emergy imbalance related to iron export indicates that the costs and benefits of iron mining to Minnesota and to the Nation should be considered as an issue for discussion. For example, one trade-off is that the economic benefits derived from taconite used in the steel mills of the mid-west and east primarily accrue outside of Minnesota, whereas, the environmental cost of extraction and processing is born primarily by the State. The environmental damage done in the State as a result of iron mining was not evaluated in this study, and it should be addressed in future research.

(4) “What actions might be taken to address an imbalance, if it exists?” Federal outlays and taxes are an obvious way to address trade inequities between a state and the Nation. The current situation with regard to taxes and outlays in Minnesota has been explored above. However, the questions that arise from noting the nature of the emergy imbalance in trade between Minnesota and the Nation are more profound than those related to tax policy. Such questions must consider how we should count the presently unaccounted for subsidies from nature’s work upon which the existence of all industrial societies depend. Questions related to the ownership of these environmental resources arise followed by a consideration of who should benefit from the millions of years of environmental work that were required for the creation of mineral and fossil energy resources. The heterogeneous distribution of natural wealth and human occupation of the land raises questions related to the equity of resource distribution among people, states, and nations. These questions can not be resolved in this short report, however, it is apparent that there should be a national and perhaps a global debate on the implications of modern society’s debt accrued as a result of its reliance on the renewable and nonrenewable resources of the environment. This debate and the questions mentioned above might be elucidated by using environmental accounting methods and emergy valuation to systematically consider all the benefits and costs accruing as consequences of the various policy choices that arise.

(5) “How does Minnesota’s standard of living compare to other states and the Nation?” The quality of life in MN as measured by the emergy use per capita is twice the national average. This index is also high in West Virginia where it is 1.57 times that of the Nation, but in this case many social indicators are depressed (CVI 2002). This paradoxical condition can occur if the benefits of high emergy use are not accurately transmitted to people by the economic system, but also see Campbell *et al.* (2005). Comparison of the situations in Minnesota and West Virginia revealed that West Virginia does not maintain a value-added surplus in the products it provides to the Nation over those it receives. As a result the emergy that can be purchased with the dollars West Virginians receive for their work is just enough to maintain an emergy balance in imported and exported goods and services but not enough to gain a comparative advantage in real wealth. The high emergy use per capita comes in large part from coal mined and used within the State and much of the emergy value of this coal is not included in the dollar flows received for it that people depend on to purchase emergy outside the State. Thus, in West Virginia there is a paradoxical situation where the emergy per capita is high but the quality of life is low. If dollars were flowing into West Virginia to pay for the uncounted work of nature and if this money was spent to benefit the people of the State, West Virginians would have the high quality of life indicated by their emergy use per capita. In contrast, Minnesotans use the dollar surplus received for their value-added manufactured goods compared to imported goods purchased, to purchase both inside and outside the State what they need for a high quality life. In this case the economy is diverse enough so that the imbalance in real wealth that results from the exchange of iron ore does not overwhelm the entire economy. This situation

might be different, if regions within the State of Minnesota were examined.

(6) "Who benefits most from the productive use of the State's resources?" The 1997 CFS shows that over 53% of the tonnage of shipments remains within the State. About 25% of shipments or half of the tonnage exported goes to the North Central states (OH, MI, IN, WI, and IL). Louisiana (3.7%), Iowa (3.2%), North Dakota (3.1%), and Pennsylvania (2.1%) account for another 12% of the tonnage or almost 80% of exports. Minnesota ships large tonnages (short tons) of agricultural products (77,391,000), metal ores and concentrates (47,367,000), gravel, sand, and crushed stone (45,201,000), and petroleum products (28,432,000). For the most part, the people of Minnesota benefit from the productive use of their resources. Minnesota maintains a favorable trade balance in the exchange of manufactured products and the skilled work force commands a premium in the value of exported goods and services compared to imports. Minnesota's long history of supporting and promoting education is undoubtedly a factor in training and maintaining a high skill level in their population. For example, in 1997 the average emergy of a person in Minnesota based on their education level (2.59E+17 sej/ind) was 22% higher than in West Virginia. Despite Minnesota's favorable position on the whole, the results of this analysis indicate that there may be some concern about the equity of the current terms of trade for taconite. This question and other questions related to accurately accounting for environmental work in the economy might be examined in more detail as a part of a regional study of Northern Minnesota.

(7) "How self-sufficient is the State based on its renewable and nonrenewable resources?" The emergy indices of self-sufficiency (emergy from home sources) and dependence (fraction of use purchased outside and fraction of use that is purchased service) presented above show Minnesota is dependent on outside sources for 79% of its emergy use. For West Virginia dependence on outside sources was only 72% of total use, primarily because West Virginia coal is used as the primary energy source for the State. Perhaps more telling is the fraction of use that is imported services, which was 27% for Minnesota but only 17% for West Virginia. All indicators demonstrate that Minnesota is better integrated with and more dependent on the economy of the Nation, than is West Virginia. A more complete understanding of the meaning of this index and of the other indices in this study will only be gained as more states are analyzed using these methods and the results added to the comparison. Minnesota's potential for self-sufficiency in a lower energy future (Odum and Odum 2001) may be more accurately shown by the fact that considerable wind and wave energies are available to be harnessed on a renewable basis. Also, there is a large storage of biomass in peat and a smaller but potentially renewable storage in forest biomass. The greatest natural biological resource in Minnesota is its fertile soil (Table 8); therefore, agriculture can be expected to remain a pillar of the Minnesota economy in a lower energy world. The large iron, copper, and nickel deposits in Minnesota may provide the capacity to trade for the fossil fuels and other items that it lacks far into the future; however, the considerable environmental impacts of these activities would need to be mitigated.

The eighth question "How can we manage the environment and economy to maximize the well-being of humanity and nature?" relates directly to the decision-making criteria for environmental managers. Financial managers have a clear criterion for overseeing the operations of a business, which is to maximize profits and shareholder value. Energy Systems Theory provides a parallel maximal principle related to the overall well-being of both mankind and nature, which managers should consider in making decisions on environmental policy. In this method, policy outcomes are compared based on the total environmental, economic, and social emergy flows realized under each alternative. The maximum power (empower) principle (Lotka 1922, Odum 1996) indicates that those systems which maximize empower in their networks will be the ones that prevail in evolutionary competition among alternatives. Campbell (2001) gives a theoretical argument and some practical examples of how maximizing empower in ecosystems is a mechanism for determining what is valuable, in the sense that it promotes system survival and well-being. Environmental accounting using emergy and energy systems model simulations allow managers to quantify the empower relations among environmental systems with alternative designs. Maximizing empower for the entire system gives a clear unified criterion for decision making and provides an answer to the eighth management question given above. The use of this criterion in environmental decision-making may help society avoid the expense of costly trials and errors, which are often required under present decision-making paradigms such as adaptive management.

3.12 Recommendations to Managers

Constructing emergy accounts for the State of Minnesota gave us quantitative and comparable information to judge the condition of the economy and environment in the State and to provide preliminary answers to some management questions. Emergy indices helped us understand the current condition of the State and how we might set policies to improve conditions there. Based on past emergy analyses (Odum 1996, Campbell *et al.* 2005a) and the insights gained from this study, we recommend that the methods and principles of emergy accounting presented in this report and in Odum (1996) be used to keep consistent and accurate books for all human enterprises, including businesses, counties, states, regions and nations. We recommend that managers' call for further development of these methods using the existing and tested methods of bookkeeping and accounting (Campbell 2005). If emergy accounting methods continue to be developed and tested so that they become generally accepted, managers will be able to use independent emergy audits of their environmental, economic, and social systems as a regular part of a system of checks and balances governing the relationship between economies, societies and the environment.

3.13 Minnesota and the Future

No system on earth exists alone. According to the maximum empower principle (Lotka 1922, Odum 1996), they all have developed interactions with the net result that empower (emergy per unit time) moves toward a maximum under a given set of external forcing energies (emergy signature). The maximum empower principle implies that human and natural systems will become coupled in ways that increase emergy flow. Therefore, we can expect Minnesota to follow this path in the future constrained by the changing emergy signature of the Earth. Present Minnesota connections include sediments, nutrients that move from this north central state to the Louisiana coast via the Mississippi River and cargo that is transported to and from Minnesota on the river. Also, goods from Minnesota and the hinterland states to the west, *e.g.*, the Dakotas and Montana, are shipped to the Atlantic Ocean through the Port of Duluth via the Great Lakes and the St. Lawrence Seaway and other goods are returned to the hinterlands via this route. Railways and highways carry Minnesota exports and imports coupling the State's economy most closely with the surrounding states of the North Central Region and Canada, but also to a lesser degree with states throughout the Nation as shown by data form the CFS *(2)*. Energies of many kinds are exchanged within and among these state systems and both the state and national systems should be better off in the long run as a result of this process. However, when the external emergy sources to a system are changing, it often takes some time for emergy flows to be maximized under the new or changing conditions (Campbell 2000b). If maximizing empower in a system network is the decision criteria in evolutionary competition as proposed by Lotka (1922) and Odum 1996), then emergy analysis can help discern where the patterns of interaction may be improved (by elucidating conditions that increase emergy flow) toward the end of attaining greater benefits (empower) for the environmental system as a whole including all its ecological, economic, and social components.

In the future if not now, world oil production will reach its peak and then decline (Campbell and Laherrere 1998) and the United States will become more dependent on the remaining deposits of fossil fuels within its borders and on the renewable energies that flow into it each year. West Virginia coal and Minnesota iron, copper and nickel will be important nonrenewable resources for the Nation in the future. Since nonrenewable resource supplies of energy and materials are limited, it is now and will continue to be important to continuously restructure societal systems to fit the global resource base. Minnesota can prepare for the challenge of meeting larger demands on its natural resources by using its education system to carry-out needed research on energy and the environment. In addition, emergy accounting methods may be widely taught and used to evaluate the environmental and socio-economic costs and benefits associated with current economic production systems, energy technologies, and development plans. Such analyses will help determine what alternative system designs lead to social and economic prosperity and which ones will maintain a healthy environment and be sustainable, *i.e.*, supported by the capacities of the existing emergy signature. The emergy accounts and indices presented above are a beginning to help Minnesota move toward a prosperous and sustainable future.

Section 4

Discussion

The publication of "Environmental Accounting: Emergy and Environmental Decision Making" by H.T. Odum in 1996 made the methods of Emergy Analysis easily available to the broader scientific community for the first time. These methods make it possible to keep "the accounting books" for an environmental system, including accounts for the economic, ecological, and social components of these systems, in common units of solar emjoules (sejs). Despite the promise that some scientists see in emergy methods, the scientific community as a whole has been slow to recognize this potential. Tests of the method and comparison of results to other methods have been infrequent; and therefore, the potential benefits of adding emergy accounting to the tools commonly used by environmental managers have been foregone. One purpose of this series of technical reports (Campbell *et al.* 2005a) is to make emergy methods and data sources easily accessible to ecologists, economists, and managers within and outside the EPA in a peer reviewed government document, so that they might be more widely tested and applied in finding solutions for practical problems encountered in managing the complex systems of humanity and nature. A second purpose was to present the results of an emergy evaluation of Minnesota and to test the efficacy of these methods by addressing questions that environmental managers have about economic and environmental conditions and policies relevant to managing a whole state.

The methods of emergy accounting are still developing, but we believe that they possess great potential as a tool to aid environmental decision-making. Several advances in the method have been incorporated into this series of reports: (1) we made the analogy between emergy accounting and financial accounting and bookkeeping explicit by proposing the use of emergy income statements and balance sheets as the standard tools of environmental accounting (Campbell 2005, Campbell *et al.* 2004). (2) We found formerly unused data sources and revised the method for evaluating imports and exports to and from states in the United States, making it possible to construct accurate accounts for these important fluxes. (3) We calculated new transformities for snow, taconite, dolomite, sulfur, and the chloride ion (Appendix B), and estimated rough transformities for commodity classes in the Standard Classification of Transported Goods (SCTG). In Appendix B we also included revised calculations of the emergy and transformity of agricultural products using updated numbers for the emergy to dollar ratio and for the transformity of evapotranspiration. Three Minnesota crops and milk production were also analyzed. The new transformities section includes an update of the calculation of the transformity of electricity generated from nuclear power first presented in Campbell *et al.* (2005). The transformities of minerals used in this report reflect the new method proposed by Cohen *et al.* (2007). This method is not perfect and it may be adjusted in the future, but we believe that it gives more accurate estimates of the emergy required to produce economically viable concentrations of the elements than those found by methods currently in use. To apply this method, the emergy of a mineral deposit needs to be adjusted by taking into account its ore grade.

4.1 Standard Methods versus Intellectual Creativity

The methods of emergy analysis have evolved over the past 37 years (Odum 1971, 1983, 1996) and the vitality and creativity of new insights and ideas have played an important role by creating the present generality and flexibility of the method. This has caused the accuracy with which the various flows have been determined to vary over time. For example, previous emergy analyses for the states of Florida (Odum, *et al.* 1986, Odum *et al.* 1998b), Texas (Odum, *et al.* 1987), Alaska (Brown *et al.* 1993), North Carolina (Tilley 1999), Arkansas (Odum *et al.* 1998a), and Maine (Campbell 1998) have each added new insights and ideas to the method for analyzing states, but differences in the quantification of inputs make the results of these analyses, done over many years, only good for first order comparisons. Comparisons are still possible because emergy analyses report relative results and thus the conclusions of a study rarely change unless there are large changes in the inputs. It is not our intent to limit the future development of emergy analysis methods; however, standards for the emergy analysis of states and other systems are needed to make results comparable and to ensure that anyone can use the proposed tools to reproduce results. We hope that the material presented here makes the method for constructing the emergy accounts for states transparent and reproducible to all those who choose to use and improve it. To this end we included extensive notes in the appendices that document the calculations of the entries on the emergy tables. Appendix D is devoted to a detailed description of the method that Campbell *et al.* (2005a) used to determine the emergy of imports and exports. We also include Appendix B that documents the sources for all the transformities used and the calculations for the new transformities that were determined in this study.

4.2 Methods Developed and Refined in this Study

The renewable emergy base for a system is an important characteristic that has been determined using various rules over the years. The objective in calculating this quantity is to determine the degree to which the renewable energy sources of the earth have been concentrated in a particular area without double counting any of the inputs. The renewable emergy delivered to the system boundaries is received by the system. The part of the renewable emergy received that is absorbed is most important because it is the emergy actually used within the system to make products and services. The mutually supporting role of the various kinds of energy transformed in the system has been clearly demonstrated by the complementary interactions of the geopotential energy of runoff and the chemical potential energy of evapotranspiration working together to structure landscapes (Romitelli 1997, Odum *et al.* 1998a, Brandt-Williams 1999). In this study, the renewable emergy received (R_R) and the renewable emergy absorbed (R_A) were clearly distinguished in definitions and in the calculation of indices. We think that it is important to distinguish these two quantities because the transformity of the system and its products are a direct consequence of the energy used in that system, whereas, the energy received by the system indicates the potential of the system for development. That is, the amount of emergy received may determine the attractiveness of an area for investment and future development. For example, all the river water entering a state could be used to support economic activities within that state, but invariably only a small portion will be used. If the boundaries are wide enough, almost all the emergy received can be used in the system, nevertheless, we believe that these two quantities should be distinguished in future calculations of emergy indices that use the renewable emergy base for the system. For Minnesota this distinction was not very important, because wind energy was the largest renewable input to the State and its calculation is only for what is absorbed. Similarly the second largest input was from waves and this calculation also is only what is absorbed. Water more often has chemical and geopotential energies that enter and then leave a region with only a part of the delivered available energy absorbed by the system. In this case, only the St. Croix River contributes to the emergy base of the State and its contribution is less than 1% of the total.

The method for calculating the imports and exports to and from a state in the United States was revised to use data from the U.S. Census Bureau's Commodity Flow Survey for 1997 (this survey was updated in 2002 but this data was not available at the time this study was performed). This revised method and new data sources represented a major improvement in accuracy over the first method used to determine the imports and exports to and from the State's economy (Campbell *et al.* 2005a). In this study, we further revised this method and used new calculations of the emergy base for the United States to put the national indices on the same basis as those calculated for the states. To reconcile all studies West Virginia was updated to use the new number for the emergy to money ratio of the United States in 1997 and 2000 (Campbell and Lu, manuscript).

4.3 Quality Assurance: Reliability of the Data and Uncertainty

One question that should be asked of any scientific analysis is, "How do we know that the results reported are correct and accurate?" This question is particularly relevant for extensive and/or complex analyses that draw upon many sources of data. In common usage, the word "uncertain" means that something is unknown or doubtful; however, in scientific language "uncertainty" pertains to the probability structure of the data. For, example, a relevant variable such as rainfall can be expressed as the mean of a normal distribution plus or minus its standard deviation. Reporting the probability structure of the data always provides more information and may in some cases (*e.g*. risk analysis) allow better decisions to be made. However, the time and effort required to obtain probability distributions for all data in an extensive analysis may not be worth it, if the variation is small or for some other reason not important. In emergy analysis there is often a great diversity in the amount and kind of information available on the various numbers used in the analysis. For this reason, emergy accounting provides 1st order answers to questions on the scale of the analysis. If more exact answers are needed to particular questions, the scale of the analysis can be reduced by using a smaller window in space and time to set the system boundaries. As a rule of thumb, emergy analysts aim to achieve estimates that are within 10-15% of the actual value of the variable used in the analysis. Some numbers will be determined with a higher degree of accuracy, but others may be less accurate. Because many systems are characterized by dominant energy flows that exceed the less important flows by an order of magnitude or more, a first order estimate of quantities is usually sufficient to produce a robust analysis. Many emergy analyses have been performed over the past 20 years and numerous errors have been found and corrected in these analyses, but the results of an emergy analysis are rarely changed by subsequent corrections.

For example, during the development of the West Virginia emergy evaluation process many errors were found and corrected and the methodology was improved. Additional improvements have been made in the process of evaluating Minnesota. The history of changes in values and indices in these reports is used to illustrate the sensitivity of emergy analysis to error correction and improvements in methodology (*e.g*., model uncertainty). In addition, the relevant characteristics of the different types of data are reported and an explanation of the techniques used to check and ensure the accuracy of the numbers used in this analysis is given.

Two sources of uncertainty are considered (1) uncertainty in the numerical values of the quantities used and (2) uncertainty in the methods and models used to make determinations. Uncertainty in the numerical values arises from imprecision of the measuring device, scanty or unrepresentative data, and systematic flaws in the measuring process (Finkel 1990). Model uncertainty arises from difficulties in determining which quantities are relevant to the analysis, from the technical methods used to determine those quantities, and from the choice of surrogates when the needed information is not directly available.

Both environmental and economic data are key inputs to emergy analyses. The broad data quality objective for these data is that values be determined to within 10-15% of the actual value with a high degree of confidence. Environmental data is generally determined to within 10-15% and meets our data quality objectives (Campbell 2003a). For example, pyroheliometers measure incident solar radiation with 2-5% accuracy, anemometers measure wind speed within about 5% and rain gauges record precipitation within about 10%, but newer electronic instruments claim ±3% accuracy.

The Energy Information Administration (EIA) provided key data on energy production, consumption and movements. The EIA obtains data from survey forms, some of which are statistical samples, as well as from many additional information sources *(14)*. They report both sampling and non-sampling errors in their surveys, and have extensive procedures in place to guarantee data quality. In some cases, almost all participants in a process are counted. In 1997, for example, EIA documented 1,850 coal producers who reported production, which included all U.S. coal mining companies with production of 10,000 short tons per year or more. Thus, almost all coal production in the U.S. is counted in the EIA estimate and therefore in most cases, EIA data would fall within our data quality objective of 10-15% accuracy.

Commodity Flow Survey (CFS) data was critical in the development of a revised method for calculating the import and export of emergy to and from a state. The CFS is a survey conducted every five years by the U.S. Census Bureau. Both sampling and non-sampling errors are considered, and the reliability of the data is reported as the coefficient of variation with its standard error *(2)*. The CFS data meets or exceeds our data quality objectives for total commodity movements. For example, the total dollar value of inbound shipments to Minnesota was determined within 3.1% and the tonnage value within 6.7%, whereas, the dollar value of shipments leaving the State was determined within 4.3% and tonnage leaving within 8.9%. Some of the estimated movements of individual commodities have higher uncertainties, which exceed our 10-15% criteria. Major energy or mineral flows are checked using EIA and USGS data as well as data from the CFS. In summary, we have a high degree of confidence that the material, energy, and monetary flows upon which the energy and emergy calculations of bulk imports and exports depend have been determined within 10 - 15% of their actual values.

The effect of the propagation of errors in the estimation of emergy can be estimated as follows. In general emergy is the product of two independent numbers the estimate of the available energy or exergy and the estimate of transformity. If we assume that the data quantity objectives specify that these two numbers be estimated to within ± 10% of the actual value, the propagation of error for two independent variables multiplied together would increase the error of the estimates from ± 10% to ± 14.1% *(89)*.

Whenever the opportunity has arisen, we have used duplicate data and different calculation methods to check the accuracy of estimates. For example, the EIA information on coal imports and exports was used to check the CFS estimates of these quantities. Petroleum imports from the CFS were checked against the petroleum imports that were required to meet the difference between in-state production and consumption obtained from the EIA data. Potential temporal anomalies in the economic data were assessed through collecting and comparing socioeconomic data for two years. Long term averages (10-50 years) were used for environmental variables. In this case, the variation is not reported because most socioeconomic systems depend on the long term average environmental conditions for support and development. Trends or variations in the long term data would be considered as a part of a dynamic energy systems model analysis of the State (not performed in this study). The effect of our improvements in the methodology for estimating imports and exports was discussed in Campbell *et al.* (2005). In general, everything that is known to be of importance in the system under analysis is included. The emergy associated with each item is an indicator of its relative importance and determines whether an item is included in the analysis.

The effect of correcting an error in the determination of the energy associated with an input is illustrated by the recalculation of the geopotential energy of runoff absorbed by the West Virginia system. In Campbell *et al.* (2004), this number was incorrectly calculated, because the energy used was determined relative to sea level rather than the minimum elevation of rivers leaving the State. When this number was corrected, the energy absorbed changed from 6.59 E+16 J/y to 6.02 E+16 J/y, a difference of 8.6%. This resulted in a change of 2 E+20 sej/y or 2.9% in the emergy absorbed by the system and a change of 0.0008 or 2.9% in the fraction of use that is locally renewable, which is an important index calculated using the renewable emergy absorbed. Other calculations that have been refined have resulted in a similar or smaller percentage change in the energy, emergy, and emdollar values. Even the large change in the ratio of imports to exports was based on a 30% decrease in the difference between emergy imported and emergy exported. The major conclusion that West Virginia was a net exporter of emergy was unchanged by methodological improvements and the correction of errors in calculations.

A second example showing the effect of model uncertainty in determining the emergy associated with an input can be seen in the evaluation of the transformity of electricity from nuclear power which appears in this study and in Campbell *et al.* (2005). Cohen *et al.* (2007) was used to determine the transformity of elemental uranium adjusting it using the ore grade of uranium mined in the United States. The former method had used the determination of the transformity of uranium ore from Odum (1996) to estimate the emergy of the uranium used in generating nuclear electricity. The calculation using the mass of uranium oxide, U_3O_8, to estimate the emergy of uranium required was 45% of the original estimate based on the ore required. This resulted in the transformity of electricity generated from nuclear power declining from 51,900 sej/J to 48,100 sej/J or 7.3%. The conclusion that nuclear power is one of the most efficient processes for generating electricity was reinforced by these calculations, *e.g.*, electricity from coal requires 162,000 sej/J, (Odum 1996).

The transformities and specific emergies by which the energy or mass flows are multiplied, respectively, to obtain emergy are critical numbers in the analysis. Campbell (2003) analyzed five global water budgets, and determined that the transformities of global hydrological flows, such as rain, evapotranspiration, and river flow, were determined within an average standard deviation of 5.9± 2.5% of the mean value of the 5 estimates. These global transformities meet our data quality criteria for emergy analysis. Multiple determinations of transformities are not often available, and an accurate estimate of the differences that arise from different sources of data and different estimation techniques is not available for most items. In a few cases, multiple determinations of transformities using different methods have been carried out. Odum (1996) determined the transformity of coal from its relative efficiency in producing electricity and from its geological production process. The former method gave an estimate of 4.3E+4 sej/J and the latter 3.4 E+4 sej/J. The two values are within 12 % of the mean value, which may be a rough estimate of the model uncertainty in determining transformities. In a similar example, Bastianoni *et al.* (2005) estimated the transformity of petroleum from its geological process of formation and found it to be 55,400 sej/J compared to 53,000 sej/J determined by Odum (1996) by the method of relative efficiencies. These two estimates are within 2.5% of the mean value.

