Environ. Sci. Technol. **2004**, *38,* 4810−4827

Thermodynamic Accounting of Ecosystem Contribution to Economic Sectors with Application to 1992 U.S. Economy

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Incorporation of ecological considerations in decision-making is essential for sustainable development, but is hindered by inadequate appreciation of the role of ecosystems, and lack of scientifically rigorous techniques for including their contribution. This paper develops a novel thermodynamic accounting framework for including the contribution of natural capital via thermodynamic input−output analysis. This framework is applied to the 1992 US economy comprising 91 industry sectors, resulting in delineation of the myriad ways in which sectors of the US economy rely on ecosystem products and services. The contribution of ecosystems is represented via the concept of ecological cumulative exergy consumption (ECEC), which is related to emergy analysis but avoids any of its controversial assumptions and claims. The use of thermodynamics permits representation of all kinds of inputs and outputs in consistent units, facilitating the definition of aggregate metrics. Total ECEC requirement indicates the extent to which each economic sector relies directly and indirectly on ecological inputs. The ECEC/money ratio indicates the relative monetary versus ecological throughputs in each sector, and indicates the relationship between the thermodynamic work needed to produce a product or service and the corresponding economic activity. This ratio is found to decrease along economic supply chains, indicating industries that are higher up in the economic food chain price ecosystem contribution more than the basic infrastructure industries such as mining and manufacturing. The ratio of CEC with and without inclusion of ecosystems indicates the extent to which conventional thermoeconomic analysis underestimates the contribution of ecosystems. Such ratios, made available for the first time, provide unique insight into the importance of natural capital, and are especially useful in hybrid thermodynamic life cycle analysis of industrial systems. The approach, data compiled in this work, and the resulting insight provide a more ecologically conscious tool for environmental decision-making, and has potential applications at micro as well as macro scales.

1. Introduction

Ecological products and services are indispensable for any industrial, economic, or social activity on earth. Examples of ecological products include coal, timber, water, and atmospheric oxygen, while ecosystem services include rain, pollination, carbon sequestration, and pollution abatement (*1*−*4*). Despite their obvious importance, traditional methods in engineering, economics, and other disciplines have tended to ignore the role of ecosystems by considering them to be an “infinite sink” or “free”. As a result, business and policy decisions are usually made with a flawed accounting system that ignores the basic life support system for all activity. The focus of such an approach tends to be on short-term gain, while longer-term sustainability issues get ignored. Such myopic and ecologically unconscious decision-making is continuing to cause significant and alarming deterioration of global ecosystem products and services, also called “natural capital” (*5*−*7*).

The importance of accounting for the contribution of ecosystems to economic activity is being slowly recognized in both academia and industry (*8*). Approaches for full or total cost assessment (*9*) to include environmental and social aspects along with economic aspects are being developed and used in industry. Techniques such as life cycle assessment (LCA) are being standardized and adopted by many corporations to obtain more holistic and complete information about the impact of their products and processes on the environment. However, LCA focuses mostly on the emissions from industrial processes and their impact, and on consumption of nonrenewable resources. It does not account for the contribution of ecosystems to industrial activity. A variety of techniques have attempted to quantify this contribution, but all techniques face common challenges of combining information represented in a diverse set of units, uncertain knowledge, and lack of adequate data about ecosystems. These techniques may be broadly categorized as preference-based and biophysical methods.

Preference-based methods assign a monetary value to ecosystem products and services by relying on human valuation. A pioneering study by Costanza et al. (*3*) estimated the value of ecosystem services to be almost twice that of the global gross economic product. A more recent study indicates that saving the existing unspoiled ecosystems is at least 100 times more valuable than developing them for economic activity (*10*). Many techniques have been developed for valuation of environmental products and services (*11*). Industry groups have also collaborated to develop preference-based methods for total cost assessment (*9*). A significant advantage of these methods is that using a single unit permits ready comparison across economic and ecological contributions. However, valuation methods are often controversial and rely on knowledge about the role of each ecological product and service. Such information, along with satisfaction of scientific laws, may be provided by biophysical methods.

Biophysical methods rely on biological and physical principles to account for the role of ecosystems. *Mass* based methods have been popular to determine the physical basis of economic activity and its interaction with ecosystems (*12*−*15*). These methods determine the mass of materials flowing from ecosystems to the economy and the emissions from the economy. Indirect or hidden flows are also quantified. Most of these studies are at the level of the entire economy, and disaggregation to more detailed levels is being developed. Since mass does not capture many other properties of materials, such as their energetic contribution and impact, these material flow analysis (MFA) studies are of limited use by themselves. However, they can provide a good database for developing other more comprehensive methods. Furthermore, existing methods are quite limited in their incorporation of ecosystem services, which cannot be readily captured in terms of mass flow.

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10.1021/es035367t CCC: $27.50

Energy-based methods such as net energy analysis and full fuel cycle analysis determine the flow of energy through various sectors of the economy (*16*−*18*). They consider energy content of industrial inputs and outputs including exchanges between economic sectors and those from ecosystems to the economy. The framework of input−output analysis is used for mathematically sound analysis of energy flow in ecological and economic systems (*19*). Like mass, energy also does not capture many aspects such as contribution of nonenergetic materials or environmental impact of emissions, and it ignores the second law of thermodynamics.