We estimated the transformity for each SGTG commodity class to determine the emergy in the tonnage of each commodity imported. These transformities are approximated by averaging known transformities of items within the class (without services); however, all items in a class are not included in the determination of the transformity. In some cases, when a transformity was not known for an item in a class, the parent material was used as a surrogate for the item's transformity. The use of parent materials results in a minimum estimate of the emergy imported and exported in these commodity classes. For example, we updated the transformity for goods in which steel is the major component by using the new transformity for iron determined in this study (Cohen *et al.* 2007). More work is needed to calculate additional transformities and to obtain better estimates for known transformities using detailed production processes, multiple data sets and different calculation methods to determine the distribution of values.

4.4 Future Research and Reports

The methods described in this report represent a significant step forward in our ability to perform accurate and comparable emergy analyses of states within the United States. Comparable state analyses provide the raw material for the analysis of regions, which is of particular concern to the USEPA and other government agencies that are responsible for the management of environmental, social, and economic conditions within regional areas, *e.g*. EPA Region 3, the Mid-Atlantic Highlands, The Chesapeake Bay watershed. There are emergy analyses for eight additional states in various stages of completion as this report is being written. The five states of the Mid-Atlantic region (WV, VA, PA, MD, and DE) are among the eight states analyzed and an emergy analysis of this region is planned in the future. In addition, the emergy accounts for the nine states (MN, WV, MD, VA, PA, NJ, DE, RI, CO) are in progress and when completed will allow a robust comparative analysis of emergy indices. Our current research is focused on the development of methods to evaluate environmental liabilities, which are needed to complete the emergy balance sheet for any enterprise, *e.g.*, nation, state, county, business, or institution. Once this work is complete, we will have an accounting method to determine directly whether any human endeavor is sustainable.

Section 5

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Section 6

Data Sources

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2) U.S. Census, Commodity Flow Survey for 1997. http://www.census.gov/econ/www/cdstate.html

3) Energy Information Administration: http://www.eia.doe.gov

4) International Trade: http://dataweb.usitc.gov/scripts/user_set.asp

5) Energy Information Administration (EIA) natural gas: http://www.eia.doe.gov/pub/oil_gas/natural_gas/data_publications/natural_gas_annual/historical/1997/nga_1997.html

6) Energy Information Administration coal: http://tonto.eia.doe.gov/FTPROOT/coal/058497.pdf

7)http://garnet.acns.fsu.edu/~tchapin/urp5261/topics/econbase.htm

8)http://www.nylovesbiz.com/nysdc/Personalincome/stpcpi9702.pdf

9) Minnesota Pollution Control Agency, http://www.pca.state.mn.us/index.cfm

10) MN ethanol production, http://blogs.citypages.com/blotter/2007/10/boom_boom_bust.php, http://www.nass.usda.gov/mn/

11) http://www.deed.state.mn.us/facts/PDFs/food.pdf

12) http://www.allbusiness.com/government/3754093-1.html, http://www.netstate.com/economy/mn_economy.htm

13) http://www.census.gov/statab/ranks/rank29.html

14) http://www.eia.doe.gov/oss/forms.html#eia-7a

15) Snow: http://www.windows.ucar.edu/tour/link=/earth/Water/water_cycle_climate_change.html

16) Electricity from uranium, http://www.ems.psu.edu/~elsworth/courses/cause2003/engineofindustry/teamnuclear.ppt

17) Uranium Industry Annual report 2002, DOE/EIA-0478(20020) http://www.eia.doe.gov/fuelnuclear.html

18) U.S. uranium mining http://www.eia.doe.gov/cneaf/nuclear/uia/table03.html

19)http://minerals.usgs.gov/minerals/pubs/commodity/iron_ore/stat/

20)http://www1.eere.energy.gov/industry/mining/pdfs/cover.pdf

21)http://www.epa.gov/ttnecas1/regdata/IPs/Taconite_IP.pdf

22)http://minerals.usgs.gov/minerals/pubs/commodity/iron_ore/stat/

23) http://www.the-innovation-group.com/ChemProfiles/Sulfur.htm

24)http://www.netstate.com/states/geography/mn_geography.htm

25) http://www.dnr.state.mn.us/faq/mnfacts/water.html

26) NASA Surface Meteorology and Solar Energy Website. http://eosweb.larc.nasa.gov/cgi-bin/sse/register.cgi?task=login&next_url=/cgi-bin/sse/ion-p&page=globe_main.ion&app=sse

27) National Renewable Energy Laboratory, Renewable Resource Data Center. http://rredc.nrel.gov/wind/pubs/atlas/tables/1-1T.html http://www.met.utah.edu/jhorel/html/wx/climate/windavg.html

28) Global Heat Flow Database of the International Heat Flow Commission, http://www.heatflow.und.edu/index2.html

29) Western Regional Climate Center, Average precipitation (1900-2000) http://www.wrcc.dri.edu/cgi-bin/divplot1_form.pl?2102

30) MN temperatures. http://www.dnr.state.mn.us/faq/mnfacts/climate.html

31) Center for Natural Resources, UM- Duluth http://www.cnr.umn.edu/FR/research/centcoop/mfric/table3a.htm

32) Evapotranspiration Data, http://walkerbranch.ornl.gov/ Estimated from graphs. http://www.esd.ornl.gov/programs/WBW/NASA.htm

33) Net-State.com http://www.netstate.com/states/tables/st_size.htm

34)http://www.grow.arizona.edu/water/temperature/evaporation.shtml

35) Precipitation http://www.wcc.nrcs.usda.gov/climate/climate-map.html

36) MN County Areas http://www.mnplan.state.mn.us/cgi-bin/datanetweb/landuse?map=n&stats=y&topic=P&area=C

37) http://www.crh.noaa.gov/ncrfc/?n=2007outlook

38) Drainage Basin Information http://www.pca.state.mn.us/water/basins/index.html

39) Runoff data http://mn.water.usgs.gov/ann-repts/annrpt01/index.htm

40) Lake Superior Wave Statistics: http://www.meds-sdmm.dfo-o.gc.ca/alphapro/WAVE/TDCAtlas/TDCProducts.htm

41) Coastline http://www.dnr.state.mn.us/waters/lakesuperior/feis/part3.html

42) Flow of the St. Croix River http://mn.water.usgs.gov/ann-repts/annrpt00/05340500.2000.sw.pdf

43) Elevation at Danbury, WI., http://water.usgs.gov/pubs/wri/wri934076/stations/05333500.html

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45) National Atmospheric Deposition Program/NTN http://nadp.sws.uiuc.edu/

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47) Ag Census 1997. Pounds/bushel for various crops. Appendix F. http://www.nass.usda.gov/census/census97/volume1/ac97-mn.pdf

48) Nutrient Data Laboratory http://www.nal.usda.gov/fnic/foodcomp/index.html

49) http://www.nass.usda.gov/census/index1997.htm

50) http://www.unicamp.br/fea/ortega/creta/emergy.htm

51) Ag Census 2001 http://www.nass.usda.gov/mn/

52)http://jan.mannlib.cornell.edu/reports/nassr/livestock/pls-bb/2000/lstk1200.pdf

53) Energy Information Administration, Total Electricity Production (1997) http://www.eia.doe.gov/cneaf/electricity/epa/generation_state.xls

54) http://www.engineeringtoolbox.com/wood-biomass-combustion-heat-9_440.html http://mb-soft.com/juca/print/311.html

55) Forest growth http://files.dnr.state.mn.us/forestry/um/2004mn_forest_resources.pdf http://www.dnr.state.mn.us/forestry/um/index.html

56) U.S. Geological Survey, Ground Water Used (1995) http://water.usgs.gov/watuse/pdf1995/pdf/summary.pdf

57)Water Quality http://mn.water.usgs.gov/ann-repts/annrpt00/40000001.2000.wq.pdf

58) Municipal Solid Waste Generation and Disposal http://www.pca.state.mn.us/programs/indicators/iom-0201.html

59) EIA, Coal Consumption, http://www.eia.doe.gov/cneaf/coal/cia/html/t67p01p1.html

60) EIA, Natural Gas, http://www.eia.doe.gov/pub/oil_gas/natural_gas/data_publications/natural_gas_annual/current/pdf/table_049.pdf

61) EIA, Petroleum http://www.eia.doe.gov/emeu/states/sep_use/pet/use_pet_mn.html

62) EIA, Electricity Production http://www.eia.doe.gov/cneaf/electricity/epa/generation_state.xls

63) EIA, Electricity Consumption. http://www.eia.doe.gov/cneaf/electricity/st_profiles/sept05mn.xls

64) http://www.eia.doe.gov/cneaf/nuclear/page/at_a_glance/states/statesmn.html

65) U.S.G.S. Mineral Yearbook http://minerals.usgs.gov/minerals/pubs/state/mn.html

66) Wind Erosion, http://www.nrcs.usda.gov/technical/NRI/1997/summary_report/table11.html

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68) Natural Resources Conservation Service, http://www.mn.nrcs.usda.gov/technical/nri/tables/82-97lcu_basin.htm

69) http://server.admin.state.mn.us/mm/indicator.html?Id=60&G=39&CI=60

70) Minnesota Department of Trade and Economic Development, http://www.dted.state.mn.us/04x00f.asp

71) Uranium price http://www.uranium.info/prices/longterm.html

72) 1997 Economic Census: Summary Statistics for Minnesota, http://www.census.gov/epcd/ec97/mn/MN000.HTM

73) U.S. Statistical Abstract 2002, http://www.census.gov/compendia/statab/past_years.html

74) IRS, http://www.irs.gov/pub/irs-soi/00db06co.xls, http://www.census.gov/population/censusdata/90den_stco.txt

75) 1997 Economic Census: Summary General Statistics http://www.census.gov/epcd/ec97/wv/WV000.HTM
Summary Statistics for the U.S., http://www.census.gov/epcd/ec97/us/US000.HTM
By industry, http://www.census.gov/epcd/ec97/industry/E3331.HTM
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76) IRS, http://www.irs.gov/pub/irs-soi/00db06co.xls

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78) Water Quality for Minnesota's Water Basins, http://www.pca.state.mn.us/water/groundwater/gwmap/basins2.pdf

79) Lake Superior Volume/Shoreline, http://www.glerl.noaa.gov/pr/ourlakes/lakes.html

80) Electrical Conductivity, Lake Superior, http://wow.nrri.umn.edu/wow/under/parameters/conductivity.html

81) Taconite Reserves, http://www.taconite.org/pdfs/factsheet4.pdf

82) Twin cities Aggregate Resources http://www.dnr.state.mn.us/lands_minerals/metroaggregate.html

83) Aggregate maps http://www.dnr.state.mn.us/lands_minerals/aggregate_maps/index.html

84) Cu, NI, Pt, Assay http://www.prnewswire.co.uk/cgi/news/release?id=94352

85) Peat
http://www.lmic.state.mn.us/chouse/metadata/peatmaps.html

86) U.S. Census Bureau, Population Statistics,
http://quickfacts.census.gov/qfd/states/27000.html

87) Bureau of Economic Analysis, State GSP,
http://www.bea.gov/bea/regional/gsp/

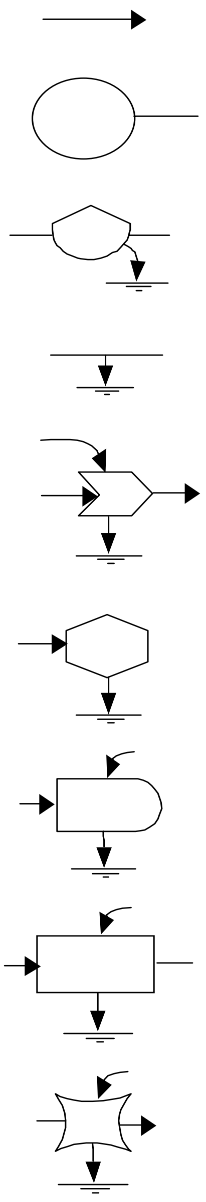
88) http://mup.asu.edu/research2006.pdf

89) Propagation of error.
http://www.chem.usu.edu/~sbialkow/Classes/3600/Overheads/Propagation/Prop.html

Section 7

Appendix A

Primary Symbols of the Energy Systems Language



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

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

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

Heat sink Dispersion of potential energy into heat accompanies all real transformation processes and storages. This energy is no longer usable by the system.

Interaction Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; a work gate.

Consumer An autocatalytic unit that transforms energy, stores it and feeds it back to improve inflow.

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

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

Switching Action A symbol that indicates one or more switching actions controlled by a logic program.

Figure A1. Primary symbols of the Energy Systems Language.

Appendix B

Sources, Adjustment, and Calculation of Transformities

B1. Information Sources For The Emergy Per Unit Values Used In This Report.

The note number links the emergy per unit values listed in this table to the values used in Tables 4-8. The emergy per unit values used in Table B1.1 are given to three significant figures and shown for the 9.26 and 15.83 E+24 sej/y baselines. Values are transformities with units of sej/J except where other units are noted. For example where emergy per unit mass is given a (g) for mass is noted next to the item and the units are sej/g. The emergy per unit of education level is sej per individual and the emergy to dollar ratio (sej/$) is used for services. Table B3.1 gives the factors used to convert one baseline to another. The 9.44 baseline was used by Odum (1996) and was revised to the 9.26 baseline by Campbell (2000a). The 9.44 values are not reported, because this baseline should no longer be used. The 15.83 baseline values are reported because some emergy researchers have been using this baseline, which was reported in Folio #2 (Odum 2000). All numbers given in the text of this report have been converted to the 9.26E+24 sej/y baseline by multiplying the number reported in the original source by the appropriate factor.

Table B1.1 The values and sources for transformities and specific emergies used in this report.

Note	Item (per J unless noted)		Source of transformity or specific emergy calculation	Emergy/unit 9.26	Emergy/unit 15.83
1	Incident solar radiation		(by definition)	1	1
2	Wind -		Odum (1996), p. 309	1470	2.51E+03
3	Earth Cycle		Odum (1996), p. 309	33700	5.76E+04
4	Rain, chemical potential		Odum (1996) Campbell (2003a)	18100	3.12E+04
5	Evapotranspiration,		Odum (1996) Campbell (2003a)	28100	4.80E+04
6	Rain, geo-potential, land		Odum (1996), p. 309	10300	1.76E+04
7	Snow, geo-potential, land		This study	101000	1.73E+05
8	Rain, geo-potential runoff		Odum (1996) (errata)	27200	4.66E+04
9	Snow, geo-potential runoff		This study	101000	1.73E+05
10	Rivers, chemical pot.		Odum (1996), Campbell (2003a)	50100	8.13E+04
11	Rivers, geo-potential		Odum (1996), p. 43	27200	4.66E+04
12	Evapotranspiration		Campbell (2003a)	28100	4.81E+04
13	Ammonia fertilizer	(g)	Odum (1996)	3.73E+09	6.37E+09
13	Ammonia, global	(g)	Campbell (2003a)	1.39E+09	2.37E+9
13	NO, NO2, NO3	(g)	Campbell (2003b)	6.84E+09	1.17E+10
14	Sulfur, S	(g)	This study	1.58E+11	2.70E+11
15	Chlorine, Cl^-	(g)	This study	1.31E+10	2.24E+10
16	Agricultural Products		Brandt-Williams (2002)	variable	variable
	A weighted average of:		See B3 #7.		
17	Livestock		Odum *et al.* (1998)	3.36E+06	
	Beef cattle		See B3 #7.	9.48E+05	
18	Hydroelectricity		Odum (1996), p. 186	120258	2.06E+05
19	Net Timber Growth		Tilley (1999), p.150	20600	3.52E+04
20	Timber Harvest		Tilley (1999)	68700	1.17E+05
21	Ground Water		Odum *et al.* (1998a)	159000	2.72E+05
22	Solid Waste	(g)	Brown & Buranakarn (2000)	6.28E+09	1.07E+10
23	Coal		Odum (1996), p. 310	39200	6.71E+04
24	Natural Gas		Bastianoni *et al.* (2005)	43500	7.44E+04
25	Crude Oil		Bastianoni *et al.* (2005)	54200	9.27E+04
26	Electricity		Odum (1996), p. 305& 311	170400	2.91E+05

Note	Item (per J unless noted)		Source of transformity or specific emergy calculation	Emergy/unit 9.26	Emergy/unit 15.83
27	Iron Ore	(g)	This study, 20% Fe	3.51E+9	6.00E+09
28	Sand and Gravel	(g)	Campbell *et al.* (2005a)	1.31E+09	2.24E+09
32	Limestone	(g)	Odum (1996)	9.81E+08	1.68E+09
33	Dolomite		This Study	1.98E+07	3.38E+07
33	Dolomite	(g)	This Study	1.08E+10	1.85E+10
34	Peat	(g)	Odum (1996) Tab. 5.4	3.89E+08	6.65E+08
34	Peat		Odum (1996) Tab. 5.4	1.86E+04	3.19E+04
35	Erosion, topsoil		Odum (1996)	72600	1.24E+0
37	Nuclear Electricity		This Study.	4.81E+04	8.22E+4
37	Uranium	(g)	Cohen *et al.* (2007)	5.49E+11	9.39E+11
38	Petroleum fuels		Odum (1996)	64100	1.10E+05
39	Aluminum ore, bauxite,		Odum (1996)	1.47E+07	2.52E+07
40	Steel	(g)	This Study	1.47E+10	2.52E+10
49	Forest Biomass		Campbell *et al.* (2005a)	28200	4.82E+04
53	People (per individual)		Odum (1988, 1996)		
	Preschool	(ind.)		3.E+16	5.70E+16
	School	(ind.)		9.E+16	1.58E+17
	College Grad	(ind.)		3.E+17	4.70E+17
	Post-College	(ind.)		1.E+18	2.20E+18
	Elderly (65+)	(ind.)	Campbell *et al.* (2005a)	1.69E+17	2.89E+17
	Public Status	(ind.)		4.E+18	6.59E+18
	Legacy	(ind.)		8.E+18	1.32E+19
NA	Net Prod.		Tilley (1999) p.150	10800	1.84E+04
NA	Aluminum	(g)	Brown & Buranakarn (2000)	1.23E+10	2.10E+10

B2. Estimation of Transformities for the SCTG Commodity Classes. Transformities and specific emergies for each SCTG commodity classes were determined by averaging items within the class, for which transformities were known. For classes where no transformities were available the transformity of the raw materials was used as a first order estimate. Transformities for the SCTG commodity class codes are given below as estimated from the transformities of the items listed. See Appendix D Table D1.1 for a definition of the items represented by the SCTG Class Code numbers. Emergy per unit is relative to the 9.26 baseline.

Table B2.1 Transformities and Specific Emergies for the SCTG Commodity Classes.

Code	Items in Class Average	Transformity se/J	Spec. Em. sej/g
1	Avg. poultry and cattle, Odum *et al.* (1987) Brandt-Williams (2001)	439,300	
2	Avg. wheat, grain corn, rice, oats, sorghum, Odum *et al.* (1987) Brandt Williams (2001)	181,800	
3	Avg. soybeans, cotton, pecans, cabbages, oranges, *etc*. Odum *et al.* (1987) Brandt-Williams (2001)	233,400	
4	Forage Ulgiati *et al.* (1994) Cornstalks & wool Odum (1996), eggs Brandt-Williams (2001)	1.22 E6	
5	Meat ,veal, mutton, shrimp, Odum (1996).	3.27 E6	

Code	Items in Class Average	Transformity sej/J	Spec. Em. sej/g
6	use flour (wheat + energy to process)	18,1800	
7	Sugar, palm oil and cacao from Odum *et al.* (1986b), milk Brandt-Williams (2001).	1.12 E6	
8	Use ethanol and avg. 10% alcohol by volume for beer and wine,, Odum (1996).	58,900	
9	Use tobacco, Scatena *et al.* (2002).	650,000	
10	Use limestone Odum (1996).		9.81 E8
11	Use sand, this study.		1.31 E9
12	Use granite rocks Odum (1996).		4.91 E8
13	Use clay, Odum (1996).		1.96 E9
14	Use ore rocks, iron, alumina, copper, nickel, zinc Odum (1996).		2.71 E9
15	Use coal Odum (1996).	39,200	
17	Use crude oil, petroleum fuels Odum (1996).	64,700	
18	Use petroleum fuels Odum (1996).	64,700	
19	Use fuel oil Odum (1996)	64,700	
20	Use hydrated lime, caustic soda, diatomite, and sulfuric acid Odum *et al.* (2000b)		2.75 E9
21	Pharmaceutical and biological products (use chemicals as feedstock)		2.75 E9
22	Fertilizer from Brandt-Williams (2001) and Odum (1996).		2.99 E9
23	Insecticide, paint and glue (Brown and Arding 1991cited in Buranakarn (1998).		9.90 E9
24	(plastic, tires, *etc*.,) Odum *et al.* (1987)		2.71 E9
25	Use avg. Softwood and hardwood logs Odum (1996).	19,600	
26	Use wood chips, lumber, particle board, plywood, Buranakarn (1998).		1.49 E 9
27	(Use avg. Wood pulp, paper, paper board), Tilley (1999)	139,800	
28	Bags, packing, toilet paper, envelopes, wallpaper, Tilley (1999)	167,400	
29	Paper from Tilley (1999) Ink assumed similar to other chemical preparations.		4.95 E9
30	Use avg. Of textiles and leather Odum *et al.* (1987)	7.18 E6	
31	Use avg. Ceramics, glass flat and float, brick, concrete, Buranakarn (1998)		3.09 E9
32	Avg. Iron , steel, copper, aluminum Buranakarn (1998), Al 1/2 weight in avg.		5.91 E9
33	Assume articles of metal have similar transformities to the unformed metal.		5.91 E9
34	Machinery non electrical, Odum et. al. (1987), updated Cohen *et al.* (2007.		1.47E+10
35	Assume the transformity for machinery applies Odum et. al. (1987), updated Cohen *et al.* (2007).		1.47E+10
36	Assume the transformity for machinery applies Odum et. al. (1987), updated Cohen *et al.* (2007).		1.47E+10
37	Assume the transformity for machinery applies Odum et. al. (1987), updated Cohen *et al.* (2007).		1.47E+10
38	Assume the transformity for machinery applies Odum et. al. (1987), updated Cohen *et al.* (2007).		1.47E+10
39	Household furniture, lamps, mattresses use hardwood, Buranakarn (1998)		2.89 E9
40	Miscellaneous manufactured goods		1.61 E9
41	Tire waste, wood waste, slag. Buranakarn (1998)		2.16 E9
43	Corn and steel for groceries and hardware		6.32 E9

B3. Calculation of New or Revised Transformities. In all cases transformity is determined by dividing the emergy (sej or sej/y) required for product or service by the energy (J or J/y) in the product or service.

Table. B3.1 Transformity of Snow

Average precipitation on land from 5 global water budgets in Campbell (2003a) was :

	$m^3 y^{-1}$
1 Oki (1999)	1.15E+14
2 Peixoto (1993)	9.90E+13
3 Baumgartner and Reichel (1975)	1.11E+14
4 L'vovich (1974)	1.10E+14
5 Odum 1996)	1.05E+14
Average precipitation on land from the 5 global water budgets	1.08E+14

The transformity of snow was estimated from the mass fraction of total precipitation assuming that all global precipitation is required for the anr snowfall.

Average snow fall in a year	1.10E+13	
Average residence time of snow *(15)*	120	days
Snow as a fraction of total precipitation *(15)*	1.02E-01	
Transformity of geopotential energy of precipitation on land is	10,300	sej/J
Transformity of geopotential energy delivered as snow	1.01E+05	sej/J

The dynamics of snow pack formation and its residence time could be used to make an alternate determination of the transformity of snow, but this was not done in this study.

B3.2 Transformity of Dolomite

(1)Assume the production rate of dolomite is proportional to abundance.

(2) The production ratio of limestone to dolomite in the U.S. is 10/1, we assume this rate holds for the entire world, and therefore, we can estimate the crustal abundance of dolomite. We also assumed that despite the fact that dolomite production has not been observed, that it has been produced in the global sedimentary cycle over the last cycle of mineral formation (Odum 1996).

Global Sedimentary Cycle Material Flux	9.36E+15	g/yr

The proportion of the continental area that is limestone is 18%, therefore, under the assumption statec proportion of continental area of dolomite is 1.8%.

Limestone flux	1.68E+15	g/yr
Dolomite flux	1.68E+14	g/yr
Fraction mass flux	1.80E-02	
Gibbs free energy of the weathered limestone (Odum 1996)	50	J/g

<u>Calculation #1:</u>

Solar transformity (sej/J)=(fraction*baseline)/(Gibbs free energy/g*flux in g/yr) Odum (1996) p. 46

Solar Transformity of Dolomite	1.98E+07	sej/J

Calculation #2:

Specific emergy of dolomite =(0.981E9 sej/g) / (Gibbs Free Energy) Odum (1996) p. 46	1.96E+07	sej/J

0.981E+9 sej/g is the emergy/mass of global sedimentary cycle on the 9.26 baseline (Campbell 2000a)

Calculation #3:

sej/g based on limestone as 9.81E+08 sej/g		
Mass ratio limestone/dolomite		
Fraction total limestone dolomite	0.09090909	
Specific emergy dolomite	1.08E+10	sej/g

B3.3 Updated Transformity for Electricity from Nuclear Power

Cohen *et al.* (2007) gives the specific emergy of uranium as 1.6E+11sej/g = 9.36E+10 sej/g on the 9.26 baseline. Items in the table are from Lapp (1991) quoted in Odum (1996) on p.154.

Item	sej/y
Emergy from the economy	9.128E+23
Emergy from the environment	4.90E+22
Emergy from uranium	6.37E+22
Total Emergy	1.03E+24
On 9.26 baseline	1.01E+24
Joules of electricity generated	2.09E+19
Transformity of nuclear electricity	4.81E+04 sej/J
Parameters	
kWh per kg U fuel *(16)*	50000
kWh per year generated, Lapp (1991)	5.80E+12
tons U in fuel used (calculated)	1.16E+05
tons ore used (calculated)	7.63E+07
Specific Emergy U.S. Uranium*	5.49E+11

* Specific Emergy from Cohen *et al.* (2007) is 1.6E+11 sej/g U adjusted to the 9.26 baseline is 9.36E+10 sej/g U., adjusting for stoichiometry the average transformity of U_3O_8 is 7.94E+10 sej/g. Cohen's Ore Grade Cutoff (OGC) is 0.026 % U and the percent U in U.S. mined ore is 0.152 giving an enrichment of 4.974.

Average uranium produced in the U.S.	Mine n=10	Data Source *(17)*
Million lbs U_3O_8	3.49	
1000 MT U	1.35	

	Concentrate n=10	Data Source *(17)*
Million lbs U_3O_8	4.26	
1000 MT U	1.64	
Fraction U in U_3O_8 from data above	0.850703226	calculated
Stochiometry	0.847980998	calculated
Oxygen, MW 16	128	
Uranium, MW 238	714	
For $30 per pound U, all sources (mining + leaching)		
Average ore grade percent U_3O_8	0.17928	Data source *(18)*

B3.4 Transformity for Taconite

Energy use for Iron Extraction *(20)*.

Year	1992	1997	1992 Joules	1997 Joules	Transformity sej/J	1992 sej	1997 sej
Iron Ore Produced (1000 tons)	61288.5	69255.1					
Energy Requirements for Extraction							
Fuel Oil (1000 bbl.)	669.6	910.7	4.30E+15	5.85E+15	64100	2.76E+20	.75E+20
Natural Gas (billion cu. Ft.)	29.7	34.3	3.27E+16	3.77E+16	40000	1.31E+21	.51E+21
Gasoline (1000 bbl.)	26.2	33.3	1.51E+11	5.03E+12	64100	9.67E+15	
Electricity Purchased (million kWh)	7300	6200	2.63E+16	2.23E+16	170400	4.48E+21	
Total						6.06E+21	.69E+21
Specific Emergy Added (sej/g)						1.09E+08	.05E+07
Average Specific Emergy Added (sej/g)							

Production Costs 1997 ***(21)***

	$	sej/y
Total $ Costs and Emergy of Service	1.68E+09	4.13E+21
Total Capital Expenditures	9.10E+07	
Buildings	8.14E+07	2.08E+20
Mineral Exploration	9.42E+06	2.41E+19
Mineral Land Rights	1.06E+05	2.71E+17
Total Labor	5.42E+08	
Payroll	3.94E+08	1.01E+21
Fringe	1.48E+08	3.78E+20
Total Cost of Supplies	1.04E+09	
Minerals and Machinery	6.04E+08	1.55E+21
Fuels	1.17E+08	3.00E+20
Electricity	2.59E+08	6.63E+20
Avg. service (sej /g)	6.56E+07	
1997 emergy/$ (sej/$)	2.56E+12	

Specific Emergy of Taconite Production

	sej/g
Sedimentary Iron Ore *(22)* Cohen *et al.* (2007) (20% Fe)	3.51E+09
Emergy for Extraction and Processing	9.97E+07
Emergy in Services	6.56E+07
Emergy Per Gram of Taconite without Services	3.61E+09
Emergy per Gram Taconite with Services	3.68E+09
Emergy Magnification Factor For Extraction And Beneficiation	22.23
Emergy Magnification Factor Compared to 63% Fe Iron Ore	47.07

Specific Emergy of Taconite Production for Comparison

	sej/g
Sedimentary Iron Ore Odum (1996)	9.81E+08
Emergy for Extraction and Processing	9.97E+07
Emergy in Services	6.56E+07
Emergy per Gram Taconite	1.15E+09
Emergy Magnification Factor For Extraction And Beneficiation	6.93
Emergy Magnification Factor Compared to 63% Fe Iron Ore	13.15

Nature's work in making ores with high iron concentration equivalent to that in taconite pellets can be estimated as follows: The ratio of the fraction of iron in beneficiated pellets to ore mined was 3.217 (0.6328/0.1967). Adjusting the specific emergy of iron (Cohen *et al.* 2007) to an ore grade cut-off (OGC) of 63% iron gives a specific emergy of 1.13E+10 sej/g. The emergy magnification factors for the extraction and beneficiation technologies using ore that is 20% iron are given above based on this number.

B3.5 Specific Emergy of Sulfur

Specific Emergy of Sulfur Estimated For Petroleum Refining *(23)*

Recovered Sulfur in the U.S. in 1999 (1000 Mt)	8220
76% is from Petroleum Refining (1000 Mt)	6247.2
Sulfur Recovered from Petroleum Refining (G)	6.25E+12
Sulfur Production Capacity, U.S. Refineries 1999 (Long Tons)	12125
Production Capacity (G)	1.23E+13
Capacity Utilization	50.66%
Emergy of Refining Average 1993-2004* (Sej/Y)	1.95E+24
Specific Emergy of Recovered Sulfur (Sej/G)	3.12E+11
Specific Emergy, if Process Was Run at Capacity (Sej/G)	1.58E+11

* Bastianoni *et al.* manuscript, Campbell unpublished data

Alternative Estimate for the Specific Emergy of Sulfur

	g/y
Sulfur Emissions, Volcanoes (Andreas & Kasgnoc 1998)	1.04E+13
Volcanic Extrusion at Surface (Odum 1996)	2.10E+15
Estimate of Sulfur Extruded	1.30E+12
Sulfur as a Fraction of Extruded Mass	0.006
Average Upper Crust Conc. S ppm (Rudnick & Gao 2003)	620

	sej/g
Specific Emergy of Volcanic Extrusions (Odum 1996)	4.41E+09
Specific Emergy Sulfur Based on Mass Concentration	7.92E+11

B3.6 Specific Emergy of the Chlorine Ion.

Adapted from the Calculation for Caustic Soda in Odum *et al.* (2000b) p. 263. All numbers converted to the 9.26 E+24 sej/y baseline

Note	Item	Solar Emergy (sej/g)	Raw Units (J, g, $)	Emergy/Mass (sej/g)
1	Salt (NaCl)	1.43E+09	g	
2	Water in Steam	7.91E+05	g	
3	Fuel	3.69E+09	J	
4	Capital and Labor	5.39E+08	$	
5	50% Caustic Soda	5.66E+09	g	5.67E+09

Notes:

1 Salt. Amount necessary from stochiometric relation = 1.46 g/g NaOH.
Emergy/gram NaCl = 9.81 E8 sej/g (Odum 1996)
Emergy = (1.46 g/g NaOH)*(9.81 E8 sej/g) = 1.43 E9 sej/g NaOH

2 Water in steam. 8.85 g/g NaOH produced (Wehle, 1974, p. 197). Gibbs free energy of water = 4.94 J/g. Transformity (rain) = 1.81 E4 sej/J (Odum 1996)
Emergy = (8.85 g)*(4.94 J/g)*(1.81 E4 sej/J) = 791313.9

3 Fuel for Electrolysis. 7.29 E7 BTU/ton NaOH (Wehle, 1974, p. 197)
Transformity of fuel (natural gas) = 43500 sej/J
Emergy = (7.29 E7 BTU/ton)*(1 ton/9.07 E5 g)*(1054.8 J/BTU)*(43500 sej/J)

4 Labor & Service Purchased Goods. Price of Caustic Soda: $208/ton (4th quarter 2000)
Emergy to money ratio in 2000: 2.35E12 sej/$
Emergy = ($208/ton)*(1 ton/9.07 E5 g)*(2.35 E12) = 5.39 E8

5 50% Caustic Soda. Sum of Inputs 1-4.

Molar Conversion from NaOH to Cl_2:

1g NaOH = 0.02439 mol
.02439 mol Cl ---> 0.0122 mol Cl_2
.0122 mol Cl2 = 0.8662 g Cl_2

Specific emergy for Cl_2:
6.55E+09 sej/g

Transformity for Cl^-: Use the reaction in water, assuming deposition is due to rain:

$2H_2O+Cl_2 \rightarrow HClO+H_3O^+ + Cl^-$

0.0122 mol $Cl_2 \rightarrow$ 0.0122 mol Cl^-

0.0122 mol $Cl^- \rightarrow$ 0.4331 g Cl^-

Specific Emergy for Cl^-:
1.31E+10 sej/g

B3.7 Revised Transformities for Agricultural Products Including Some New Determinations for Minnesota.

Transformities for the agricultural products given in Brandt-Williams (2002) and Odum *et al.* (1998) were recalculated with and without services using the 28100 sej/J as the transformity for evapotranspiration as in Campbell *et al.* (2005) and using new values for the emergy to money ratio of the United States (Campbell and Lu manuscript). The transformities without services included were used to determine the emergy of agricultural commodity flows. All transformities are on the 9.26 E+24 sej/y planetary baseline. Table numbers and year of study refer to Brandt-Williams (2001, revised 2002).

Key to Transformities Used

Item	Source
Evapotranspiration	Campbell (2003a)
Topsoil loss	Odum 1996 * 0.981
Fuel	Odum 1996 * 0.981
Electricity	Odum 1996 * 0.981
Potash	Odum 1996 * 0.981
Lime	Odum 1996 * 0.981
Phosphorus	Brandt-Williams (2001 revised 2002) *0.981
Nitrogen	Brandt-Williams (2001 revised 2002) *0.981
Pesticides	Brown and Arding (1991)
Labor	Unskilled, Odum 1996 * 0.981
Services	Campbell and Lu (manuscript)

B3.7.1 Revised Transformities for Florida and Arkansas Crops and Livestock.

Modified from Brandt-Williams (2002)

Beef cattle (2 per ha)

Table 2		Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
	1981	Evapotranspiration	1.15E+11	J	28,100
		Topsoil loss	6.33E+07	J	72,398
		Fuel	1.20E+10	J	64,746
		Potash	6.84E+04	g	1.707E+09
		Lime	5.52E+05	g	9.81E+08
		Phosphorus	7.63E+03	g	2.158E+10
		Nitrogen	3.09E+04	g	2.364E+10
		Pesticides	1.08E+04	g	1.452E+10
		Labor	8.40E+07	J	4.41E+06
		Services	3.68E+02	$	4.97E+12
		Total w/o services	5.72E+15	sej	
		Total w services	7.92E+15	sej	
		Yield dry wt.	1.84E+05	g	
		Yield energy	1.04E+10	J	
		Specific emergy	3.11E+10	sej/g	
		Transformity w/o services	5.50E+05	sej/J	
		Transformity with services	7.62E+05	sej/J	

Modified from Brandt-Williams (2002)
Eggs per 100 hens per year

Table 4	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, \$)
1988	Evapotranspiration	6.05E+10	J	28,100
	Topsoil loss	4.25E+09	J	72,398
	Fuel	4.89E+10	J	64,746
	Electricity	3.06E+09	J	170,694
	Potash	1.57E+05	g	1.71E+09
	Lime	5.25E+05	g	9.81E+08
	Phosphorus	2.95E+04	g	2.16E+10
	Nitrogen	7.99E+04	g	2.36E+10
	Pesticides	0.00E+00	g	1.45E+10
	Labor	1.56E+10	J	4.41E+06
	Services	1.21E+03	\$	3.17E+12
	Total w/o services	9.00E+15	sej	
	Total w services	8.17E+16	sej	
	Yield dry wt.	8.55E+05	g	
	Yield energy	2.08E+10	J	
	Specific emergy	1.05E+10	sej/g	
	Transformity w/o services	4.33E+05	sej/J	
	Transformity with services	3.93E+06	sej/J	

Modified from Brandt-Williams (2002)
Milk per cow per year

Table 16	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, \$)
1980	Evapotranspiration	1.51E+11	J	28,100
	Topsoil loss	7.69E+09	J	72,398
	Fuel	1.75E+10	J	64,746
	Electricity	5.02E+09	J	170,694
	Potash	1.49E+05	g	1.71E+09
	Lime	9.28E+05	g	9.81E+08
	Phosphorus	3.35E+04	g	2.16E+10
	Nitrogen	5.07E+04	g	2.36E+10
	Pesticides	2.33E+03	g	1.45E+10
	Labor	1.28E+08	J	4.41E+06
	Services	2.19E+03	\$	5.54E+12
	Total w/o services	9.91E+15	sej	
	Total w services	2.26E+16	sej	
	Yield dry wt.	7.63E+05	g	
	Yield energy	1.98E+10	J	
	Specific emergy	1.30E+10	sej/g	
	Transformity w/o services	5.01E+05	sej/J	
	Transformity with services	1.14E+06	sej/J	

Odum *et al.* (1998) Arkansas
Poultry (50,000 per ha, 3 months)

1977	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
	Evapotranspiration	1.48E+10	J	28,100
	Topsoil loss	9.95E+08	J	72,398
	Fuel	2.66E+11	J	64,746
	Machinery (oil equivalent)	1.64E+10	J	64,746
	Ration corn	1.35E+12	J	66,123
	Ration soybeans	5.82E+11	J	2.54E+05
	Electricity	2.70E+10	J	1.71E+05
	Groundwater	1.79E+10	J	1.67E+05
	Buildings (oil equivalent)	2.98E+11	J	6.47E+04
	Services 1977$	8.02E+04	$	7.23E+12
	Total w/o services	2.63E+17	sej	
	Total w services	8.63E+17	sej	
	Yield dry wt.	9.00E+07	g	
	Yield energy	8.02E+11	J	
	Specific emergy	2.93E+09	sej/g	
	Transformity w/o services	3.28E+05	sej/J	
	Transformity with services	1.08E+06	sej/J	

Odum *et al.* (1998) Arkansas
Wheat

Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
Evapotranspiration	1.48E+10	J	28,100
topsoil loss	9.92E+08	J	72,398
fuel	4.98E+10	J	64,746
Machinery (oil equivalent)	1.32E+09	J	64,746
Pesticide (oil equivalent)	1.79E+08	J	64,746
Phosphate	3.90E+05	J	1.00E+07
Nitrogen	1.95E+08	J	1.90E+06
seed (oil equivalent)	9.11E+08	J	6.47E+04
electricity	1.79E+09	J	1.71E+05
groundwater	1.76E+10	J	1.67E+05
services 1977$	2.60E+02	$	7.23E+12
Total w/o services	7.48E+15	sej	
Total w services	9.36E+15	sej	
Yield dry wt.	2.60E+06	g	
Yield energy	3.81E+10	J	
Specific emergy	2.88E+09	sej/g	
Transformity w/o services	1.96E+05	sej/J	
Transformity with services	2.46E+05	sej/J	

Odum *et al.* (1998)
Rice

Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
Evapotranspiration	1.48E+10	J	28,100
topsoil loss	9.92E+08	J	72,398
fuel	1.35E+10	J	64,746
Machinery (oil equivalent)	2.87E+08	J	64,746
Pesticide (oil equivalent)	3.97E+09	J	64,746
Nitrogen	2.92E+08	J	1.86E+06
Potassium	2.36E+07	J	2.94E+06
seed (oil equivalent)	2.63E+09	J	6.47E+04
electricity	3.78E+09	J	1.71E+05
groundwater	3.72E+10	J	1.57E+05
services 1977$	7.30E+02	$	7.23E+12
Total w/o services	8.91E+15	sej	
Total w services	1.42E+16	sej	
Yield dry wt.	4.72E+06	g	
Yield energy	6.95E+10	J	
Specific emergy	1.89E+09	sej/g	
Transformity w/o services	1.28E+05	sej/J	
Transformity with services	2.04E+05	sej/J	

Odum *et al.* (1998)
Corn

Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
Evapotranspiration	1.48E+10	J	28,100
topsoil loss	9.92E+08	J	72,398
fuel	6.82E+09	J	64,746
Machinery (oil equivalent)	4.14E+09	J	64,746
Pesticide (oil equivalent)	9.28E+08	J	64,746
Nitrogen	2.68E+08	J	1.86E+06
Potassium	4.00E+07	J	2.94E+06
seed (oil equivalent)	1.29E+09	J	6.47E+04
electricity	6.85E+07	J	1.71E+05
Phosphate	1.81E+07	J	7.70E+06
services 1977$	3.53E+02	$	7.23E+12
Total w/o services	2.11E+15	sej	
Total w services	4.66E+15	sej	
Yield dry wt.	3.90E+06	g	
Yield energy	6.95E+10	J	
Specific emergy	5.72E+10	sej/g	
Transformity w/o services	3.03E+04	sej/J	
Transformity with services	6.71E+04	sej/J	

Odum *et al.* (1998)

Sorghum

Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
Evapotranspiration	1.48E+10	J	28,100
Topsoil loss	9.92E+08	J	72,398
Fuel	2.99E+09	J	64,746
Machinery (oil equivalent)	5.27E+08	J	64,746
Pesticide (oil equivalent)	5.78E+08	J	64,746
Phosphate	1.18E+06	J	1.00E+07
Nitrogen	8.20E+07	J	1.90E+06
Seed (oil equivalent)	1.97E+08	J	6.47E+04
Potassium	6.31E+05	J	3.00E+06
Groundwater	1.76E+10	J	1.67E+05
Services 1977$	1.47E+02	$	7.23E+12
Total w/o services	3.87E+15	sej	
Total w services	4.93E+15	sej	
Yield dry wt.	1.82E+06	g	
Yield energy	3.87E+10	J	
Specific emergy	2.13E+09	sej/g	
Transformity w/o services	1.00E+05	sej/J	
Transformity with services	1.27E+05	sej/J	

Modified from Brandt-Williams (2002)

Corn (grain)

Table 15	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1987	Evapotranspiration	6.05E+10	J	28,100
	topsoil loss	4.25E+10	J	72,398
	fuel	8.12E+09	J	64,746
	electricity	7.85E+08	J	170,694
	potash	1.12E+05	g	1.71E+09
	lime	3.73E+05	g	9.81E+08
	phosphorus	2.11E+04	g	2.16E+10
	nitrogen	5.71E+04	g	2.36E+10
	pesticides	1.69E+03	g	1.45E+10
	labor	1.32E+07	J	4.41E+06
	services	4.39E+02	$	3.17E+12
	Total w/o services	7.82E+15	sej	
	Total w services	9.28E+15	sej	
	Yield dry wt.	9.17E+05	g	
	Yield energy	1.81E+10	J	
	Specific emergy	8.53E+09	sej/g	
	Transformity w/o services	4.32E+05	sej/J	
	Transformity with services	5.12E+05	sej/J	

Modified from Brandt-Williams (2002)

Corn (sweet)

Table 7	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1990	Evapotranspiration	6.05E+10	J	28,100
	topsoil loss	2.44E+10	J	72,398
	fuel	1.25E+10	J	64,746
	potash	1.39E+05	g	1.71E+09
	lime	0.00E+00	g	9.81E+08
	phosphorus	3.95E+04	g	2.16E+10
	nitrogen	5.71E+04	g	2.36E+10
	pesticides	1.11E+04	g	1.45E+10
	labor	2.54E+08	J	4.41E+06
	services	7.76E+02	$	2.88E+12
	Total w/o services	6.88E+15	sej	
	Total w services	1.02E+16	sej	
	Yield dry wt.	5.29E+06	g	
	Yield energy	1.04E+11	J	
	Specific emergy	1.30E+09	sej/g	
	Transformity w/o services	6.61E+04	sej/J	
	Transformity with services	9.84E+04	sej/J	

Modified from Brandt-Williams (2002)

Soybeans

Table 18	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1989	Evapotranspiration	6.15E+10	J	28,100
	topsoil loss	1.81E+07	J	72,398
	fuel	7.01E+06	J	64,746
	electricity	2.97E+08	J	170,694
	potash	3.73E+04	g	1.71E+09
	lime	3.72E+05	g	9.81E+08
	phosphorus	1.05E+04	g	2.16E+10
	nitrogen	2.38E+03	g	2.36E+10
	pesticides	7.07E+02	g	1.45E+10
	labor	7.34E+06	J	4.41E+06
	services	1.48E+02	$	2.99E+12
	Total w/o services	2.50E+15	sej	
	Total w services	2.98E+15	sej	
	Yield dry wt.	4.04E+05	g	
	Yield energy	9.86E+09	J	
	Specific emergy	6.19E+09	sej/g	
	Transformity w/o services	2.54E+05	sej/J	
	Transformity with services	3.02E+05	sej/J	

Modified from Brandt-Williams (2002)

Oats

Table 17	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1985	Evapotranspiration	6.05E+10	J	28,100
	topsoil loss	7.69E+09	J	72,398
	fuel	2.59E+09	J	64,746
	electricity	0.00E+00	J	170,694
	potash	9.29E+05	g	1.71E+09
	lime	0.00E+00	g	9.81E+08
	phosphorus	1.32E+04	g	2.16E+10
	nitrogen	5.11E+04	g	2.36E+10
	pesticides	0.00E+00	g	1.45E+10
	labor	4.79E+06	J	4.41E+06
	services	1.30E+02	$	3.51E+12
	Total w/o services	5.50E+15	sej	
	Total w services	5.98E+15	sej	
	Yield dry wt.	1.36E+06	g	
	Yield energy	2.72E+10	J	
	Specific emergy	4.05E+09	sej/g	
	Transformity w/o services	2.02E+05	sej/J	
	Transformity with services	2.20E+05	sej/J	

Modified from Brandt-Williams (2002)

Peanuts

Table 11	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1987	Evapotranspiration	5.27E+10	J	28,100
	topsoil loss	7.69E+09	J	72,398
	fuel	1.01E+10	J	64,746
	electricity	2.05E+09	J	170,694
	potash	8.38E+04	g	1.71E+09
	lime	9.04E+05	g	9.81E+08
	phosphorus	1.19E+04	g	2.16E+10
	nitrogen	3.56E+03	g	2.36E+10
	pesticides	1.52E+03	g	1.45E+10
	labor	3.00E+07	J	4.41E+06
	services	6.67E+02	$	3.17E+12
	Total w/o services	4.43E+15	sej	
	Total w services	6.68E+15	sej	
	Yield dry wt.	2.95E+05	g	
	Yield energy	9.50E+09	J	
	Specific emergy	1.50E+10	sej/g	
	Transformity w/o services	4.67E+05	sej/J	
	Transformity with services	7.04E+05	sej/J	

Modified from Brandt-Williams (2002)

Cabbages

Table 6	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1989	Evapotranspiration	6.30E+10	J	28,100
	topsoil loss	7.69E+09	J	72,398
	fuel	1.74E+10	J	64,746
	electricity	1.36E+09	J	170,694
	potash	1.86E+05	g	1.71E+09
	lime	5.65E+05	g	9.81E+08
	phosphorus	4.60E+04	g	2.16E+10
	nitrogen	4.75E+04	g	2.36E+10
	pesticides	6.60E+03	g	1.45E+10
	labor	2.05E+08	J	4.41E+06
	services	4.43E+02	$	2.99E+12
	Total w/o services	6.77E+15	sej	
	Total w services	9.00E+15	sej	
	Yield dry wt.	2.31E+06	g	
	Yield energy	4.47E+10	J	
	Specific emergy	2.93E+09	sej/g	
	Transformity w/o services	1.51E+05	sej/J	
	Transformity with services	2.01E+05	sej/J	

Modified from Brandt-Williams (2002)

Potatoes

Table 12	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1990	Evapotranspiration	5.77E+10	J	28,100
	topsoil loss	7.69E+09	J	72,398
	fuel	1.75E+10	J	64,746
	electricity	1.36E+09	J	170,694
	potash	1.63E+05	g	1.71E+09
	lime	5.65E+05	g	9.81E+08
	phosphorus	3.95E+04	g	2.16E+10
	nitrogen	4.75E+04	g	2.36E+10
	pesticides	3.45E+04	g	1.45E+10
	labor	1.37E+08	J	4.41E+06
	services	1.59E+03	$	2.88E+12
	Total w/o services	6.85E+15	sej	
	Total w services	1.20E+16	sej	
	Yield dry wt.	5.43E+06	g	
	Yield energy	8.55E+10	J	
	Specific emergy	1.26E+09	sej/g	2.22E+09
	Transformity w/o services	8.01E+04	sej/J	
	Transformity with services	1.41E+05	sej/J	

Modified from Brandt-Williams (2002)

Cucumbers

Table 8	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1990	Evapotranspiration	6.02E+10	J	28,100
	topsoil loss	7.69E+09	J	72,398
	fuel	2.19E+10	J	64,746
	electricity	0.00E+00	J	170,694
	potash	1.49E+05	g	1.71E+09
	lime	5.65E+05	g	9.81E+08
	phosphorus	4.20E+04	g	2.16E+10
	nitrogen	4.75E+04	g	2.36E+10
	pesticides	4.90E+04	g	1.45E+10
	labor	6.41E+08	J	4.41E+06
	services	1.50E+03	$	2.88E+12
	Total w/o services	7.22E+15	sej	
	Total w services	1.44E+16	sej	
	Yield dry wt.	1.33E+07	g	
	Yield energy	2.61E+11	J	
	Specific emergy	5.43E+08	sej/g	
	Transformity w/o services	2.76E+04	sej/J	
	Transformity with services	5.50E+04	sej/J	

Modified from Brandt-Williams (2002)

Green Beans

Table 9	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1990	Evapotranspiration	5.65E+10	J	28,100
	topsoil loss	7.69E+09	J	72,398
	fuel	1.94E+10	J	64,746
	electricity	1.65E+09	J	170,694
	potash	6.98E+04	g	1.71E+09
	lime	5.65E+05	g	9.81E+08
	phosphorus	1.98E+04	g	2.16E+10
	nitrogen	2.38E+04	g	2.36E+10
	pesticides	1.22E+04	g	1.45E+10
	labor	6.23E+07	J	4.41E+06
	services	1.87E+03	$	2.88E+12
	Total w/o services	5.52E+15	sej	
	Total w services	1.12E+16	sej	
	Yield dry wt.	5.55E+05	g	
	Yield energy	1.12E+10	J	
	Specific emergy	9.95E+09	sej/g	
	Transformity w/o services	4.93E+05	sej/J	
	Transformity with services	9.98E+05	sej/J	

Modified from Brandt-Williams (2002)

Lettuce (Romaine)

Table 10	Item	Inputs $ha^{-1}\ y^{-1}$	Units	Emergy per Unit sej/(J, g, $)
1990	Evapotranspiration	5.27E+10	J	28,100
	topsoil loss	7.69E+09	J	72,398
	fuel	2.63E+10	J	64,746
	electricity	0.00E+00	J	170,694
	potash	1.86E+05	g	1.71E+09
	lime	0.00E+00	g	9.81E+08
	phosphorus	2.63E+04	g	2.16E+10
	nitrogen	4.75E+04	g	2.36E+10
	pesticides	4.43E+04	g	1.45E+10
	labor	3.87E+08	J	4.41E+06
	services	1.65E+03	$	2.88E+12
	Total w/o services	6.39E+15	sej	
	Total w services	1.28E+16	sej	
	Yield dry wt.	8.08E+05	g	
	Yield energy	1.87E+10	J	
	Specific emergy	7.91E+09	sej/g	
	Transformity w/o services	3.42E+05	sej/J	
	Transformity with services	6.87E+05	sej/J	

Modified from Brandt-Williams (2002)

Bell Peppers

Table 3	Item	Inputs $ha^{-1}\ y^{-1}$	Units	Emergy per Unit sej/(J, g, $)
1981	Evapotranspiration	5.43E+10	J	28,100
	topsoil loss	7.69E+09	J	72,398
	fuel	5.57E+10	J	64,746
	electricity	7.49E+08	J	170,694
	potash	1.72E+05	g	1.71E+09
	lime	0.00E+00	g	9.81E+08
	phosphorus	5.27E+04	g	2.16E+10
	nitrogen	4.40E+04	g	2.36E+10
	pesticides	1.31E+05	g	1.45E+10
	labor	1.64E+09	J	4.41E+06
	services	2.11E+03	$	4.97E+12
	Total w/o services	1.02E+16	sej	
	Total w services	2.79E+16	sej	
	Yield dry wt.	1.82E+06	g	
	Yield energy	3.87E+10	J	
	Specific emergy	5.60E+09	sej/g	
	Transformity w/o services	2.63E+05	sej/J	
	Transformity with services	7.22E+05	sej/J	

Modified from Brandt-Williams (2002)

Tomatoes

Table 13	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1990	Evapotranspiration	6.02E+10	J	28,100
	topsoil loss	6.33E+07	J	72,398
	fuel	7.37E+10	J	64,746
	electricity	0.00E+00	J	170,694
	potash	1.39E+05	g	1.71E+09
	lime	3.29E+06	g	9.81E+08
	phosphorus	4.60E+04	g	2.16E+10
	nitrogen	4.75E+04	g	2.36E+10
	pesticides	1.59E+05	g	1.45E+10
	labor	8.56E+08	J	4.41E+06
	services	4.38E+03	$	2.88E+12
	Total w/o services	1.44E+16	sej	
	Total w services	3.07E+16	sej	
	Yield dry wt.	2.43E+06	g	
	Yield energy	4.54E+10	J	
	Specific emergy	5.91E+09	sej/g	
	Transformity w/o services	3.16E+05	sej/J	
	Transformity with services	6.77E+05	sej/J	

Modified from Brandt-Williams (2002)

Watermelons

Table 14	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1981	Evapotranspiration	5.43E+10	J	28,100
	topsoil loss	7.69E+09	J	72,398
	fuel	2.07E+10	J	64,746
	electricity	0.00E+00	J	170,694
	potash	7.44E+04	g	1.71E+09
	lime	0.00E+00	g	9.81E+08
	phosphorus	2.63E+04	g	2.16E+10
	nitrogen	2.86E+04	g	2.36E+10
	pesticides	3.79E+04	g	1.45E+10
	labor	4.00E+08	J	4.41E+06
	services	1.05E+03	$	4.97E+12
	Total w/o services	5.34E+15	sej	
	Total w services	1.23E+16	sej	
	Yield dry wt.	1.88E+07	g	
	Yield energy	3.29E+11	J	
	Specific emergy	2.84E+08	sej/g	
	Transformity w/o services	1.62E+04	sej/J	
	Transformity with services	3.75E+04	sej/J	

Modified from Brandt-Williams (2002)

Oranges

Table 5	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1983	Evapotranspiration	6.51E+10	J	28,100
	topsoil loss	6.33E+08	J	72,398
	fuel	1.99E+10	J	64,746
	electricity	4.68E+08	J	170,694
	potash	2.36E+05	g K	1.71E+09
	lime	2.40E+05	g	9.81E+08
	phosphorus	1.12E+04	g P	2.16E+10
	nitrogen	3.01E+04	g N	2.36E+10
	pesticides	1.79E+04	g	1.45E+10
	labor	2.71E+08	J	4.41E+06
	services	3.01E+02	$	3.79E+12
	Total w/o services	5.09E+15	sej	
	Total w services	7.43E+15	sej	
	Yield dry wt.	4.91E+06	g	
	Yield energy	8.65E+10	J	
	Specific emergy	1.04E+09	sej/g	
	Transformity w/o services	5.89E+04	sej/J	
	Transformity with services	8.59E+04	sej/J	

Modified from Brandt-Williams (2002)

Pecans

Table 22	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1989	Evapotranspiration	6.50E+10	J	28,100
	topsoil loss	6.33E+08	J	72,398
	fuel	1.32E+10	J	64,746
	electricity	2.96E+08	J	170,694
	potash	7.54E+04	g	1.71E+09
	lime	3.73E+05	g	9.81E+08
	phosphorus	2.11E+04	g	2.16E+10
	nitrogen	4.88E+04	g	2.36E+10
	pesticides	7.20E+03	g	1.45E+10
	labor	4.53E+07	J	4.41E+06
	services	2.11E+03	$	2.99E+12
	Total w/o services	4.99E+15	sej	
	Total w services	1.15E+16	sej	
	Yield dry wt.	8.00E+05	g	
	Yield energy	2.30E+10	J	
	Specific emergy	6.23E+09	sej/g	
	Transformity w/o services	2.17E+05	sej/J	
	Transformity with services	5.00E+05	sej/J	

Modified from Brandt-Williams (2002)

Sugarcane

Table 19	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1985	Evapotranspiration	6.83E+10	J	28,100
	topsoil loss	7.69E+09	J	72,398
	fuel	5.46E+09	J	64,746
	electricity	0.00E+00	J	170,694
	potash	1.49E+05	g	1.71E+09
	lime	0.00E+00	g	9.81E+08
	phosphorus	1.05E+04	g	2.16E+10
	nitrogen	0.00E+00	g	2.36E+10
	pesticides	1.96E+03	g	1.45E+10
	labor	1.37E+07	J	4.41E+06
	services	1.35E+03	$	1.99E+03
	Total w/o services	3.34E+15	sej	
	Total w services	3.40E+15	sej	
	Yield dry wt.	2.27E+07	g	
	Yield energy	4.12E+11	J	
	Specific emergy	1.47E+08	sej/g	
	Transformity w/o services	8.10E+03	sej/J	
	Transformity with services	8.25E+03	sej/J	

Modified from Brandt-Williams (2002)

Cotton

Table 20	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1987	Evapotranspiration	5.80E+10	J	28,100
	topsoil loss	8.23E+10	J	72,398
	fuel	9.70E+09	J	64,746
	electricity	3.15E+08	J	170,694
	potash	7.44E+04	g	1.71E+09
	lime	5.65E+05	g	9.81E+08
	phosphorus	1.58E+04	g	2.16E+10
	nitrogen	1.90E+04	g	2.36E+10
	pesticides	4.97E+03	g	1.45E+10
	labor	8.90E+07	J	4.41E+06
	services	4.07E+02	$	3.17E+12
	Total w/o services	9.81E+15	sej	
	Total w services	1.15E+16	sej	
	Yield dry wt.	7.38E+05	g	
	Yield energy	1.25E+10	J	
	Specific emergy	1.33E+10	sej/g	
	Transformity w/o services	7.85E+05	sej/J	
	Transformity with services	9.20E+05	sej/J	

Modified from Brandt-Williams (2002)

Pasture (Bahia Grass)

Table 21	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1985	Evapotranspiration	5.43E+10	J	28,100
	topsoil loss	6.33E+07	J	72,398
	fuel	2.46E+09	J	64,746
	electricity	2.22E+08	J	170,694
	potash	3.63E+04	g	1.71E+09
	lime	3.73E+05	g	9.81E+08
	phosphorus	7.38E+03	g	2.16E+10
	nitrogen	1.55E+04	g	2.36E+10
	pesticides	0.00E+00	g	1.45E+10
	labor	4.85E+06	J	4.41E+06
	services	2.24E+01	$	3.51E+12
	Total w/o services	2.68E+15	sej	
	Total w services	2.78E+15	sej	
	Yield dry wt.	3.63E+06	g	
	Yield energy	6.88E+10	J	
	Specific emergy	7.39E+08	sej/g	
	Transformity w/o services	3.90E+04	sej/J	
	Transformity with services	4.04E+04	sej/J	

B3.7.2. Minnesota Agriculture

New transformities calculated for a study to determine the empower density of Minnesota agriculture.

Dairy (Minnesota)

Milk per cow per year

	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1980	Evapotranspiration	1.51E+11	J	28,100
	Topsoil loss	7.69E+09	J	72,398
	Fuel	2.26E+09	J	64,746
	Electricity	1.00E+09		170,694
	Potash	1.49E+05	g	1.71E+09
	Lime	9.28E+05	g	9.81E+08
	Phosphorus	3.35E+04	g	2.16E+10
	Nitrogen	5.07E+04	g	2.36E+10
	Pesticides	2.33E+03	g	1.45E+10
	Labor	1.28E+08	J	4414500
	Services	2.19E+03	$	5.54E+12
	Total w services	8.24E+15	sej	
	Total w/o services	2.09E+16	sej	
	Yield dry wt.	7.63E+05	g	
	Yield energy	1.98E+10	J	
	Specific emergy	1.08E+10	sej/g	
	Transformity w/o services	4.16E+05	sej/J	
	Transformity with services	1.06E+06	sej/J	

Spring Wheat (Minnesota)

Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
Evapotranspiration	1.29E+10	J	28,100
Topsoil loss	1.91E+10	J	72,398
Fuel	5.06E+08	J	64,746
Potash	4.00E+03	g	1.71E+09
Pesticide and herbicide	5.66E+02	g	1.45E+10
Phosphate	5.95E+03	g	2.16E+10
Nitrogen	1.37E+04	g	2.36E+10
Labor	3.88E+06	J	4.41E+06
Electricity	4.35E+07	J	1.71E+05
Groundwater	0.00E+00	J	1.67E+05
Services 2003$	4.09E+02	$	2.00E+12
Total w services	2.27E+15	sej	
Total w/o services	3.09E+15	sej	
Yield dry wt.	2.14E+06	g	
Yield energy	3.04E+10	J	
Specific emergy	1.06E+09	sej/g	
Transformity w/o services	7.48E+04	sej/J	
Transformity with services	1.02E+05	sej/J	

Grain Corn (Minnesota)

	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1987	Evapotranspiration	2.55E+10	J	28,100
	Topsoil loss	1.11E+10	J	72,398
	Fuel	9.96E+08	J	64,746
	Electricity	5.19E+07	J	170,694
	Potash	9.98E+03	g	1.71E+09
	Herbicide	2.84E+03	g	1.4519E+10
	Phosphorus	7.83E+03	g	2.1582E+10
	Nitrogen	2.49E+04	g	2.3642E+10
	Pesticides	6.16E+02	g	1.4519E+10
	Labor	3.88E+06	J	4.41E+06
	Operator	7.75E+06	J	7.19E+07
	Services	6.27E+02	$	3.17E+12
	Total w/o services	2.42E+15	sej	
	Total w services	4.43E+15	sej	
	Yield dry wt.	3.46E+06	g	
	Yield energy	6.81E+10	J	
	Specific emergy	7.00E+08	sej/g	
	Transformity w/o services	3.55E+04	sej/J	
	Transformity with services	6.50E+04	sej/J	

Soybeans (Minnesota)

	Item	Inputs ha^{-1} y^{-1}	Units	Emergy per Unit sej/(J, g, $)
1989	Evapotranspiration	2.55E+10	J	28,100
	Topsoil loss	1.11E+10	J	72,398
	Fuel	5.15E+08	J	64,746
	Electricity	4.95E+05	J	170,694
	Potash	1.63E+03	g	1706940000
	Herbicide	1.61E+03	g	1.4519E+10
	Phosphorus	1.27E+03	g	2.1582E+10
	Nitrogen	1.01E+03	g	2.3642E+10
	Pesticides	8.63E+02	g	1.4519E+10
	Labor	3.88E+06	J	4.41E+06
	Operator	7.75E+06	J	7.19E+07
	Services	4.20E+02	$	2.99E+12
	Total w/o services	1.64E+15	sej	
	Total w services	2.92E+15	sej	
	Yield dry wt.	9.41E+05	g	
	Yield energy	2.30E+10	J	
	Specific emergy	1.75E+09	sej/g	
	Transformity w/o services	7.16E+04	sej/J	
	transformity with services	1.27E+05	sej/J	

B3.7.2.1 Inputs for Minnesota Dairy per cwt Milk and assuming 172 cwt/cow

Prices 1995	$/gal, cents/kWh
Diesel	0.77
Gasoline	1.11
LPG	0.73
Electricity	0.05

Note: 1995 Prices are used to estimate fuel and electricity inputs to all Minnesota crops.

Milk Production

$ Cost/acre	Fuel type	gal. per acre	kWh/ ac.	J/m2/cwt/y	J/cow/y
0.10	Diesel	0.13		7.60E+06	1.31E+09
0.02	Gasoline	0.02		1.11E+06	1.91E+08
0.08	LPG	0.11		4.41E+06	7.59E+08
	Total Fuels			1.31E+07	2.26E+09
0.20	Electricity		4	5.83E+06	1.00E+09
0.40	Total Cost				

Fertilizer (lbs per treatment * # treatments *%treated)

	lbs/acre/y	g/ha/y
Nitrogen	75	13,714
Phosphorus	32	5,947
Potash	22	3,996

Pesticide (lbs per treatment * # treatments *%treated)

	lbs/acre/y	g/ha/y
Chlorpyrifos	0.94	172.71
Permethrin	0.11	20.21
Phorate	1.11	203.94
Terbufos	1.19	218.64
Total		615.51

Herbicides: 2,4D, Bromoxynil, Dicamba, Diclofop-methyl, Fenoxaprop-ethyl, Imazamethabenz-methy, MCPAC, Thifensulfron, Triallate, Tribenuron-methyl

	lbs/acre/y	g/ha/y
Total	3.08	565.53

Services 2003

$/acre	$/ha
165.75	409.40

Labor	hours/acre	hours/ha	J/ha/y	Labor expense, $
Operator	0.00	0.00	0.00	7.01
Unskilled	1.00	2.47	3.88E+06	

Avg. Yield	bu/acre	g/acre
1995-2001	136	3,457,664

B3.7.2.2 Inputs for Minnesota Corn

Use 1995 prices for fuels.

Corn Production

$ cost/acre	Fuel type	gal. per acre	kWh/ acre	J/ha/y
7.21	Diesel	9.37		5.48E+08
1.28	Gasoline	1.15		6.38E+07
6.99	LPG	9.58		3.84E+08
	Total Fuels			9.96E+08
1.78	Electricity		35.63	5.19E+07
17.27	Total			

Fertilizer (lbs per treatment * # treatments *%treated)

	lbs/acre/y	g/ha/y
Nitrogen	105	19,263
Phosphorus	43	7,826
Potash	54	9,983

Pesticide (lbs per treatment * # treatments *%treated)

	lbs/acre/y	g/ha/y	lbs/acre/y	g/ha/y
Chlorpyrifos	0.94	172.71	135.36	24870
Permethrin	0.11	20.21		
Phorate	1.11	203.94		
Terbufos	1.19	218.64		
		615.51		

Herbicide: 2,4D, Alachlor, Atrazinw, Bromoxynil, Cyanazine, Dicamba, ETC, Metolachlor, Nicosulfuron, Pendimethakin, Propaclor

	lbs/acre/y	g/ha/y
All in order	15.47	2,842.36

Services 2002	$/acre	$/ha
	254	627.38

Labor	hours/acre	hours/ha	J/ha/y
Operator	2	4.94	7.75E+06
Unskilled	1	2.47	3.88E+06

Yield	bu/acre	g	J/g
	136	3,457,664	19,690

B3.7.2.3 Inputs for Minnesota Wheat

Transpiration rate	3	mm/d
Growing season	90	day
Transpiration	0.27	m
Energy Wheat trans.	1.29E+10	J/y
Erosion Rate	12.6	short tons/acre/y
Erosion Rate	28.2338784	MT/ha
Energy of Erosion	1.91E+10	J/y

Use 1995 Prices

Wheat Production

$ cost/acre	Fuel type	gal./ acre	kWh/ acre	J/ha/y
5.57	Diesel	7.24		4.23E+08
0.99	Gasoline	0.89		4.94E+07
0.60	LPG	0.82		3.29E+07
	Total Fuels			5.06E+08
1.49	Electricity		29.88	4.35E+07
8.66	Total Cost			

Fertilizer, herbicide and service inputs are assumed similar to dairy above.

Wheat Yield	bu/acre	lbs dry wt./bu	J/g
	34	56	14,230

B3.7.2.4 Inputs for Minnesota Soybeans

Use 1995 Prices given above.

Soybean Production

$ cost/acre	Fuel type	gal./acre	kWh/ acre	J/ha/y
5.72	Diesel	7.43		4.35E+08
1.01	Gasoline	0.91		5.05E+07
0.55	LPG	0.75		3.01E+07
	Total Fuels			5.15E+08
0.02	Electricity			
7.30	Total Cost		0.34	4.95E+05

Fertilizer	(lbs per treatment * # treatments *%treated)	
	lbs/acre/y	g/ha/y
Nitrogen	6	1,011
Phosphorus	7	1,269
Potash	9	1,627

Pesticide	(lbs per treatment * # treatments *%treated)	
	lbs/acre/y	g/ha/y
Chlorpyrifos	No data	No data
Permethrin	No data	No data
Phorate	No data	No data
Terbufos	No data	No data
Total		863.46

Herbicides used: 2,4-D, Aciflourfen, Alachlor, Bentazon, Ethalfluralin, Fluazifop-p butyl, Glphosate, Imazethapyr, Metolachlor, Metribuzin, Pendimethalin, Quizalofop ethyl, Sethoxydim, Thifensulfuron, Trifluralin, Propachlor

	lbs/acre/y	g/ha/y
All herbicides	8.76	1,610

Services 2002	$/acre	$/ha
	170	419.9

Labor	hours/acre	hours/ha	J/ha/y
Operator	2	4.94	7.75E+06
Unskilled	1	2.47	3.88E+06

Yield	bu/acre	g/ha	J/g
	37	940,688	24,420

B3.8 Revised Transformities for Fossil Fuels

There are two major ways to determine the transformities of fossil fuels. The first method is based on back calculation from solar based electricity using relative quality factors. This was the original way that the fossil fuel transformities were determined by Odum (1996), The second method is to calculate the transformity based on the geological process of formation of the mineral. Odum used both the first and second methods for coal in Odum (1996). The transformities for oil and natural gas were determined by the first method only in 1996, but coal was determined using both methods. Bastianoni *et al.* (2005) calculated the transformity for oil and petroleum natural gas by the second method. Their results closely conformed to Odum's original numbers determined by the first method. The transformity of oil being slightly and higher and the transformity of natural gas slightly lower than the original numbers. Odum (1996) used an average of the two methods to determine a transformity for coal. If a similar average is used for oil and natural gas we obtain the following numbers. All numbers are expressed relative to the 9.26E+24 sej/y planetary baseline, which is the corrected version of Odum's 9.44 line used in Odum (1996).

Fossil Fuel Transformities sej J^{-1}

	Relative Efficiency	Geologic Processes	Average	3 sig. figs.
Coal	42,180	33,350	37,770	37,800
Natural gas	47,080	40,000	43,540	43,500
Oil	52,640	55,400	54,020	54,000

Table B4.1 The factors needed to convert one planetary baseline to another.

To convert,

Baseline X	To baseline, Y	Multiply by
9.44	9.26	0.981
9.44	15.83	1.677
9.26	9.44	1.019
9.26	15.83	1.710
15.83	9.26	0.585
15.83	9.44	0.596

Table B4.2 Emergy to Money Ratio of the United States for 1997 and 2000

These numbers are different from those used in the West Virginia Report (Campbell *et al.* 2005a). These preliminary values are taken from a new study of the Emergy to Money Ratio for the United States from 1900 to 2004, which is a manuscript by Campbell and Lu to be published later this year.

Year	sej/$
1997	2.56E+12
2000	2.35E+12

Appendix C

Calculation of Energy and Economic Values Used to Determine the 1997 Energy and Emergy Accounts for Minnesota

C1 Notes for Table 4 – Annual Renewable Resources and Production in 1997.

The numbers in parentheses and italics refer to data sources given above. The notation E+3 = 10^3.

Note

Total Area (*24*)	2.25E+11	m^2
Land area	1.72E+11	m^2
Water Area *(25)*	1.55E+10	m^2
Area of inland water and wetlands	5.32E+10	m^2
Wetlands 2003	3.76E+10	m^2
Wetlands 1850	7.53E+10	m^2
Surface Waters	1.55E+10	m^2

1 **Solar Energy** **Received** **1.074E+21 J y^{-1}**
Absorbed **8.841E+20 J y^{-1}**

Solar energy received (J) = (avg. insolation)(area)(365 day/y)(4186 J/kcal)
Solar energy absorbed = (received) (1-albedo)
The average insolation and albedo were obtained from the NASA website *(26)* referenced in sources. Twenty-six, one-degree latitude by one-degree longitude, sectors covering the state were averaged.

	kWh/m2/y	J/m2/y
Solar energy received over the state	1324	4.77E+09
Solar energy absorbed by the state	1091	3.93E+09

2 **Kinetic Energy of Wind Used at the Surface** **1.2639+19 J y^{-1}**

Wind energy = (density)(drag coefficient)(geostrophic wind velocity)^3(area)(sec/year)

This formula is given in a manuscript by Odum (1999) titled "Evaluating Landscape Use of Wind Kinetic Energy".
The wind velocity used was taken from the National Renewable Energy Laboratory (NREL) web site *(59)*. The common drag coefficient over water is about 1.0E-3 for ordinary winds of 10 m/s or less (Miller 1964) 2.0E-3 over land and 3.0E-3 over low mountains Garratt (1977). Winds over land are about 0.6 of the wind velocity that the pressure system would generate in the absence of friction (Reiter 1969).

Area NREL Class #2 *(27)*

Air Density	1.3 kg m^{-3}
Geostrophic Wind	7.92 m/s
Drag Coefficient	2.00E-03 dimensionless
Area of Class	9.5490 E+10 m^2
Sec / Year	3.16E+07
Energy	3.89E+18 J/yr

Area NREL Class #3 *(27)*

Air Density	1.3 kg m^{-3}
Geostrophic Wind	8.92 m/s
Drag Coefficient	2.00E-03 dimensionless

Area	5.3927E+10 m^2
Sec/Year	3.16E+07
Energy	3.14E+18 J/yr

Area NREL Class #4 *(27)*

Air Density	1.3 kg m^{-3}
Geostrophic Wind	9.67 m/s
Drag Coefficient	2.00E-03 dimensionless
Area	7.5762E+10 m^2
Sec/Year	3.16E+07
Energy	5.61E+18 J/yr

3 **Earth Cycle Energy** **2.80E+17 J y^{-1}**

Earth cycle energy (steady-state uplift balanced by erosion) =
(land area)(heat flow/area)
The heat flow per area is an average of nine wells throughout the state *(28)*.

Area	2.252E+11 m^2
Heat flow/area	39.40 mW m^{-2}
	1.24E+06 J m^2 yr^{-1}

4 **Rain Chemical Potential** **7.07E+17 J y^{-1}**

Chemical potential energy in rain =
(area)(rainfall)(density water)(Gibbs Free Energy water relative to seawater)
Average annual rainfall based on a one hundred year average from the Western Regional Climate Center *(29)* and temperature of the growing season *(30)*.

Area	2.2518 E+11 m2
Rainfall	0.658 m/y
Gibbs Free Energy (Odum 1996)	4.77 J/g
Density	1.00E+06 g/m3

5 **Chemical Potential Energy of Evapotranspiration** **3.14E+17 J y^{-1}**

Chemical potential energy in evapotranspiration =
(Area in land use)(Evapotranspiration for that use)(Density)(Gibbs Free Energy per gram)
In general, forest evapotranspiration can be estimated as 0.85 times pan evaporation (Odum *et al.* (1998). Forest area data is from UM-Duluth *(31)* and forest evapotranspiration was estimated using Oak Ridge National Laboratory data from Walker Branch, TN *(32)*. Evapotranspiration rates for crops and pasture from Arnold and Williams (1985) and Ritter *et al.* (1985). The area of wetlands is from Net-State data *(33)* and wetland evapotranspiration was estimated using Hussey and Odum (1992) by using the average of peak beginning and end from their data, along with Water Resources data from the University of Arizona *(34)*.

Deciduous Forest Area	4.80E+10 m^2
Evapotranspiration	1.83E-01 m y^{-1}
	1.00E+06 g m^{-3}
	4.77 J g^{-1}

Energy	4.19E+16 J/y

Coniferous Forest Area	1.82E+10 m^2
Evapotranspiration	1.83E-01 m y^{-1}
Energy	1.59E+16 J y^{-1}

Crop Area	8.70E+10 m^2
Evapotranspiration	4.50E-01 m y^{-1}
Energy	1.87E+17 J y^{-1}

Wetlands Area	3.76E+10 m^2
Evapotranspiration	3.88E-01 m y^{-1}
Energy	6.97E+16 J y^{-1}

Total Area	1.91E+11 m^2
Urban & Barren Area (by difference)	3.43E+10 m^2

6 Geopotential Energy of Rain and Snow on Land

Rain	**4.58E+17 J y^{-1}**
Snow	**7.22E+16 J y^{-1}**

Geo-potential energy = (area)(mean elevation)(rainfall)(density)(gravity)
An area weighted average of rainfall *(35)* and elevation by county *(36)* was used to determine the geopotential energy of rain and snow on land. We assumed that on average snow is 7.5% water *(37)*. In the Table below the superscripts have the following meaning:

*: Estimated Elev.

^{T}: Estimated Precipitation and Snow. Averaged from the given values of the bordering counties.

Table C1.1. Data used to determine the geopotential energy of rainfall.

County	Area m^2	Elev. (m)	Precip. (m)	Snow (m)	Geopotential rain J y^{-1}	Geopotential snow J y^{-1}
Aitkin	5163064408	384.048	0.721360	1.2573	1.21E+16	1.96E+15
Anoka	1153730438	277.368	0.796290	1.397	2.15E+15	3.51E+14
Becker	3743560721	451.104	0.616204	1.03124	8.84E+15	1.37E+15
Beltrami	7911341260	387.096	0.735076	1.13284	1.94E+16	2.72E+15
Benton [*T]	1968803109	347.472	0.721868	1.17602	2.29E+15	3.43E+14
Big Stone	1368974637	329.184	0.612902	1.01346	2.35E+15	3.58E+14
Blue Earth [*T]	1981729403	231.648	0.769366	1.04394	3.09E+15	3.76E+14
Brown	1600944494	294.132	0.715772	1.09728	2.90E+15	4.06E+14
Carlton	2265235967	362.712	0.779018	1.3462	5.41E+15	8.68E+14
Carver	972997830	219.456	0.769874	1.12522	1.42E+15	1.89E+14
Cass	6248852173	408.432	0.663448	1.20396	1.42E+16	2.41E+15
Chippewa	1523188195	310.896	0.628396	1.143	2.49E+15	4.25E+14
Chisago	1145151102	277.368	0.802132	1.21666	2.20E+15	3.03E+14
Clay	2728649599	271.272	0.564642	0.97028	3.54E+15	5.64E+14
Clearwater	2666918850	454.152	0.6858	1.21158	7.00E+15	1.15E+15
Cook	4158606316	185.928	0.626618	1.25476	3.99E+15	7.61E+14
Cottonwood	1679591102	420.624	0.733552	1.10236	4.47E+15	6.11E+14
Crow Wing	2993787491	371.856	0.71374	1.14554	6.79E+15	1.00E+15
Dakota	1517453800	295.656	0.837438	1.14554	3.28E+15	4.03E+14
Dodge[*T]	1137712980	335.28	0.81407	1.17602	2.69E+15	3.52E+14
Douglas[*T]	1865204219	362.712	0.64897	1.02362	3.76E+15	5.43E+14
Faribault	1868101768	335.28	0.79502	1.05918	4.36E+15	5.21E+14
Fillmore	2231752286	329.184	0.864362	1.07188	5.61E+15	6.18E+14
Freeborn	1869481746	374.904	0.840994	1.0541	5.20E+15	5.80E+14
Goodhue	2018053986	256.032	0.844804	1.19634	3.80E+15	4.85E+14
Grant[*]	1491505356	298.704	0.591566	0.9525	2.25E+15	3.33E+14
Hennepin	1570580930	274.32	0.743204	1.2446	2.72E+15	4.21E+14
Houston	1472687474	381	0.8636	1.13538	4.25E+15	5.00E+14
Hubbard	2587993010	438.912	0.662686	1.22428	6.29E+15	1.09E+15
Isanti	1167821592	304.8	0.743204	0.9906	2.32E+15	2.77E+14
Itasca	7577079013	396.24	0.71501	1.1811	1.83E+16	2.78E+15
Jackson	1862581856	198.12	0.866902	0.92202	2.87E+15	2.67E+14
Kanabec	1380767177	301.752	0.723392	1.08712	2.60E+15	3.55E+14
Kandiyohi	2233225342	362.712	0.771398	1.29032	5.31E+15	8.20E+14
Kittson	2860888726	356.616	0.637286	1.13284	5.47E+15	9.07E+14
Koochiching	8162614622	371.856	0.664464	1.30048	1.67E+16	3.10E+15
Lac Qui Parle	2016645680	316.992	0.619252	1.02362	3.37E+15	5.14E+14
Lake	5922744342	402.336	0.757682	1.75006	1.44E+16	3.27E+15
Lake of the Woods	4609203544	329.184	0.568706	1.09474	7.16E+15	1.30E+15
Le Seuer[*]	1226270339	237.744	0.734314	0.86868	1.90E+15	1.99E+14
Lincoln	1421612099	533.4	0.658622	0.88138	4.37E+15	5.25E+14
Lyon	1869975463	377.952	0.660146	1.08966	3.97E+15	6.04E+14
McLeod	1308542930	326.136	0.699008	0.94996	2.61E+15	3.18E+14

County	Area m^2	Elev. (m)	Precip. (m)	Snow (m)	Geopotential rain J y^{-1}	Geopotential snow J y^{-1}
Marshall	4698630977	307.848	0.52959	1.00076	6.38E+15	1.14E+15
Martin	1888303675	362.712	0.796798	1.08966	4.77E+15	5.86E+14
Meeker	1669194728	277.368	0.747522	1.0287	3.02E+15	3.74E+14
Mille Lacs	1763207250	332.232	0.706374	1.05918	3.57E+15	4.87E+14
Morrison	2984896547	341.376	0.668274	1.27	5.66E+15	1.02E+15
Mower	1841457265	393.192	0.842772	1.11252	5.35E+15	6.32E+14
Murray	1864220833	509.016	0.694944	1.07442	5.67E+15	8.00E+14
Nicollet	1208112095	259.08	0.753618	0.75184	2.13E+15	1.85E+14
Nobles	1872245749	478.536	0.707898	1.01092	5.51E+15	7.11E+14
Norman	2271144960	268.224	0.55499	0.73914	2.96E+15	3.53E+14
Olmsted	1693241149	396.24	0.798322	1.30302	4.57E+15	6.86E+14
Otter Tail	5762399797	371.856	0.622808	1.20904	1.11E+16	2.03E+15
Pennington	1601025432	344.424	0.518414	0.91694	2.41E+15	3.97E+14
Pine	3711343697	316.992	0.791464	1.34366	7.89E+15	1.24E+15
Pipeston	1208059486	521.208	0.657098	0.86106	3.63E+15	4.25E+14
Polk	5177770684	335.28	0.579628	1.00838	8.50E+15	1.37E+15
Pope	1857126693	365.76	0.629666	0.93218	3.70E+15	4.97E+14
Ramsey	440018746	280.416	0.825754	1.32842	8.71E+14	1.29E+14
Red Lake	1121525555	316.992	0.580644	1.23444	1.68E+15	3.44E+14
Redwood	2283127128	329.184	0.683514	0.98298	4.46E+15	5.80E+14
Renville	2556520608	326.136	0.700278	1.10236	5.01E+15	7.21E+14
Rice	1334689670	286.512	0.80391	1.07442	2.69E+15	3.22E+14
Rock	1251081616	457.2	0.706628	1.11252	3.47E+15	4.99E+14
Roseau	4346870123	323.088	0.546354	0.92456	6.51E+15	1.02E+15
St. Louis	17450352454	432.816	0.736092	1.62814	4.49E+16	9.65E+15
Scott	953063015	283.464	0.741172	0.63246	1.83E+15	1.34E+14
Sherburne	1166340443	301.752	0.744982	1.15062	2.25E+15	3.18E+14
Sibley	1554551332	310.896	0.739394	1.016	3.12E+15	3.85E+14
Stearns	3598254294	371.856	0.719582	1.17856	8.21E+15	1.24E+15
Steele	1119117675	350.52	0.80391	1.04394	2.77E+15	3.21E+14
Stevens	1490663610	347.472	0.646938	1.2065	2.80E+15	4.90E+14
Swift	1948314509	316.992	0.70739	1.0541	3.77E+15	5.11E+14
Todd	2536083983	393.192	0.747776	1.30302	6.30E+15	1.02E+15
Traverse	1518712372	307.848	0.572516	1.05664	2.24E+15	3.88E+14
Wabasha	1421956082	252.984	0.849884	0.96266	2.73E+15	2.72E+14
Wadena	1406695386	411.48	0.67183	1.22682	3.26E+15	5.57E+14
Waseca	1120615012	350.52	0.878332	1.39446	2.95E+15	4.30E+14
Washington	1095245269	216.408	0.809244	1.02362	1.69E+15	1.90E+14
Watonwan	1138170275	329.184	0.704342	1.06172	2.28E+15	3.12E+14
Wilkin*	1947254233	234.696	0.544322	1.016	2.08E+15	3.64E+14
Winona	1660409003	201.168	0.837438	0.90424	2.51E+15	2.37E+14
Wright	1849874727	304.8	0.72009	0.94742	3.56E+15	4.19E+14
Yellow Medicine	1977544953	377.952	0.65278	1.06426	4.16E+15	6.24E+14
Total	2.1849E+11	29445.204	61.849254	96.35236	**4.58E+17**	**7.22E+16**

7 Geopotential of Runoff

Total	**7.21E+16 J y^{-1}**
Rain	**2.55E+16 J y^{-1}**
Snow	**4.67E+16 J y^{-1}**

Geopotential energy of runoff (physical energy of streams) = (area)(mean elevation)(runoff)(density)(gravity)
The annual runoff is a 100 year average. Drainage basin *(38)* and runoff data (*39)* were obtained on-line from the United States Geological Survey and the State of Minnesota.
Assume 8% sublimation (Essery *et al.* 2003) for snow and that all snow melt runs off; thus 65% of runoff is from snow melt.

Watershed		
(Scanlon, MN)	Area*	1.61E+10 m^2
	Elevation	335.6 m
(St. Louis River)	Runoff	0.242316 m y^{-1}
	Density	1000 kg m^{-3}
	Gravity	9.81 m s^{-2}
	Energy	1.28E+16 J y^{-1}

* Assumed to be the whole Lake Superior Drainage Basin

(Crookston, MN)	Area	9.61E+10 m^2
(Red Lake River)	Elevation	254 m
	Runoff	0.078232 m y^{-1}
	Density	1000 kg m^{-3}
	Gravity	9.81 m s^{-2}
	Energy	1.87E+16 J y^{-1}
(Manitou Rapids, MN)	Area	2.91E+10 m^2
(Rainy River)	Elevation	324 m
	Runoff	0.231 m y^{-1}
	Density	1000 kg m^{-3}
	Gravity	9.81 m s^{-2}
	Energy	2.14E+16 J y^{-1}
St. Paul, MN	Area	m^2
(**Mississippi River**)	Elevation	208.4 m
	Runoff	0.112 m y^{-1}
	Density	1000 kg m^{-3}
	Gravity	9.81 m s^{-2}
	Energy	1.92E+16 J y^{-1}

8 Wave Energy (Lake Superior) **1.55E+16 J y^{-1}**

Assuming deep water waves and data from an offshore buoy *(40)*. Calculation method from Pierson *et al.* (1958).

Length of Coastline *(41)*	3.30E+05 m
Density	1.00E+03 kg m^{-3}

Gravity	9.81 m s^{-2}
Average Wave Height*	0.57 m
Period, T_{max}	4.8 s
Wave length	35.95 m
Phase speed	7.49 m s^{-1}
Group speed	3.74 m s^{-1}

9 River Chemical Potential

Absorbed	**6.44E+12 J y^{-1}**
Received	**9.15E+15 J y^{-1}**

River chemical potential energy received = (volume flow)(density)(Gibbs free energy relative to seawater)
River chemical potential energy absorbed = (volume flow)(density) (Gibbs free energy solutes at river entry - Gibbs free energy solutes at river egress)

The St. Croix River begins outside state boundaries and flows along the border with Wisconsin delivering part of the chemical potential energy that it carries to the state.
Total Dissolved solids concentration from the USGS data *(42).*
Gibbs Free Energy, G = RT/w ln(C2/C1) = [(8.3143 J/mol/deg)(288 °K)/(18 g/mol H_2O)] * ln [(1E6 - S)ppm)/965000]

St. Croix*

Volume flow	3.87E+09 m^3y^{-1}
Density	1000000 g m^{-3}
Solutes in	106 ppm
Solutes out	131 ppm
G in	4.73 J g^{-1}
G out	4.72 J g^{-1}
Absorbed	1.29E+13 J y^{-1}
Received	1.83E+16 J y^{-1}

*The river flows along the border the state, so the energy was distributed equally between the states on opposite sides of the river.

10 River Geopotential

Absorbed	**1.51E+15 J y^{-1}**
Received	**5.09E+15 J y^{-1}**

Geopotential energy = (flow vol.)(density)(height entry - height egress)(gravity)
Data on water flow and height of the gauge are from USGS Water Resources Data *(42, 43, and 44).*

St. Croix River*	Vol. Flow	3.86E+09 m^3/yr
	Density	1000 kg/m^3
	Height In (Height at Danbury, MN)	268.8 m
	Height Out (Height at Reno, MN)	189.3 m
	Gravity	9.81 m/s^2
	Absorbed	3.01E+15 J/y
	Received	1.02E+16 J/y

*If the river borders the state half the calculated energy was used

11 **Nitrogen (Atmospheric Deposition)** **2.00E+11 g y^{-1}**
Deposition is a 5 year average (77% NH4 and 23% NO_x). **1.36E+15 J y^{-1}**

Area	2.25E+11 m2
Rate *(45)*	8.8636 kg ha^{-1} y^{-1}
Conversion	10000 m^2 ha^{-1}
Total Deposition	2.00E+08 kg y^{-1}
Energy per gram	6789.5 J g^{-1} (Weast, 1981)
Energy	1.36E+15 J y^{-1}

12 **Sulfur (Atmospheric Deposition)** **5.26E+10 g y^{-1}**
Deposition is a 5 year average. **3.91E+14 J y^{-1}**

Area	2.25E+11 J y
Rate *(45)*	2.33547 kg ha^{-1} y^{-1}
Conversion	10000 m^2 ha^{-1}
Total Deposition	5.26E+07 kg y^{-1}
Energy per gram	7429.06 J g^{-1} (Weast, 1981)
Energy	3.91E+14 J y^{-1}

13 **Chlorine, Cl^- (Atmospheric Deposition)** **8.81E+09 g y^{-1}**
Deposition is a 5 year average. **3.26E+13 J y^{-1}**

Area	2.25E+11 m^2
Rate *(45)*	0.3913 kg ha^{-1} y^{-1}
Conversion	10000 m^2 ha^{-1}
Total Deposition	8.81E+06 kg y^{-1}
Energy per gram	3700 J g^{-1} (Weast, 1981)
Energy	3.26E+13 J y^{-1}

14 **Agricultural Products** **6.99E+17 J y^{-1}**

(amount sold)(energy/unit)
From the 1997 Census of Agriculture. See Appendix B for energy per unit values except as noted.

Hay	Mass (dry) *(46)*	4.57E+12 g y^{-1}
	Energy/unit	18901 J g^{-1}
	Energy	8.63E+16 J y^{-1}
Oats	Production *(46)*	1.62E+07 bu y^{-1}
	Conversion *(47)*	14515 g bu^{-1}
	Mass	2.35E+11 g y^{-1}
	Energy/unit	16280 J g^{-1}
	Energy	3.82E+15 J y^{-1}
Corn	Production *(46)*	7.84E+08 bu y^{-1}
	Conversion *(47)*	25401 g bu^{-1}
	Mass	1.99079E+13 g y^{-1}
	Energy/unit	19736 J g^{-1}
	Energy	3.93E+17 J y^{-1}

Soybeans	Production *(46)*	2.34E+08 bu y^{-1}
	Conversion *(47)*	27216 g bu^{-1}
	Mass	6.36E+12 g y^{-1}
	Energy/unit	17410 J g^{-1}
	Energy	1.11E+17 J y^{-1}
Wheat	Production *(46)*	1.49E+08 bu y^{-1}
	Conversion (*47)*	27216 g bu^{-1}
	Mass	4.06E+12 g y^{-1}
	Energy/unit *(48)*	14230 J g^{-1}
	Energy	5.77E+16 J y^{-1}
Barley	Production *(46)*	2.19E+07 bu y^{-1}
	Conversion (*47)*	21772 g bu^{-1}
	Mass	4.77E+11 g y^{-1}
	Energy/unit *(48)*	14810 J g^{-1}
	Energy	7.07E+15 J y^{-1}
Sunflower	Production *(46)*	1.06E+08 lb.y^{-1}
	Conversion factor	454 g lb. $^{-1}$
	Mass	4.83E+10 g y^{-1}
	Energy/unit *(48)*	23850 J g^{-1}
	Energy	1.15E+15 J y^{-1}
Wool	Production *(49)*	9.47E+05 lb. y^{-1}
	Conversion factor	454 g lb.$^{-1}$
	Mass	4.29E+08 g y^{-1}
	Energy/unit Odum *et al.* (1987)	20934 J g^{-1}
	Energy	8.99E+12 J y^{-1}
Honey	Production *(49)*	9.31E+06 lb. y^{-1}
	Conversion factor	454 g lb. $^{-1}$
	Mass	4.22E+09 g y^{-1}
	Energy/unit *(48)*	12720 J g^{-1}
	Energy	5.37E+13 J y^{-1}
Goat's Milk	Production *(49)*	1.37E+05 gal y^{-1}
	Conversion factor	3904 g gal. $^{-1}$
	Mass	5.33E+08 g y^{-1}
	Energy/unit *(48)*	2880 J g^{-1}
	Energy	1.54E+12 J y^{-1}
Flaxseed	Production *(46)*	8.17E+04 bu y^{-1}
	Conversion factor	25401 g bu^{-1}
	Mass	2.07E+09 g y^{-1}
	Energy/unit *(48)*	20590 J g^{-1}
	Energy	4.27E+13 J y^{-1}

Potatoes	Production *(46)*	1.89E+07 cwt y^{-1}
	Conversion factor	45359 g cwt^{-1}
	Mass	8.55E+11 g y^{-1}
	Energy/unit *(48)*	2990 J g^{-1}
	Energy	2.56E+15 J y^{-1}
Sugar Beets	Production *(46)*	8.27E+06 tons y^{-1}
	Conversion factor	907185 g ton^{-1}
	Mass	7.50E+12 g y^{-1}
	Energy/unit *(50)*	3390 J g^{-1}
	Energy	2.54E+16 J y^{-1}
Milk	Production *(50)*	4.75E+06 tons y^{-1}
	Conversion factor	907185 g ton^{-1}
	Mass	4.31E+12 g y^{-1}
	Energy/unit *(48)*	2680 J g^{-1}
	Energy	1.15E+16 J y^{--1}
Eggs	Number *(49)*	3.27E+09 # y^{-1}
	Energy/unit	2010 J g^{-1}
	Energy (50g per egg)	3.29E+14 J y^{-1}

15 **Livestock** **3.49E+16 J y^{-1}**

(annual production mass)(energy/mass)

The amount sold is taken from the 1997 Census of Agriculture *(49)*.

Turkeys	# sold *(49)*	4.72E+07	
	wt (Live) *(51)*	11063 g $animal^{-1}$	
	Energy /unit *(48)*	8200 J g^{-1}	All classes, meat and skin
	Energy	4.28E+15 J y^{-1}	
Cows	# sold *(49)*	8.25E+05	
	wt (Live) *(51)*	625050 g $animal^{-1}$	
	Energy /unit *(48)*	12225 J g^{-1}	Choice carcass
	Energy	6.31E+15 J y^{-1}	
Hogs/Pigs	# sold *(49)*	1.29E+07	
	wt (Live) *(51)*	118388 g $animal^{-1}$	
	Energy /unit *(48)*	15742 J g^{-1}	Fresh carcass
	Energy	2.41E+16 J y^{-1}	
Sheep/Lambs	# sold *(49)*	1.65E+05	
	wt (Live) *(52)*	48081 g $animal^{-1}$	
	Energy /unit *(48)*	27820 J g^{-1}	Raw leg, shoulder, arm
	Energy	2.20E+14 J y^{-1}	

16 **Fish Production** **1.32E+11 J y^{-1}**

(mass)(energy/mass)

Trout, from the 1997 Census of Agriculture.

Mass *(49)*	47,000 lbs.y^{-1}
	453.59 g lb^{-1}
Energy/mass *(48)*	6,190 J g^{-1}

17 **Hydroelectricity (1999)** **4.10E+15 J y^{-1}**

E.I.A. *(53)*	1,034,697,000 kWh y^{-1}	3.72E+15 J y^{-1}
Other Renewable (Wind)	1,174,570,000 kWh y^{-1}	4.23E+15 J y^{-1}
Total Renewable Electricity	2,209,267,000 kWh y^{-1}	7.95E+15 J y^{-1}

18 **Net Timber Growth (1990)** **1.28E+17 J y^{-1}**

See Haugen and Mielke (2002) and web references below.
(vol. forest growth)(density)(G)
G (no moisture, *(54)*)=20086 J g^{-1}

Forest Growth *(55)*	4.51E+08 ft^{3}
	1.28E+13 cm^{3}
Green wt.	1 g cm^{-3}
Forest growth	1.28E+13 g y^{-1}
G at 50% moisture	10043 J g^{-1}

19 **Timber Harvest (1997)** **6.47E+16 J y^{-1}**

Reading and Krantz (2002) give data on harvest and waste.
(vol forest growth)(density)(organic fraction)(G)
G=(4.2 kcal g^{-1})(4186 J kcal^{-1})

Forest Harvest	2.85E+08 ft^{3}
	8.06E+12 cm^{3}
Dry wt.	0.5 g cm^{-3}
Forest mass	4.03E+12 g y^{-1}
Energy (20% moisture)	16069 J g^{-1}
Waste	1.42E+08 ft^{3}

20 **Groundwater Chemical Potential Energy** **4.61E+15 J y^{-1}**

(vol.)(density)(Gibbs free energy)
Based on the volume of ground water withdrawn in 1995 *(56)*.
G = RT/w ln(C2/C1) = [(8.3143 J/mol/deg)(288 K)/(18 g/mol)] * ln [(1E6 - S)ppm)/965000]
Concentration taken as an average of all groundwater quality data given for the year 2000.

Volume used *(56)*	9.87E+08 m^{3} y^{-1}
Density	1000000 g m^{-3}
Solute conc. *(57)*	510 ppm
G	4.67 J g^{-1}

21 **Solid Waste Production (1997)** **4.55E+12 g y^{-1}**

From the Minnesota Pollution Control Agency *(58)*.

5,019,980 short tons y^{-1}
907185 g ton^{-1}
4.55E+12 g y^{-1}

C2 Notes for Table 5 – Annual Production and Use of Nonrenewable Resources in 1997.

Note

Coal, natural gas and oil are not produced in commercial quantities in the state.

22 **Coal Used in the State *(59)*** **5.09E+17 J y^{-1}**

Amount 1.91E+07 short tons y^{-1}
9.07E+05 g ton^{-1}
2.94E+04 J g^{-1}

23 **Natural Gas Used in the State *(60)*** **3.89E+17 J y^{-1}**

Amount 3.54E+08 1000 ft^{3}
1.1E+09 J 1000 ft^{-3}

24 **Petroleum Used in the State *(61)*** **7.4E+17 J y^{-1}**
Amount 1.17E+08 Barrels

25 **Electricity Produced** (w/o hydroelectric and wind) **1.5E+17 J y^{-1}**
Energy Information Administration *(62)*.
Amount 4.103E+10 kWh

26 **Electricity Used in the State** **2.0E+17 J y^{-1}**
Energy Information Administration *(63)*
Amount **6.017E+10 kWh**

27 **Nuclear Electricity Produced in the State** **3.89E+16 J y^{-1}**
Energy Information Administration *(64)*
Amount 1.082E+10 kWh

Mineral Production
Taken from the preliminary estimates of production found in the US Geological Survey Minerals Yearbook – 2000 *(65)*. Energy per mass from Odum (1996) except dolomite (Rock et al 2001)).

28	**Iron**		4.79E+07 MT	**4.79E+13 g y^{-1}**
		Energy/Mass	14.2 J g^{-1}	**6.80E+14 J y^{-1}**
29	**Sand and Gravel**		3.45E+07 MT	**3.45E+13 g y^{-1}**
		Energy/Mass	6.11E+02 J g^{-1}	**2.11E+16 J y^{-1}**
30	**Limestone**		7.35E+06 MT	**7.35E+12 g y^{-1}**
		Energy/Mass	50 J g^{-1}	**3.68E+14 J y^{-1}**
31	**Dolomite**		3.08E+06 MT	**3.08E+12 g y^{-1}**
		Energy/Mass	5.00E+01 J g^{-1}	**1.54E+14 J y^{-1}**
32	**Peat**		2.90E+04 MT	**2.90E+10 g y^{-1}**
		Energy/Mass	2.15E+04 J g^{-1}	**6.24E+14 J y^{-1}**

33 **Soil Erosion** Total **9.79E+16 J/y**
Agricultural lands 9.73E+16 J/y
(farmed area)(erosion rate)(organic fraction)(energy)

The farmed area was taken from the 1997 census of Agriculture *(49)*.
The organic fraction was taken from Odum (1996). Erosion rates from wind and water (*66)* and *(67)* for cropland and pasture. Energy per gram of soil Campbell (1998).
Erosion rate for forests was from personal communication of one of us (Ohrt) with personnel of the National Resources Conservation Service (WEPP, 2002).

Cropland	Area *(49)*	2.15E+07 acres
	Erosion rate	7.3 tons acre^{-1} y^{-1}
	Erosion	1.57E+08 ton y^{-1}
	Organic fraction	0.03
		9.07E+05 g ton^{-1}
		22604 J g^{-1}
	Energy	9.65E+16 J y^{-1}
Pastureland	Area *(68)*	3.43E+06 acres
	Erosion rate	0.4 tons acre^{-1} y^{-1}
	Erosion	1.37E+06 ton y^{-1}
	Organic fraction	0.03
		9.07E+05 g ton^{-1}
		22604 J g^{-1}
	Energy	8.45E+14 J y^{-1}
Forest Land	Area *(69)*	1.65E+07 acres
	Erosion rate	0.05 tons acre^{-1} y^{-1}
	Erosion	8.25E+05 ton y^{-1}
	Organic fraction	0.03
		9.07E+05 g ton^{-1}
		22604 J g^{-1}
	Energy	5.08E+14 J y^{-1}

C3. Notes for Table 6 Imports to the Minnesota economy in 1997

34 **Tourism** **7.20E+09 $**
Estimate for 1997 provided by the Minnesota Department of Trade and Economic Development *(70)*.

35 **Electricity Imported**
Use - Production **4.48E+16 J y^{-1}**
12,433,998,000 kWh

36 **Uranium Imported in 2000** 60000000 $
2000 price Average *(71)* 0.0204 $/g **2.94E+09 g y^{-1}**
2.94E+09 g

37 **Coal** **5.09E+14 J y^{-1}**
Energy Information Association

Short tons/yr *(59)*	1.91E+04
g/short ton	9.07E+05
J/g	2.94E+04

38 **Petroleum** **7.45E+17 J y^{-1}**
Value is the difference between the production and consumption within the state.

39 **Natural Gas** **3.89E+17 J y^{-1}**
The difference between the production and consumption within the state *(60)*.

40 **Imported Minerals** **1.06E+22 sej y^{-1}**
Data from The 1997 Commodity Flow Survey *(2)*.

41 **Goods (Materials minus Fuels and Minerals)** **3.92E+13 g y^{-1}**
1997 Commodity Flow Survey of Minnesota (Table C3.1) **2.75E+23 sej y^{-1}**

42 **Goods (Services) w/o fuels and minerals (Table C3.1)** **6.63E+10 \$ y^{-1}**

42 **Emergy of Services in all Imported Goods** **1.84E+23 sej y^{-1}**

Estimated from data on shipments in the 1997 Commodity Flow Survey, US. Census Bureau *(2)*. This number includes fuels and minerals, but not electricity.

	Units
Total In Bound Shipments	1.31E+11 \$ y^{-1}
Shipments Of Minnesota Origin	5.94E+10 \$ y^{-1}
Dollar Value Of Imported Goods	7.19E+10 \$ y^{-1}
Emergy To Money Ratio For The US In 1997	2.56E+12 sej $\$^{-1}$
Emergy In The Services Required For Imported Goods	1.84E+23 sej y^{-1}

43 **Fuels Services (Table 3.6.1)** **5.51E+09 \$ y^{-1}**

44 **Minerals Services (2)** **6.60E+10 \$ y^{-1}**

45 **Electricity Services (Table 3.6.1)** **6.22E+08 \$ y^{-1}**

46 **Pure Services** **1.62E+10 \$ y^{-1}**
Base-Nonbase Analysis using data from the U.S. Census Bureau's 1997 Economic Census *(72)*.(See Table C3.2)

47 **Immigration (1997)** 8223 Ind.
Assume that the skill level of immigrants to Minnesota is similar to the skill levels entering the U.S. in 1997 *(73)*. **1.13E+21 sej y^{-1}**

48 **Federal Government** **1.98E+10 \$**
Total Outlay in 1997 *(74)*.

Table C2.1 Detailed Account of the Emergy Imported in Material Inflows.
This table contains detailed data for note 41 above *(2)*.

SCTG Code	Commodity Class	J or g y^{-1}	Emergy per unit	Units	Emergy sej y^{-1}
1	Live animals and live fish.	6.72E+14	4.39E+05	sej/J	2.95E+20
2	Cereal grains	1.50E+17	1.82E+05	sej/J	2.72E+22
3	Other agricultural product	7.91E+15	2.33E+05	sej/J	1.87E+21
4	Animal feed and products of animal origin	2.68E+16	1.22E+06	sej/J	3.26E+22
5	Meat, fish, seafood, and their preparations	6.30E+15	3.27E+06	sej/J	2.06E+22
6	Milled grain products and preparations	9.46E+15	1.82E+05	sej/J	1.72E+21
7	Other prepared foodstuffs , fats and oils	5.98E+16	1.12E+06	sej/J	6.71E+22
8	Alcoholic beverages	1.24E+16	5.89E+04	sej/J	7.56E+20
9	Tobacco products	1.31E+14	6.50E+05	sej/J	1.09E+20
10	Monumental or building stone	2.05E+10	9.81E+08	sej/g	2.01E+19
11	Natural sands	1.51E+12	1.96E+09	sej/g	2.96E+21
12	Gravel and crushed stone	7.09E+12	4.91E+08	sej/g	3.48E+21
13	Nonmetallic minerals	1.70E+12	1.96E+09	sej/g	3.34E+21
14	Metallic ores and concentrates	2.94E+11	2.71E+09	sej/g	8.07E+20
15	Coal	4.79E+17	3.92E+04	sej/J	1.88E+22
17	Gasoline and aviation turbine fuel	1.17E+17	6.47E+04	sej/J	7.58E+21
18	Fuel oils	7.47E+16	6.47E+04	sej/J	8.19E+21
19	Coal and petroleum products	1.28E+17	6.47E+04	sej/J	8.32E+21
20	Basic chemicals	9.90E+11	2.75E+09	sej/g	3.74E+21
21	Pharmaceutical products	5.19E+10	2.75E+09	sej/g	1.43E+20
22	Fertilizers	7.31E+11	2.99E+09	sej/g	2.19E+21
23	Chemical products and preparations	7.61E+11	9.90E+09	sej/g	7.54E+21
24	Plastics and rubber	1.09E+12	2.71E+09	sej/g	3.09E+21
25	Logs and other wood in the rough	1.09E+15	1.96E+04	sej/J	2.15E+19
26	Wood products	1.47E+12	1.49E+09	sej/g	3.99E+21
27	Pulp, newsprint, paper, and paperboard	2.67E+16	1.40E+05	sej/J	3.75E+21
28	Paper or paperboard articles	4.98E+15	1.67E+05	sej/J	2.37E+21
29	Printed products	5.75E+11	4.95E+09	sej/g	2.85E+21
30	Textiles, leather, and articles	2.35E+15	7.18E+06	sej/J	1.73E+22
31	Nonmetallic mineral products	4.11E+12	3.09E+09	sej/g	1.29E+22
32	Base metal in primary or semi-finished form	2.17E+12	5.91E+09	sej/g	1.32E+22
33	Articles of base metal	8.79E+11	5.91E+09	sej/g	5.35E+21
34	Machinery	5.01E+11	7.76E+09	sej/g	7.99E+21
35	Electronic and other electrical equipment	4.20E+11	7.76E+09	sej/g	6.87E+21
36	Motorized and other vehicles	8.27E+11	7.76E+09	sej/g	1.22E+22
37	Transportation equipment	3.14E+10	7.76E+09	sej/g	1.09E+21
38	Precision instruments and apparatus	1.55E+10	7.76E+09	sej/g	2.28E+20
39	Furniture, mattresses, lamps, lighting	1.64E+11	2.89E+09	sej/g	5.27E+20
40	Miscellaneous manufactured products	5.26E+11	1.61E+09	sej/g	1.37E+21
41	Waste and scrap	8.17E+11	2.16E+09	sej/g	1.78E+21
43	Mixed freight	4.05E+11	6.32E+09	sej/g	2.56E+21
0	Commodity unknown	1.80E+11	4.26E+09	sej/g	1.31E+21
	Total			sej/y	3.20E+23
	Total without fuels and minerals			sej/y	2.75E+23

Table C2.2 Export and Import of Services Between Minnesota and the Nation

The emergy of imported and exported services was determined using a variation of the base-nonbase method from economic analysis. Data on employment and revenues for economic sectors classified using the North American Industry Classification System (NAICS) for MN and the U.S. *(75)* were used to estimate the services exported and imported from the state. The formulae in the text are evaluated using data in the table below. The rows in the table below are (1) U.S. employment by sector, (2) Minnesota employment by sector, (3) the fraction of total U.S. employment in each sector, (4) the fraction of total state employment in each sector. Row (5) and (6) give the money received per paid employee in the nation and state, respectively. Row (7) is the location quotient, *i.e.*, row 4 divided by row 3, while (8) is the number of employees, S_i, in each state sector (row 2) divided by the number of employees, N_i, (row 1) in the corresponding national sector. Row (9) is the sum of state employees in all sectors divided by sum of employees in all sectors of the national economy. Row (10) calculates basic sector jobs as the difference between rows (8) and (9) times the U.S. employment in each sector, and (11) estimates the dollar value of potential exports by multiplying the state dollars generated per employee by the number of basic employees (row 10) that could be making products or services for export. We extend this calculation to potential imports by multiplying any deficient in employment in row 10 by the dollars generated per employee in that sector of the national economy.

	Economic Sectors								
Parameters	Agricult.	Mining	Utilities	Construct.	Manufact.	Wholesale	Retail trade	Transport.	Informat.
U.S. Employees	3085992	509006	702703	5664840	16888016	5796557	13991103	2920777	3066167
MN Employees	101593	7154	13205	103200	382530	131787	282413	53811	58855
US (sector /total)	0.0249	0.0041	0.0057	0.0457	0.1362	0.0468	0.1128	0.0236	0.0247
MN (sector/total)	0.0414	0.0029	0.0054	0.0420	0.1558	0.0537	0.1150	0.0219	0.0240
$/employee US	63793	341840	585899	151563	227502	700357	175889	108959	203255
$/employee MN	81603	243130	336321	179574	199317	754585	170311	1052356	164138
Location Quotient	1.6621	0.7096	0.9487	0.9198	1.1436	1.1478	1.0191	0.9301	0.9691
$(S_i) \div (N_i)$	0.0329	0.0141	0.0188	0.0182	0.0227	0.0227	0.0202	0.0184	0.0192
$(S_t) \div (N_t)$	0.0231	0.0231	0.0231	0.0231	0.0231	0.0231	0.0231	0.0231	0.0231
Basic jobs (B)	30246	-4614	-3041	-27769	-7914	-2227	-41056	-13716	-12034
Potential Imp./Exp.	2.47E+09	-1.58E+09	-1.78E+09	-4.21E+09	-1.58E+09	-1.68E+09	-6.99E+09	-1.49E+09	-2.45E+09
Exp(+) or imp(-) $[#]	0.00E+00	-1.35E+09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.22E+09
Services in Sector	All goods	Imported	Local	Local	All goods	Local	Local	Local	Imported
Assumed type	Basic	Basic	Nonbasic	Nonbasic	Basic	Nonbasic	Nonbasic	Nonbasic	Basic

[#] We assume that only basic sectors can export. Some of the potential export and import sectors summed here are only part service at this level of sector aggregation. Subtracting the dollar value of the goods exported in the sector from total estimated exports may give a better estimate of the services exported. An alternate method considers higher resolution sector data where more detailed sectors can be identified as primarily service. Considering higher resolution data the fraction of potential service imports was estimated, but a full analysis using this method was not used here.

Economic Sectors continued:

	Finance& Insurance	Real Estate/ Rental	Profession. Scientific	Managem.	Admin. Support	Education Services	HealthCare Social Ser.	Arts& Entertain.	Accomo. & Food
U.S. Employees	5835214	1702420	5361210	2617527	7347366	321073	13561579	1587660	9451226
MN Employees	65996	30172	97818	86754	133839	6064	298312	37343	179487
US (sector /total)	0.0471	0.0137	0.0432	0.0211	0.0593	0.0026	0.1094	0.0128	0.0762
MN (sector/total)	0.0269	0.0123	0.0398	0.0353	0.0545	0.0025	0.1215	0.0152	0.0731
$/employee US	376639	141515	111029	35328	40278	63659	65262	65956	37074
$/employee MN	262568	128809	108001	49107	39132	63249	56416	52030	33062
Location Quotient	0.5710	0.8948	0.9212	1.6733	0.9197	0.9535	1.1106	1.1875	0.9588
$(S_i) \div (N_i)$	0.0113	0.0177	0.0182	0.0331	0.0182	0.0189	0.0220	0.0235	0.0190
$(S_t) \div (N_t)$	0.0231	0.0231	0.0231	0.0231	0.0231	0.0231	0.0231	0.0231	0.0231
Basic jobs (B)	-10081	-9187	-26131	26238	-36006	-1359	-15226	637	-39022
Potential Imp./Exp.	-1.40E+09	-1.30E+09	-2.90E+09	1.29E+09	-1.45E+09	-8.65E+07	-8.59E+08	3.31E+07	-1.45E+09
Exp(+) imp(-) $$^{\#}$	-7.00E+08	0.00E+00	-1.45E+09	1.29E+09	0.00E+00	-4.33E+07	0.00E+00	3.31E+07	0.00E+00
Services in Sector	Imported	Local	Imported	Exported	Local	Imported	Local	Exported	Local
Assumptions	Basic	Nonbasic	Basic	Basic	Nonbasic	Basic	Nonbasic	Basic	Nonbasic

***Economic Sectors continued*:**

	Other Ser.	Auxiliary	Govern.
U.S. Employees	3256178	792370	19521000
MN Employees	77235	13734	294388
US (sector /total)	0.0263	0.0064	0.1576
MN (sector/total)	0.0315	0.0056	0.1199
$/employee US	81659	14231	42453
$/employee MN	71947	4650	26899
Location Quotient	1.0194	0.7449	5.1086
$(S_i) \div (N_i)$	0.0237	0.0173	0.1189
$(S_t) \div (N_t)$	0.0231	0.0231	0.0231
Basic jobs (B)	1953	-4585	194895
Potential Imp./Exp.	1.41E+08	-6.53E+07	8.27E+09
Exp(+) imp(-) $$^{\#}$	3.51E+07	-1.63E+07	0.00E+00
Services in Sector	Local	Imported	Local
Assumptions	Nonbasic	Nonbasic	Nonbasic

Total Employment U.S	107,274,984
Total Employment Minnesota	2,480,156

Table C2.3 Determination of Imported and Exported Services

Potential for Importing ($)	8.39E+09	Multiply deficit employment times U.S. worker productivity in sectors assumed to be capable of importing services and sum over the sectors.
Estimate of Imported Ser. ($)	4.22E+09	Use detailed NAICS categories; determine a fraction of potential imports that is non local service. Assume MN imports everything that they need
Estimate of Exported Ser ($)	1.36E+09	The sum of basic exporting sectors in Table C3.2 above.

Emergy exported services (sej y^{-1})	3.47E+21	Multiply the exports in dollars by the emergy to dollar ratio of the U.S. in 1997 to estimate the emergy exported
Emergy imported services (sej y^{-1})	1.08E+22	Multiply the dollar value of the imported services times the emergy to dollar ratio of the U.S. in 1997.

C4. Notes for Table 7 - Exports from the Minnesota Economy in 1997.

49 **Materials in Goods Exported Minus Fuels and Taconite** **3.85E+23 sej y^{-1}**

Data from Commodity Flow Survey of Minnesota *(2)*.See Table C4.1 for totals.

50 **Taconite Exported *(2)*** **3.58E+13 g**

Total Shipments	4.30E+13 g
Instate Shipments	7.25E+12 g
Exported	3.58E+13 g

51 **Services in Goods Exported.**

Data on shipments from the 1997 Commodity Flow Survey *(2)*.

	Units
Emergy to dollar ratio for the US in 1997	2.56E+12 sej/$
Dollar value of shipments to all destinations	1.55E+11 $/y
Dollar value final destinations in MN	5.94E+10 $/y
Dollar value of exported goods w/o iron	9.46E+10 $/y
Emergy exported in services in goods w/o iron	**2.42E+23 sej y^{-1}**
Value of exported metallic ores	
Total value shipments *(2)*	1.44E+09 $
Fraction leaving the state	0.83
Dollar value metallic mineral exports	1.20E+09 $/y
Emergy in services associated with iron export	**3.06E+21 sej y^{-1}**
Total value of services in exported goods	**2.45E+23 sej y^{-1}**

Table C3.1 Emergy in the materials exported from Minnesota. Data on material shipments from Minnesota to all states by commodity is from The U.S. Census Bureau's 1997 Commodity Flow Survey *(2)*, Additional State Data, Table 12. In some cases in Table C4.1 shipment weight was converted to energy. See Appendix B for the calculation of average emergy per unit for the commodity classes and a table giving the mass to energy conversions for the commodity class.

SCTG Code	Commodity Class	J or g	Emergy per unit	Units	Emergy sej y^{-1}
1	Live animals and live fish.	0	4.393E+05	sej J^{-1}	0
2	Cereal grains.	2.55E+17	1.818E+05	sej J^{-1}	4.63E+22
3	Other agricultural product.	4.61E+16	2.334E+05	sej J^{-1}	1.08E+22
4	Animal feed and products of animal origin.	2.26E+16	1.217E+06	sej J^{-1}	2.75E+22
5	Meat, fish, seafood, and their preparations.	1.10E+16	3.270E+06	sej J^{-1}	3.61E+22
6	Milled grain products and preparations.	2.62E+16	1.818E+05	sej J^{-1}	4.76E+21
7	Other prepared foodstuffs and fats and oils.	1.05E+17	1.120E+06	sej J^{-1}	1.17E+23
8	Alcoholic beverages.	4.90E+15	5.886E+04	sej J^{-1}	2.88E+20
9	Tobacco products.	1.06E+14	6.500E+05	sej J^{-1}	6.91E+19
10	Monumental or building stone	0	9.810E+08	sej g^{-1}	0
11	Natural sands	1.21E+12	1.962E+09	sej g^{-1}	2.37E+21

Table C3.1 continued

12	Gravel and crushed stone	6.14E+12	4.905E+08	sej g^{-1}	3.01E+21
13	Nonmetallic minerals	0	1.962E+09	sej g^{-1}	0
14	Metallic ores and concentrates	3.57E+13	3.61E+09	sej g^{-1}	1.29E+23
15	Coal	1.60E+15	3.78E+04	sej J^{-1}	6.07E+19
17	Gasoline and aviation turbine fuel	8.38E+16	6.475E+04	sej J^{-1}	5.43E+21
18	Fuel oils	6.80E+16	6.475E+04	sej J^{-1}	4.40E+21
19	Coal and petroleum products	2.58E+17	6.475E+04	sej J^{-1}	1.67E+22
20	Basic chemicals	1.04E+12	2.750E+09	sej g^{-1}	2.86E+21
21	Pharmaceutical products	8.71E+10	2.750E+09	sej g^{-1}	2.39E+20
22	Fertilizers	5.72E+11	2.993E+09	sej g^{-1}	1.71E+21
23	Chemical products and preparations	7.72E+11	9.902E+09	sej g^{-1}	7.64E+21
24	Plastics and rubber	6.90E+11	2.709E+09	sej g^{-1}	1.87E+21
25	Logs and other wood in the rough	0	1.962E+04	sej J^{-1}	0
26	Wood products	2.07E+12	1.490E+09	sej g^{-1}	3.08E+21
27	Pulp, newsprint, paper, and paperboard	3.08E+16	1.398E+05	sej J^{-1}	4.31E+21
28	Paper or paperboard articles	5.17E+15	1.674E+05	sej J^{-1}	8.66E+20
29	Printed products	8.99E+11	4.951E+09	sej g^{-1}	4.45E+21
30	Textiles, leather, and articles	3.85E+15	7.177E+06	sej J^{-1}	2.77E+22
31	Nonmetallic mineral products	4.73E+12	3.094E+09	sej g^{-1}	1.46E+22
32	Base metal primary or semi-finished form	3.29E+12	5.906E+09	sej g^{-1}	1.94E+22
33	Articles of base metal	8.24E+11	5.906E+09	sej g^{-1}	4.86E+21
34	Machinery	4.65E+11	1.47E+10	sej g^{-1}	6.84E+21
35	Electronic and other electrical equipment	3.85E+10	1.47E+10	sej g^{-1}	5.65E+21
36	Motorized and other vehicles	7.82E+11	1.47E+10	sej g^{-1}	1.15E+22
37	Transportation equipment	5.26E+10	1.47E+10	sej g^{-1}	7.73E+20
38	Precision instruments and apparatus	6.44E+10	1.47E+10	sej g^{-1}	9.47E+20
39	Furniture, mattresses, lamps, lighting	1.70E+11	2.890E+09	sej g^{-1}	4.90E+20
40	Miscellaneous manufactured products	8.13E+11	1.613E+09	sej g^{-1}	1.31E+21
41	Waste and scrap	3.18E+12	2.161E+09	sej g^{-1}	6.87E+21
43	Mixed freight	1.32E+12	6.316E+09	sej g^{-1}	8.35E+21
0	Commodity unknown	1.38E+11	5.710E+09	sej g^{-1}	7.87E+20
	Natural Gas (joules)	0	4.80E+04	sej/J	0
	Total				5.41E+23
	Total without fuels (15,17,18, natural gas)				5.15E+23
	Exported fuels				2.66E+22
	Total without fuels and iron ore				3.85E+23

52 **Pure Service Exported at the U.S. Em/$ Ratio** **3.47E+21 sej y^{-1}**
1.36E+09 $

53 **Federal Government** **2.60E+10 $**
Taxes 1997 *(76)*.

54 **Tourists (experiences taken home)**

Money spent	7.2E+09 $
Emergy purchased	**3.352E+22 sej y^{-1}**

A rough approximation of the experiences taken home by tourists is the dollars spent in recreation times the emergy to money ratio of Minnesota in the year of their visit.

C5. Notes for Table 8 - Value of Minnesota Storages in 1997.

55 **Forest Storage** **6.26E+18 J**
Based on the forest inventory for Minnesota in Haugen and Mielke (2002)

Timberland Standing Mass	4.29E+6 Tons dry wt.
	3.895E+15 g
	16069 J g^{-1}

56 **Water (Lakes)** **6.76E+17 J**

Total Volume *(77)*	1.43E+11 m3
Density	1000000 g/m3
Concentration *(78)*	7.9 ppm
Gibbs	4.74 J/g

57 **Water (Minnesota Part of Lake Superior)** **3.30E+17 J**
Chemical Potential

Total Volume *(79)*	1.22E+13 m3
% of Shoreline in MN	0.0755 Dimensionless
Density	1000000 g/m3
Solute Concentration *(80)*	63 ppm
Gibbs	4.73 J/g
Energy Stored in The Lake	4.37E+18 J
Turnover Time	191 y
Net Volume Water per Year	6.41E+10 m3
Gibbs Free Energy at 5 ppm	4.74 J/g
Energy Inflow per Year	3.04E+17 J/y
Transformity Chemical Potential Of Rain	1.81E+04 sej/J
Emergy Input per Year	5.49E+21 sej/y
Emergy to Support Storage	1.05E+24 sej
Transformity Lake Superior Water	2.40E+05 sej/J

58 **Soil (Organic Matter)**

	Low	High	Mean	Units
Soil Org M. In The Upper 1m*	1.88E+15	8.10E+15	**4.46E+15**	g
Average Calories In Soil OM	5.04			kcal g^{-1}

Energy in Soil Organic Matter	21097			J/g
Energy of Stored OM In Soils	3.96E+19	1.71E+20	**9.42E+19**	J
Transformity of Topsoil	7.26E+04			sej/J
Emergy Stored In Soils	2.87E+24	1.24E+25	**6.84E+24**	sej

Soil organic matter estimates were made by Denis White of the Office of Research and Development Western Ecology Division with the assistance of Jeff Kern of Dynamic Corporation. The formula given below was used for the calculation of OM in each horizon (or layer in STATSGO) in each component of each map unit (USDA 1994):

Layer OM = Depth * Bulk Density * Proportion Organic Matter * Proportion Not.Rock

The variable called "proportion.not.rock" (Tan *et al.* 2004) was computed from seven STATSGO variables. The script used for the mean value computation was written in R by Denis White. The results above were derived using the low values of bulk density (bdl) and organic matter (oml) for each layer and also the high values (bdh and omh), The mean values are taken as our best estimate for this study.

	Mineral Reserves			
59	**Iron *(81)***		1.40E+10 MT	**1.40E+16 g**
		Energy/Mass	14.2 J/g	**1.98E+17 J**
60	**Sand & Gravel**		Short tons	**3.19E+16 g**
	(construction)		3.51E+10	
			6.11E+02 J/g	**2.15E+19 J**

Estimate based reserves in a seven county metro area *(82)* prorated to areas of the state where the Minnesota Department of Natural Resources is assessing the sand and gravel resource *(83)*. We assume the maximum value for the reserves.

61	**Limestone**		2.82E+09 MT	**2.82E+15 g**
		Energy/Mass	50 J/g	**1.41E+17 J**

Based on the projected reserves of Vetter Stone Co. in Kasota, MN and present production rate

62	**Dolomite**		1.32E+08 MT	**1.32E+14 g**
		Energy/Mass	11635.6 J/g	**1.54E+18 J**

Assumes dolomite has the same projected resources as limestone.

63	**Copper***		4.50E+09 MT	**4.50E+15 g**
		Energy/Mass	1.00E+06 g/moon	
64	**Nickel***		4.50E+09 MT	**4.50E+15 g**
		Energy/Mass	1.00E+06 g/moon	

*There is a Copper/Nickel complex of 4.5 billion tons of ore, according to Ojakangas and Matsch 1982. Assume that Ni and Cu are by-products. Ore grade is given at *(84)*.

Minnesota Nickel, Copper and Platinum ore relative to Cohen *et al.* (2007) OGC.

Element	**Concentration %**	**Ore Grade Cutoff % Cohen *et al.* (2007)**	**Transformity adjustment**
Copper	0.694	0.35	1.983
Nickel	0.218	1.0	0.218
Platinum	5.73E-05	1.1E-04	0.521

65 **Peat**		3.52E+09 MT	**3.52E+15 g**
	Energy/Mass	2.15E+04 J/g	**7.57E+19 J**

Estimate based on Minnesota Department of Natural Resources estimate of peat lands *(85)* and the dry weight and area of peat lands in Aiken county, which is about 7% of the total resource.

66 **Platinum**

Platinum (PtEq)	3.20E+07 short tons	**2.90E+13 g**

67 **People** **1.41E+24 sej**

Using the population percentages from the 2000 Census *(86).*

1997 Population (Estimate) 4735830 people

Number of individuals

	2000	Fraction	1997	sej/ind.	sej
Preschool	329605	6.70%	317301	3.34E+16	1.06E+22
School	2402204	48.83%	2312528	9.22E+16	2.13E+23
College Grad	1882631	38.27%	1812350	2.75E+17	4.98E+23
Post-College	255844	5.20%	246293	1.29E+18	3.17E+23
Public Status*	49195	1.00%	47358	3.86E+18	3.65E+23
Legacy#	765		765	7.70E+18	5.89E+21
Total	4919479	100%	4735830		1.41E+24

*Public Status is estimated as one per cent of total population.

#All individuals listed in the index to *Minnesota: A History of the State* by Theodore C. Blegen are counted as part of Minnesota's legacy.

A few of those legacy individuals are:

Ignatius Donnelly - Minnesotan congressman
F. Scott Fitzgerald – Author
Alexander Ramsey – First governor
Dr. Archibald Graham – Author, "Shoeless Joe" (Field of Dreams)
Walter Mondale – Politician
Hubert Humphrey – Presidential Candidate, Vice President

C6. Notes for Table 9– Summary Flows for Minnesota in 1997

68 The largest renewable emergy sources are the wind energy absorbed in the planetary boundary layer, the wave energy absorbed on the shore of Lake Superior and the geo- and chemical- potential energy delivered to the state in the St. Croix River.

69 Electricity from renewable sources includes wind, hydropower, and other renewable sources. This renewable class of energy was added for this study. It represents the amount of energy for concentrated use that has been extracted from the renwebale emergy base o fthe system.

70 Nonrenewable sources (Table 5) include fuels and minerals coal, natural gas, petroleum, sand and gravel, limestone dolomite, iron ore and soil erosion where it exceeds soil building, *i.e*., in agricultural areas.

71 Extracted fuels and minerals from within the state. This flow was used in the West Virginia study but it was given a symbol that was inconsistent with past usage. Here it has been designated uniquely by adding a prime to N1.

72 Dispersed Rural Source (Table 5) is the soil erosion in agricultural areas. This category includes any renewable resource that is being used more rapidly then it is being replaced.

73 Concentrated Use is the emergy in the mined tonnage of fuels and minerals used within the state plus the emergy of electricity, from nuclear, hydropower, wind and other nonfossil fuel and internal renewable sources.

74 Fuels and minerals exported without use are the quantities of iron ore exported directly and as taconite. In the case of taconite pellets some value is added to the Minnesota economy before export; however, this value is relatively small compared to the wealth generating potential of the ore when used in steel-making.

75 Imported fuels are coal, petroleum, natural gas and uranium plus some minerals (Table 6).

76 Fuels and minerals used. Add mineral production and fuel and mineral imports and subtract minerals exported without use.

77 In state minerals used: Subtract minerals exported without use from mineral production.

78 The material imported in goods was determined from the 1997 Commodity Flow Survey by summing the tonnage by commodity class from states with significant exports to Minnesota. (Table C3.1).

79 Dollars paid for imports is the sum of the dollar value of imported goods including fuels and minerals and all other goods and services.

80 The services in imported fuels and minerals and electricity are determined below.

Table C4.1 Services in Imported Fuels and Minerals

Fuel	Quantity	Unit	Price ($/Unit)	$ y^{-1}
Coal	1.91E+07	short tons	26.64	5.08E+08
Petroleum	4.92E+09	gallons	0.8	3.94E+09
Natural Gas	3.54E+08	1000 cu-ft	3	1.06E+09
Electricity	1.E+10	kWh	0.05	6.22E+08
Uranium	6.49E+6	Lb.	9.25	6.00E+07

The prices of these items can be found in the data sources given in Campbell *et al.* (2005)

81 Dollars paid for goods without fuels and minerals is the total dollar value of goods imported from the CFS minus the dollar value in fuels and minerals calculated above.

82 Dollars paid for imported services as determined using the base-nonbase method (Table C3.3).

83 Dollars spent by tourists in the State of Minnesota. in 1997 or 2000

84 Federal transfer payments are the total outlay of funds in MN by the Federal government.

85 Imported Services Total is the sum of the emergy in services associated with imported goods, fuels, and minerals, and pure services.

86 Imported Services in fuels and minerals is the emergy equivalent of the human service represented by the money paid for fuels and minerals. Dollars are converted to emergy using the 1997 emergy/$ ratio for US.

87 Imported Services in Goods is the emergy equivalent of the money paid for goods minus that paid for fuels and minerals.

88 Imported Service is the emergy equivalent of the money paid for services again assuming an average emergy backing a dollar spent for human service in a given year.

89 Emergy Purchased by Tourists is the emergy purchased when tourists $ are spent in Minnesota, *i.e.*, at Minnesota's emergy to dollar ratio.

90 Net Emergy purchased by Federal dollars spent in the state. Use Minnesota emergy/$ ratio and the difference between outlays and taxes. A negative number shows the emergy flow forgone by failure to spend tax dollars in the state.

91 Exported Products is the emergy in the goods exported including electricity, excluding iron ore.

92 Dollars Paid For All Exports. This is the sum of the money paid for goods, iron ore and services.

93 Dollars Paid for Services in Goods. This is the money paid for products listed in 88 above.

94 Dollars Paid for Services in Iron. This is the money paid for taconite exported..

95 Dollars Paid for Services. This is the money paid for pure services supplied by Minnesota to the rest of the nation as determined by the Base-Nonbase method.

96 Federal Taxes Paid is the sum of personal income, social security, and business taxes

97 Total Exported Services is the sum of the emergy equivalents in human service in fuels, goods and services exported.

Table C4.2 Services in Exported Minerals

	Amount	1997 prices $/Ton.	$
Taconite Pellets	3.94E+07	36.50	1.2E+09

98 Exported Services in Goods. This is the emergy equivalent of the dollar value of all exported goods excluding taconite. It is determined by multiplying the dollars paid for goods by the emergy to money ratio for the U.S. in 1997 or 2000. In using P_2 to determine services, our implicit assumption is that the emergy of human service in Minnesota is not much different from the average for the U.S.

99 Exported Services in iron is the emergy equivalent of the human service in the dollars paid for taconite pellets exported. Service is determined using the US emergy/$ ratio for 1997 or 2000 under the assumption given in 98 above.

100 Exported service is the emergy equivalent of the dollar value of exported pure services. This number was determined as in 98 and 99 above.

101 Gross State Product *(87)* for Minnesota in 1997 or 2000.

102 Emergy-to-dollar ratio for the U.S. in 1997 and in 2000(sej/$).

103 Emergy-to-dollar ratio for the State of Minnesota in 1997 and in 2000 (sej/$).

C7. Notes for Table 10. Calculation of Emergy Indices

104 Renewable Emergy Used (see Note 68).

105 In-State Nonrenewable Use is the sum of dispersed rural sources (N_0) and in-state mineral production.

106 Imported Emergy is the sum of imported fuels and minerals (F), goods (G), and services (PI).

107 Total Emergy Inflow is the sum of renewable emergy absorbed (R_A), and the emergy imported in the previous note.

108 The total emergy used in the state (U) is the sum of the renewable emergy absorbed (R_A), the emergy used from dispersed rural sources (N_0), fuels and minerals used (F_1), and the goods (G) and services (PI) imported.

109 Total exported emergy is the sum of the emergy in the materials of exported goods (B), the emergy of services associated with goods and with pure service (PE) and the emergy of fuels and minerals exported without use (N_2).

110 The emergy used from home sources is the sum of emergy from dispersed rural sources, in-state minerals and fuels used (F_2), and renewable emergy absorbed divided by total use (U).

111 Import minus export is the difference between imported emergy and exported emergy.

112 Ratio of exports to imports is the quotient of the expression in Note 109 divided by the expression in Note 106.

113 Fraction of use that is locally renewable is the ratio of renewable emergy absorbed to total use.

114 Fraction of use that is purchased is the ratio of imported emergy to total use.

115 Fraction of use in imported service is PI divided by U.

116 Fraction of use that is free is the sum of the renewable emergy absorbed and emergy from dispersed rural sources divided by total use.

117 Ratio of purchased to free is the quotient of the sum of imported fuels and minerals (F_1), imported goods (G) and imported services (PI) divided by the sum of the renewable emergy absorbed (R_A) and the emergy from dispersed rural sources (N_0).

118 Environmental loading ratio is the quotient of the sum of the emergy from dispersed rural sources (N_0), imported fuels and minerals (F_1), imported goods (G) and imported services (PI) divided by the renewable emergy absorbed (R_A).

119 Investment Ratio. There are several possible investment ratios (Odum 1996). This one compares imported emergy to the emergy supplied form within the state. The emergy from within the state is the sum of the renewable emergy absorbed (R_A), the emergy from dispersed rural sources (N_0), and the emergy from in-state fuels and minerals (F_2).

120 Emergy use per unit area (Empower density) is the total emergy use (U) divided by the area.

121 Use per person is the total emergy U divided by the population.

122 Renewable carrying capacity at the present standard of living is found by dividing the renewable emergy received by total use and then multiplying this fraction times the present population.

123 Developed carrying capacity at the present standard of living is approximately eight times the renewable carrying capacity.

124 Minnesota State Economic Product *(87)* in 1997 or 2000.

125 Ratio of Minnesota emergy use to GSP. Divide U by X, the GDP.

126 Ratio of U.S. Emergy use to GNP. See Appendix B4.2.

127 Ratio of emergy in electricity use to total use (El/U). See Table 5 for electricity use.

128 Ratio of electricity production to total use (Elp/U).). See Table 5 for electricity production.

129 Fuel use per person is the sum of coal, natural gas, and petroleum used in the state divided by population.

130 Population of the State *(86)* in 1997 and in 2000

131 Area of the State *(24)*

132 Renewable Empower Density is the emergy flow of renewable energy per unit area.

Appendix D.

Calculating the Import and Export of Materials

D1. Creating Export/Import Spreadsheets for Materials

The method used to determine the emergy exported from and imported to a state was further developed in this study to take advantage of the extensive data on this subject provided by the U.S. Census Bureau's Commodity Flow Survey *(2)*, which is performed every five years. This innovation resulted in a marked improvement in the accuracy with which imports and to a lesser extent exports from a state's economy can be determined. Even though the CFS provides all the information needed to document exports and imports it is not tabulated in the form that we need and some of the information is hidden rather deeply in the data base. To make our method transparent and reproducible, we have described in detail the characteristics of the database, data sources and methods that we used to determine the emergy imported and exported from Minnesota. These methods should be applicable to the determination of imports and exports for any other state and to regions, if data at that level can be obtained. To facilitate following the method described below the appropriate tables from the CFS should be referred to when needed. If the data tables or presentation of information change in the future these instructions will have to be altered.

Export Calculations

Determining material and energy flows for exports is straightforward with few extrapolations or assumptions needed, because the data are relatively complete as provided in the CFS. Data on dollar value and tonnage of export shipments between states by commodity class comes from the Commodity Flow Survey (CFS), Table 12 (Additional State Data). This data is also summarized in Tables 5, 7, and 8 in the CFS report on each state. The CFS uses several data codes when a numeric measurement is not given and these codes were handled in a consistent manner. For example, most states have an S or a D in one or more data fields for some commodity shipments. These letters indicate variable data (S) or a single source of information (D) that would risk disclosure of the data source, if reported. In the export calculation method, no estimate of exports was made for commodity classes with and S or D in both the $ value and tonnage columns for instate shipments. When this occurs there is often an S or a D in the "all destinations" category, as well. In this case there are too many unknowns to make an estimate. Materials moving in these classes were assumed to remain within the state or to constitute a negligible fraction of exports. Commodities with a dollar value but no information on tonnage were retained in the data because the tonnage could be reasonably estimated using the price per ton obtained from the dollar value and tonnage of the commodity going to all destinations.

Before transferring data from Table 12 to an interim spreadsheet, all dashes (indicating no data) were replaced with zeroes. If there was evidence that some flows were not actually zero, remain uncounted, or are different from the estimates provided, additional information was added when the emergy exported in each commodity class was determined. For example, coal exports were determined using Energy Information Administration (EIA) Data *(6)*. The Commodity Flow Survey provides a summary table (Table 7) of shipments to all states from the state of origin. Note that the top row in this table gives the total dollar value and tonnage of shipments from the state followed by a set of rows for dollar value and tonnage shipments to each state to which the state of origin is shipping. This includes a row for the state of origin itself, which will be referred to as instate shipments from now on.

The commodity classes for Standard classification of Transported goods (SCTG), Standard Industrial Classification (SIC), and the North America Industry Classification System (NAICS) industry classification codes and the approximate conversions used in this paper are shown in Table D1. An export table (see Table D2) with 11 columns was made to use in determining the tonnage exported in various commodity classes. The column headings for the export table are as follows (1) SCTG code, (2) Description of the class, (3) All Destinations Value($ mil), (4) All Destinations Tons(000), (5) $/Ton, (6) Instate Shipments ($ mil), (7) Instate Shipments Tons(000), (8) Known (directly measured) exports Tons(000), (9) Instate Tons (000) estimated using $/T, (10) Estimated exports tons (000), (11) Final Exports (estimated exports are adjusted to sum to the total missing tonnage).Table D2 omits column 2, the verbal description, because of space considerations.

Table D1 Approximate conversion between SCTG , SIC and NAICS industry classification codes developed for this study. These conversions are only approximate and better information might be developed of used if available.

Class	Combined Code	SCTG code	SIC code	NAICS Code
Agricultural products, grain	A	2,3	1	111
Livestock, seafood, animal products	B	1,4	2,9	112
Logs, rough wood	C	25	8	113
Metallic ores	D	14	10	2122
Coal	E	15	12	2121
Non-metallic minerals, gravel, stone, sand	F	11,12,13	14	2123
Prepared food products, alcohol, tobacco	G	5,6,7,8,9	20,21	311,312
Textiles, leather, apparel	H	30	22,23,31	313
Lumber wood product	I	26	24	321
Furniture, fixtures	J	39	25	337
Paper products	K	27,28	26	322
Printed products	L	29	27	323
Chemicals	M	20,21,22,23	28	325
Refined petroleum products	N	17,18,19	29	324
Plastics and rubber	O	24	30	326
Building materials, non-metallic	P	10,31	32	327,331
Primary metal products, semi-finished	Q	32	33	331
Fabricated metal products. Cans *etc*.	R	33	34	332
Machinery (not electrical)	S	34	35	333
Electrical equipment, precision instruments	T	35.38	36,38	334,335
Transportation equipment	U	36,37	37	336
Miscellaneous manufactured goods	V	40	39	339
Scrap and waste	W	41	49	562
Unknown, mixed or special classes	Y	43	92,98,99	99999

The steps in estimating exports from a state, *e.g.*, Minnesota, using the data in the spreadsheet columns described above are as follows:
First, copy the Commodity Class code and description from the Commodity Flow Survey Table 12 (Additional Data) for the state, for which exports are to be calculated Columns (1 and 2). Remember in following the instructions below that column numbers refer to the 11 column headings recommended above. The 10 columns shown in Table D2, which is missing column 2, have been numbered to match the verbal description.

1. Copy the $ value and tons moving from the state to all destinations for all commodities, Columns (3) and (4).
2. Calculate or otherwise determine the $ per ton. Column (5)
3. Copy data ($ and Tonnage) for shipments of all commodities with final destination in the state of origin, *e.g.*, from MN to MN, Columns (6) and (7).
4 Calculate known exports by subtracting instate shipments (column 7) from the shipments moving to all destinations (column 4) for all commodities for which tonnage has been measured, directly, Column (8).
5. Sum the tonnage of directly measured export shipments (Column 8) and subtract from the total tonnage moving to all destinations. The total tonnage is given at the top of the All Destinations column in Table D2 and in CFS Table 12.

6. Calculate the tonnage of instate shipments for any commodity for which a $ value of instate shipments is given in column 6 by dividing by the $ per ton (column 5). Record in Column 9 the estimated instate shipments.
7 Estimate the tonnage exported in these commodity classes by subtracting the instate tonnage estimates (column 9) from tonnage moving to all destinations (column 4). Record these estimates in Column 10.
8. Sum the estimated export shipments (column 9) and divide into the difference between directly measured exports and total exports. If this ratio equals 1 combine directly measured and estimated exports in their respective commodity classes into a single column (11) and you are done. If greater or less than 1 multiply each estimated commodity by this ratio to adjust the flows so that directly measured and estimated exports will sum to the known tonnage of total exports shipped to all destinations. Record these numbers in Column (11), Final Adjusted Exports, and fill in column with the directly measured values from Column (8).

Table D2. Calculation of Minnesota Exports from the state to state commodity shipments found in the Commodity Flow Survey as Additional Data in Table 12.

SCTG Code Col. 1	All Destinations Value($ mil) Column 3	All Destinations Tons(000) Column 4	$/ton Col. 5	Instate Value (mil $) Col. 6	Instate Tons (000) Col. 7	Directly Measured Exports Col.8	Estimate Instate Tons(000) Col.9	Estimate State Exports Col. 10	Final Adjusted Exports Col. 11
Total	35570	233760		8336	66249	167511			167511
1	-	-	0	-	-	0			0
2	-	-	0	-	-	0			0
3	S	S	356	S	S	S	S		0
4	129	467	276	87	438	29			29
5	609	259	2351	50	21	238			238
6	29	14	2071	20	11	3			3
7	223	S	843	S	S	S	S		0
8	365	351	1040	365	351	0			0
9	440	19	23158	177	7	12			12
10	S	S	94	S	S	S	S		0
11	32	793	40	4	347	446			446
12	53	5667	9	51	5484	183			183
13	S	S	29	S	S	S	S		0
14	S	S	689	S	S	S	S		0
15	4943	187835	26	1107	44488	143347			143347
17	393	S	272	S	S	S	S		0
18	227	964	235	224	954	10			10
19	532	3335	160	78	163	3172			3172
20	3918	5152	760	425	897	4255			4255
21	1996	S	32716	S	S	S	S		0
22	S	S	216	S	S	S	S		0
23	1512	946	1598	518	290	656			656
24	2582	1316	1962	485	387	929			929
25	370	5627	66	132	S	S	2007	3620	3406
26	900	3869	233	216	1045	2824			2824
27	69	108	639	S	S	S	S		0
28	123	87	1414	58	S	S	41	46	43
29	483	S	2499	S	S	S	S		0
30	S	S	9097	S	S	S	S		0
31	937	5007	187	263	3658	1349			1349
32	4158	6306	659	449	S	S	681	5625	5294
33	860	851	1011	525	465	386			386

Table D2 Continued

SCTG Code	All Destinations Value($ mil)	All Destinations Tons(000)	$/ton	Instate Value (mil $)	Instate Tons (000)	Directly Measured Exports	Estimate Instate Tons(000)	Estimate State Exports	Final Adjusted Exports
34	2109	187	11278	483	48	139			139
35	1326	120	11050	242	S	S	22	98	92
36	2900	519	5588	212	S	S	38	481	453
37	320	S	10622	S	S	S	S		0
38	234	2	117000	S	-	S	S		0
39	159	45	3533	57	12	33			33
40	692	134	5164	140	S	S	27	107	101
41	S	S	148	S	S	S	S		0
43	794	425	1868	605	314	111			111
--	99	38	2605	S	S	S	S		0
Class Totals						158122		9977	167511
Difference (Total - Class Total from Column 7 in this Table.						9389			
Fraction (Difference/Class Total (Column 7/Column 9 this table)						0.941			

Import Calculations

Table 12 from the CFS web site, “Additional State Data”, used in the export calculation, has information on the exports by commodity class going from all the other states to the state of destination (Minnesota). Data from the other 49 states that might be exporting to Minnesota were combined to determine imports. Inbound shipments by state of origin to the state of destination are summarized in Table 8 of the CFS, but commodity classes are not shown. For states without a U.S. Customs port, state to state commodity shipments will capture almost everything entering the state for use or transshipment. When one or more U.S. customs ports are located in a state the accounting becomes more difficult. Should the foreign imports be added, if they are destined for other places and are thus immediately exported to another state? If the majority of imports entering through a major port belong to some other place the international flows could greatly exceed the interstate flows and lead to large errors in our estimates. We assume that most international shipments pass through Minnesota and do not pertain to the state’s economy, thus our estimate of Minnesota imports will be conservative, because some unknown fraction of the international flows will be used in Minnesota directly.

The inbound tonnage shipped in each commodity category was used to calculate the emergy imported in goods. The five steps used to estimate imported emergy to a state are as follows: (1) a quick tally of the total tonnage coming into the state from other states was obtained by consulting Table 8 in the CFS report. The states that had a number entered in the percent of total inbound shipments column were identified. The total percentage of imports directly measured was determined by summing the percentages. The total percent of tonnage from the states used to estimate imports should be at least 95% of the tonnage of total inbound shipments. (2) Once the subset of states exporting to the study state was identified, missing values for the tonnage for specific commodities coming from each state were estimated. (3) If a dollar value of the inbound commodity shipments was known and tonnage was not listed, the tonnage was estimated based on the cost per ton as described above and shown in Table D2. A large fraction of total inbound shipments from some states had missing values for both dollar value and tonnage (an S or D entered into the field). In this case, the missing data would have resulted in large errors in the estimate of total imports and thus the development of a method to handle this situation was warranted. The tonnage fields for inbound shipments from a state of origin to Minnesota containing and S or a D were handled by assuming that a state’s exports to any other state would on average follow its overall export profile*, i.e.,* the fraction of total shipments accounted for by each commodity. Missing tonnage data was distributed among commodity classes by adjusting the overall export profile. The missing tonnage is equal to total shipments to Minnesota from the state minus commodities with numeric entries for tonnage. This tonnage was distributed among the commodity classes with inbound shipments by adjusting using the state's overall export profile so that the unknown inbound shipments made up 100% of the missing inbound tonnage. (4) The inbound tonnage in each commodity class for a state was transferred as a single column to a second worksheet with data from all of the identified import states. (5) Then each commodity class was summed across the rows for all states to create the column of data with imported tonnages in each commodity class for the emergy table.

1. The following steps describe the estimation of the unknown tonnage (S and D) as illustrated for Alabama's shipments to West Virginia (our original example) shown in Table D3. For all of the states importing to the study state, copy the total tonnage in each commodity class exported to all destinations and the tonnage exported to the state you are evaluating (columns 2 and 3 in Table D3), onto a spreadsheet..
2. Calculate the price per ton for all inbound shipments by commodity class from any state exporting to the study state according to the instructions given above for exports.
3. Replace all dashes with a zero. Although Table D3 only presents one state, the same procedure will be used for all states sending a significant quantity of imports to the study state.
4. Next, missing tonnage values are estimated for any commodity class that reported a dollar value of exports to the state but no tonnage. In some cases calculating the price per ton for the state of origin is not possible, but there is still a dollar value for exports. Prices per ton can be quite variable but find an adjacent state (or use a better estimation method) and substitute this price in the spreadsheet making a note on its origin. Fill in all tonnage movements possible using this method. Combine the tonnages estimated on the basis of average price with the tonnages that were directly measured. Sum this column and subtract from the total tonnage exported to the study state to get the tonnage that will be distributed using the export profile (see the number in italics at the top of column 4 in Table D3). For example, the total export from Alabama to West Virginia is 318 thousand tons but the sum of all commodities determined directly and estimated based on dollar value only adds up to 27 thousand tons, the difference is then 291 thousand tons.
5. Create a fourth column for the export profile, which will be used to distribute the missing tonnage across the remaining commodities that had either an S or D in both the dollar value and tonnage fields. The export profile is the fraction of the total tonnage accounted for by each commodity as determined from the shipments to all destinations. Calculate the profile by dividing the tonnage for each commodity exported by the total tonnage exported for that state. Only those commodities that have an S or D in both dollar value and tonnage fields are recorded in column 4. Sum the fractions to determine the fraction of total tons accounted for by the commodities with missing data.
6. The next step is to adjust these fractions to represent the expected fractions of the missing tonnage imported to the state in each commodity class with missing data. Create a fifth column, the adjusted fraction of missing tonnage imported in each class, where each fraction of the tons in the export profile (individual values in column 4) will be divided by the fraction of the total tons that is missing (the sum of all fractions in column four). The sum of all values in column 5 should equal one, or 100%.
7. In the last column (column 6), copy over the reported and estimated data for tonnage for any commodity where it is available from column 3. For all of the missing commodities (those with and S or D in both the $ value and tonnage fields), multiply the total missing tonnage (at the top of Column 4) by the corresponding percentage (in Column 5) for each commodity class known to have a flow but for which tonnage is unknown, and transfer this number to the appropriate field in column 6. For example, if data is missing for textiles, multiply 291 thousand tons by the fraction of textiles or 0.0172, to get 5 thousand tons textiles imported. Sum this column to make sure it adds up to the total tonnage.
8. Transfer this tonnage data for each commodity to an import table creating a column for each state.
9. Sum across the states (rows) for each commodity to find the total tonnage imported in each commodity class and transfer this to the import section of the emergy evaluation.

Use Table D1 or better conversion system to convert from NAICS to SCTG code. Create a column for this data and include it in the summation of imports described in step 9 above.

Table D3: Our original example of estimating missing import data. Alabama to West Virginia.

Description	Total Tons from Alabama (thousands)	Tons to WV (thousands)	Fraction of total tons for missing data	Fraction of missing tonnage to WV	Total Tons to WV (thousands)
All commodities	256234	318	*291*		
Live animals and live fish	125	-			0.0
Cereal grains	S	-			0.0
Other agricultural products	1682	-			0.0
Animal feed and products of animal origin	7194	S	0.028	0.059	17.2
Meat, fish, seafood, and their preparations	1836	S	0.007	0.015	4.4
Milled grain and bakery products	386	S	0.002	0.003	0.9
Other prepared foodstuffs and fats and oils	4408	S	0.017	0.036	10.5
Alcoholic beverages	482	-		0.000	0.0
Tobacco products	51	S	0.000	0.000	0.1
Monumental or building stone	S	-		0.000	0.0
Natural sands	S	-		0.000	0.0
Gravel and crushed stone	36211	-		0.000	0.0
Nonmetallic minerals	2905	S	0.011	0.024	6.9
Metallic ores and concentrates	S	-		0.000	0.0
Coal	30993	-		0.000	0.0
Gasoline and aviation turbine fuel	12659	-		0.000	0.0
Fuel oils	3605	-		0.000	0.0
Coal and petroleum products,	4671	S	0.018	0.038	11.1
Basic chemicals	7460	S	0.029	0.061	17.8
Pharmaceutical products	33	S	0.000	0.000	0.1
Fertilizers	2382	S	0.009	0.020	5.7
Chemical products and preparations	1271	S	0.005	0.010	3.0
Plastics and rubber	1585	S	0.006	0.013	3.8
Logs and other wood in the rough	40817	S	0.159	0.334	97.3
Wood products	12443	S	0.049	0.102	29.7
Pulp, newsprint, paper, and paperboard	8949	S	0.035	0.073	21.3
Paper or paperboard articles	977	-		0.000	0.0
Printed products	324	S	0.001	0.003	0.8
Textiles, leather, and articles of textiles or leather	2120	S	0.008	0.017	5.1
Nonmetallic mineral products	16613	S	0.065	0.136	39.6
Base metal in primary or semi finished forms and in finished basic shapes	11212	17			17.0
Articles of base metal	4208	S	0.016	0.034	10.0
Machinery	753	1		0.000	1.0
Electronic and other electrical equipment and components	688	S	0.003	0.006	1.6

Motorized and other vehicles (including parts)	957	S	0.004	0.008	2.3
Transportation equipment	251	S	0.001	0.002	0.6
Precision instruments and apparatus	10	-		0.000	0.0
Furniture, mattresses and mattress supports, lamps, lighting fittings, and...	501	S	0.002	0.004	1.2
Miscellaneous manufactured products	2965	9			9.0
Waste and scrap	2130	-			0.0
Mixed freight	2000	-			0.0
Commodity unknown	S	-			
subtotals to check		27	0.476	1.000	318

Custom's Imports

Our present view on customs data is that the portion of these imports that are used within the state is captured by the CFS data. Including these flows that really pertain to the whole nation in the analysis of an individual state alters the indices so they are not longer comparable to states without customs facilities. Nevertheless, we repeat our original instructions for obtaining customs' data in case it is of interest in a particular analysis. If the state has a Customs' port, locate the appropriate data on the USITC data web site (37). The Customs' site requires a password, but registration is free. To get the correct data report, a series of dialogue boxes must be completed. The choices that should be made are as follows:

- Dialogue 1 – U.S. General Imports; NAICS code; current US Trade
- Dialogue 2 – Customs value; 1997; All import commodities; All countries; All country sub-codes; create new district list
- ▪ Enter the name, select the districts, then highlight the name when you return to original page;
  In 1,000,000; annual; NAICS 3 digit; aggregate all countries together; aggregate import programs; display districts separately
- Dialogue 3 – Arrange in this order: District; NAICS 3
- Dialogue 4 – District; General customs value; Show all; Sort 1997; 5000 records; other display options are optional

Appendix E

Minnesota Emergy Accounts for 2000

Table E1. Annual Renewable Resources and Production in 2000.

Note*	Item	Data J, g, $, ind/yr	Units	Emergy/ Unit sej/unit	Emergy E+20 sej	2000 Emdollars E+6 Em$
	Renewable Resources within Minnesota					
1	Sun, Incident	1.07E+21	J	1	10.74	456.9
1	Sun, Absorbed	8.84E+20	J	1.21	10.74	456.9
2	Wind Kinetic Energy	1.26E+19	J	1,467	185.47	7892.3
3	Earth Cycle Energy	2.80E+17	J	33,720	94.35	4014.7
4	Rain, Chemical Potential Energy Received	7.07E+17	J	18,100	127.95	5444.6
5	Evapotranspiration, Chemical Potential Absorbed	3.14E+17	J	28,100	88.30	3757.5
6	Rain, Geo-Potential On Land	4.58E+17	J	10,100	46.23	1967.1
6	Snow, Geo-Potential On Land	7.22E+16	J	101,100	73.04	3108.1
7	Rain, Geo-Potential Of Runoff	2.55E+16	J	27,200	6.93	294.9
7	Snow, Geo-Potential Of Runoff	4.67E+16	J	101,100	47.19	2008.0
8	Wave Energy (Lake Superior)	1.55E+16	J	30,000	4.66	198.1
9	Rivers, Chemical Potential Energy Received	9.15E+15	J	50,100	4.58	195.0
9	Rivers, Chemical Potential Energy Absorbed	6.44E+12	J	50,100	0.003	0.1
10	Rivers, Geo-Potential Energy Received	5.09E+15	J	27,200	1.39	59.0
10	Rivers, Geo-Potential Energy Absorbed	1.51E+15	J	27,200	0.41	17.4
11	NH4-N In Dry/Wet Deposition	1.55E+11	g	1.4E+09	2.15	91.6
11	NO3-N In Dry/Wet Deposition	4.44E+10	g	6.8E+09	3.04	129.2
	Total N Deposition	2.00E+11	g	Variable	5.19	220.8
12	S In Dry/Wet Deposition	5.26E+10	g	1.58E+11	83.18	3539.9
13	Cl In Dry/Wet Deposition	8.81E+09	g	1.31E+10	1.15	49.1
	Minnesota					
14	Agricultural Products	7.00E+17	J	Variable	2,632.5	112023.1
15	Livestock	5.97E+16	J	Variable	533.8	22714.9
16	Fish Production	1.32E+11	J	1,961,800	0.003	0.1
17	Hydroelectricity and Other Renewable	1.07E+16	J	120,300	12.9	548.2
18	Net Timber Growth	1.28E+17	J	20,600	26.4	1124.5
19	Timber Harvest	6.40E+16	J	68,700	43.9	1869.5
20	Groundwater Chemical Potential	4.61E+15	J	159,100	7.3	311.9
21	Solid Waste Recycled or Recovered	3.28E+12	g	6.28E+09	206.2	8772.8

* The notes for Table 4 can be found in Appendix C at C.1.

Table E2. Annual Production and Use of Nonrenewable Resources in 2000.

Note*	Item	Data J, g, $, ind/yr	Units	Emergy/Unit sej/unit	Emergy E+20 sej	2000 Emdollars E+6 Em$
Fuels and renewables used in a nonrenewable manner						
22	Coal Used In The State	5.53E+17	J	37,800	209.1	8899.7
23	Natural Gas Used In The State	3.98E+17	J	43,500	173.2	7370.9
24	Petroleum Used In The State	7.20E+17	J	64,800	466.8	19865.4
25	Electricity Production	1.74E+17	J	170,400	297.0	12636.6
26	Electricity Used In The State	2.15E+17	J	170,400	366.4	15592.9
27	Nuclear Electricity	4.67E+16	J	170,400	79.5	3383.1
28	Iron Ore Mined	4.67E+13	g	3.51E+9	1639.0	69745.5
29	Sand And Gravel	3.95E+13	g	1.31E+9	517.5	22019.1
30	Limestone	6.40E+12	g	9.81E+8	63.8	2671.4
31	Dolomite	3.37E+12	g	1.08E+10	363.3	15460.6
32	Peat	7.50E+10	g	3.53E+8	0.3	11.3
33	Soil Erosion	9.79E+16	J	72,600	71.1	3023.6

* The notes for Table E2 can be found in Appendix C at C2.

Table E3. Annual Imports to the Minnesota Economy in 2000.

Note*	Item	Data J, g, $, ind/yr	Units	Emergy/Unit sej/unit	Emergy E+20 sej	2000 Emdollars E+6 Em$
34	Tourism (Money Imported)	9.00E+09	$	2.35E+12	211.5	9000.0
35	Electricity	3.01E+16	J	1.70E+05	51.3	2182.0
36	Uranium	2.94E+09	g	4.66E+11	13.7	583.1
37	Coal	5.53E+17	J	3.78E+04	209.1	8899.7
38	Petroleum	7.20E+17	J	6.48E+04	466.8	19865.4
39	Natural Gas	3.98E+17	J	4.35E+04	173.2	7370.9
40	Minerals	1.06E+13	g	variable	106.0	4512.6
41	Goods (Materials)	3.92E+13	g	variable	2747.9	116930.0
42	Goods (Services)	6.60E+10	$	2.35E+12	1550.5	65977.0
43	Fuels (Services)	5.51E+09	$	2.35E+12	129.5	5509.2
44	Minerals including Uranium (Services)	4.78E+08	$	2.35E+12	11.2	477.9
45	Electricity (Services)	6.22E+08	$	2.35E+12	14.6	621.7
46	Services	4.22E+09	$	2.56E+12	108.1	4598.8
47	Immigration	8.67E+03	Ind.	variable	4.2	180.5
48	Federal Government Outlays (If spent in US)	2.24E+10	$	2.35E+12	526.2	22391.9

Table E4. Annual Exports from the Minnesota Economy in 2000.

Note*	Item	Data J, g, $, ind/yr	Units	Emergy/Unit sej/unit	Emergy E+20 sej	2000 Emdollars E+6 Em$
49	Goods w/o Iron Ore and Fuels (Materials)	7.37E+13	g	mixed	3855	164037.5
50	Iron Ore as Taconite	3.57E+13	g	3.61E+09	1290.4	54909.2
51	Goods (Services)	9.46E+10	$	2.35E+12	2223.0	94597.0
52	Services	1.36E+09	$	2.35E+12	31.9	1356.7
53	Federal Government Taxes (Spent in the US)	2.85E+10	$	2.35E+12	668.8	28460.0
54	Tourists (Experiences Taken Home)	9.00E+09	$	3.97E+12	357.3	15202.9

* The notes for Table E4 can be found in Appendix C at C4.

Table E5. Assets of Minnesota in 2000.

Note*	Item	Data J, g, $, ind/yr	Units	Emergy/Unit sej/unit	Emergy E+20 sej	2000 Emdollars E+6 Em$
55	Forest Biomass Storage	6.26E+18	J	28,200	1767	75,202
56	Water (Lakes)	6.76E+17	J	18,100	122	5,206
57	Water (Lake Superior)	3.30E+17	J	2.40E+05	792	33,692
58	Soils	9.42E+19	J	72,600	68375	2,909,574
59	Iron	1.40E+16	g	3.51E+09	490324	20,864,869
60	Sand & Gravel	3.19E+16	g	1.31E+09	417826	16,321,327
61	Limestone	2.82E+15	g	9.81E+08	27661	1,177,080
62	Dolomite	1.32E+14	g	1.08E+10	14231	605,577
63	Copper	4.50E+15	g	1.14E+11	5115002	217,659,670
64	Nickel	4.50E+15	g	2.55E+10	1147664	48,836,772
65	Peat	7.57E+19	J	1.86E+04	14100	599,999
66	Platinum	2.90E+13	g	1.13E+11	32728	1,392,699
67	People	329605	Ind.	Various	12738	542,061
	Preschool	2402204	Ind.	3.34E+16	110	4678
	School	1882631	Ind.	9.22E+16	2215	94253
	College Grad	255844	Ind.	2.75E+17	5171	220029
	Post-College	49195	Ind.	1.28E+18	3288	139895
	Public Status	765	Ind.	3.85E+18	1896	80699
	Legacy	329605	Ind.	7.70E+18	59	2507

* Evaluation notes for Table E5 are given in Appendix C at C5.

Table E6. Summary of Flows for Minnesota in 2000.

Note	Letter in Fig. 2	Item	Emergy E+20 sej	2000 Dollars E+9 $/y	2000 Emdollars E+9 Em$/y
68	R_A	Renewable Sources Used	191		8.1
69	R_1	Renewable Electricity	13		0.5
70	N	Nonrenewable Source Flows	2654		112.9
71	N_1'	Extracted Fuels and Minerals	2583		109.9
72	N_0	Dispersed Rural Source	71		3.0
73	N_1	Concentrated Use (from state)	1385		58.9
74	N_2	Exported (without full use)	1290		54.9
75	F	Imported Fuels and Minerals)	1020		43.4
76	F_1	Fuels, Minerals Used ($F+F_2$)	2313		98.4
77	F_2	In State Minerals Used ($N_1'-N_2$)	1292		55.0
78	G	Imported Goods (Materials)	2748		116.9
79	I	Dollars Paid For All Imports		82.3	
80	I_1	Dollars Paid For Service In Fuels		6.9	
81	I_2	Dollars Paid For Service In Goods		70.8	
82	I_3	Dollars Paid For Services		4.6	
83	I_4	Dollars Spent By Tourists		9.0	
84	I_5	Federal Transfer Payments		22.4	
85	P_2I	Imported Services Total	1933		82.3
86	P_2I_1	Imported Services In Fuels	161.5		6.9
87	P_2I_2	Imported Services In Goods	1664		70.8
88	P_2I_3	Imported Services	108		4.6
89	P_1I_4	Emergy Purchased By Tourists	357		15.3
90	P_1I_5	Net Emergy Purchased By Fed. $	-241		-10.3
91	B	Exported Products w/o Taconite	3855		164.0
92	E	Dollars Paid For All Exports		104.2	
93	E_1	Dollars Paid For Goods		101.5	
94	E_2	Dollars Paid For Mineral Exports		1.3	
95	E_3	Dollars Paid For Services		1.5	
96	E_4	Federal Taxes Paid		28.5	
97	P_2E	Total Exported Services	2449		104.2
98	P_2E_1	Exported Services In Goods	2385		101.5
99	P_2E_2	Exported Services In Iron	30.1		1.3
100	P_2E_3	Exported Services	34.2		1.5
101	X	Gross State Product		185.1	
102	P_2	Emergy/ $ Ratio U.S. 2000 sej/$	2.35E+12		
103	P_1	Emergy/ $ Ratio MN 2000 sej/$	3.97E+12		

Table E7. Minnesota Emergy Indicators and Indices for 2000.

Item	Name of Index	Expression	Quantity	Units
104	Renewable Use	R_A	1.91E+22	sej y^{-1}
105	In State Non-Renewable Use	$N_0 + N_1$	1.46E+23	sej y^{-1}
106	Imported Emergy	$F + G + P_2I$	5.70E+23	sej y^{-1}
107	Total Emergy Inflows	$R + F + G + P_2I$	5.89E+23	sej y^{-1}
108	Total Emergy Used	$U = (R_A+N_0+F_1+G+ P_2I)$	7.35E+23	sej y^{-1}
109	Total Exported Emergy	$B+ P_2E +N_2$	7.59E+23	sej y^{-1}
110	Emergy Used From Home Sources	$(N_0+F_2+ R)/U$	0.21	
111	Imports-Exports	$(F+G+ P_2I)-(B+P_2 E+N_2)$	-1.89E+23	sej y^{-1}
112	Ratio Of Export To Imports	$(B+P_1E+N_2)/(F+G+P_2I)$	1.33	
113	Fraction Used, Locally Renewable	R /U	0.026	
114	Fraction Of Use Purchased Outside	$(F + G + P_2I)/U$	0.778	
115	Fraction Used, Imported Service	P_2I/U	0.271	
116	Fraction Of Use That Is Free	$(R+N_0)/U$	0.036	
117	Ratio Of Purchased To Free	$(F_1+G+P_2I)/(R+N_0)$	26.73	
118	Environmental Loading Ratio	$(F_1+N_0+G+P_2I)/R$	37.08	
119	Investment Ratio	$(F+G+P_2I)/(R+N_0+F_2)$	3.67	
120	Use Per Unit Area	U/Area	3.26E+12	sej/m^2
121	Use Per Person	U/Population	1.49E+17	sej/ind.
122	Renewable Carrying Capacity	(R/U)*(Pop.)	127,574	people
123	Developed Carrying Capacity	8*(R/U)*(Population)	1,020,589	people
124	MN State Econ. Product	GSP	1.9E+11	$/yr
125	Ratio MN Emergy Use To GSP	U/GSP	3.97E+12	sej/$
126	Ratio U.S. Emergy Use To GNP	U/GNP	2.35E+12	sej/$
127	Ratio Electricity Use/Emergy Use	El/U	0.047	J/sej
128	Ratio Elec. Prod./Emergy Use	Elp/U	0.034	J/sej
129	Emergy Fuel Use Per Person	F_2/Population	1.73E+16	sej/ind
130	Population		4,919,479	people
131	Area		2.25E+11	m^2
132	Renewable Empower Density		8.46E+10	sej/m^{-2}

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