Exergy-based methods satisfy the first and the second law and can capture an array of material and energy streams. They have been popular for assessing thermodynamic efficiency of industrial processes (*20*) and to analyze the behavior of ecosystems (*21*). Exergy is the energy available to do useful work. It can capture various quality aspects of streams as indicated by their mass, energy, concentration, velocity, and location. Thus, *exergy can characterize both mass and energy streams, and is the only truly limiting resource on this planet* (*22*−*24*). Various extensions of exergy analysis such as industrial cumulative exergy consumption (ICEC) analysis (*20*) and exergetic LCA (*25*) have been developed in the past to analyze industrial systems. ICEC analysis considers cumulative exergy consumption in the industrial links of a production chain, and has a strong basis in engineering thermodynamics. However, exergy-based methods ignore the contribution of ecosystems and the impact of emissions. *Furthermore, exergy analysis at the level of economic sectors is not yet available*. Other studies that account for the contribution of ecosystems are at the scale of the entire national or global economy, and rely on economic valuation (*3*) or material flow analysis (*5*). Studies at the level of economic sectors are available in energy analysis (*26*), but these are not as comprehensive as the study presented in this paper, and may violate the second law. Exergy analysis has also been used to analyze societies (*27, 28*), but the focus is mainly on comparing exergetic efficiencies of economic sectors, and neither the impact of emissions nor contribution of ecosystems are included.

Emergy-based methods developed by systems ecologists have also been used to analyze ecological and economic systems. Emergy is the available energy used directly or indirectly to make any product or service, and is measured in solar equivalent joules (sej) (*4*). The key strength of emergy analysis is that it *does* account for the contribution of ecological products and processes. However, emergy analysis is often misunderstood, faces quantitative and algebraic challenges, and its broad claims about ecological and economic systems are quite controversial (*29, 30*). Besides, emergy analysis has not been done at the economic input−output scale.

Ecological cumulative exergy consumption (ECEC) is an extension of industrial cumulative exergy consumption to include ecosystems (*31*). ECEC provides insight into emergy analysis by exposing its thermodynamic underpinning, and its close relationship with ICEC analysis. Under conditions of identical analysis boundary, allocation method, and approach for combining global exergy inputs, emergy is shown to be identical to ECEC, with transformities being equivalent to the reciprocal of the cumulative degree of perfection (CDP), a measure of efficiency, in ICEC analysis. Very importantly, ECEC is free from all the controversial aspects of emergy analysis such as the maximum empower principle and the emergy theory of value that have hindered its use. Other issues such as considering solar inputs from prehistory are also not used in the proposed approach, since ECEC only includes concurrent exergy flows. ECEC relies only on those elements of emergy analysis that quantify the direct contribution of ecosystem products and services. Thus, ECEC combines the scientific rigor of exergy analysis with the ability of emergy analysis to account for ecological products and services without relying on any of the controversial aspects of emergy analysis. Additional details about ECEC are outside the scope of this article, but are available in ref *31*.

This paper applies ECEC analysis to determine ecosystem contribution to the 1992 U.S. economy comprising 91 industry sectors. The proposed analysis provides a unique insight into the reliance of economic sectors on ecosystems for obtaining their inputs and dealing with their outputs. The application considers a variety of ecological products, ecosystem services, human resources, and impact of emission on human health. It calculates ECEC/money ratio to demonstrate the discrepancy between the thermodynamic work required to produce an ecological resource and the willingness of people to pay for it. Such discrepancy could lead to a suboptimal allocation of ecological resources through the economic system (*32*). Moreover, the industry-specific ECEC/money ratios calculated in this analysis provide a more accurate alternative to a single emergy/money ratio (*4*) or exergy/money ratio (*23*) currently being used in emergy and exergy analysis. The application also calculates ECEC/ICEC ratio to demonstrate the extent to which existing thermoeconomic analysis underestimates the contribution of ecosystems. This ratio does reflect quality differences between ecological resources including their renewable or nonrenewable nature. Besides ECEC/money and ECEC/ICEC ratios can be used together to generate industry-specific ICEC/money ratios that could be useful to improve upon the ad hoc procedures currently used in thermoeconomics to determine exergy content of purchased goods and services. The application, in general, may also provide a complementary biophysical approach to valuation-based methods (*3*) for quantifying the importance of ecosystems, and a foundation for further work in many areas including identifying and incorporating more information about ecosystems, addressing uncertainty, and hierarchical modeling. Economic input−output LCA (*33*) is similar to the proposed approach in its use of the toxic release inventory data to determine the emissions from each sector. However, unlike previous approaches, the work described in this article also accounts for ecological inputs, and uses end-point methods for impact assessment, with exergy as the common thermodynamic unit.

The rest of the paper is organized as follows. Section 2 presents the algorithm of thermodynamic input−output analysis. Additional details about theoretical aspects of thermodynamic input−output analysis can be found in the Supporting Information. Section 3 lists various ecological resources considered in this analysis along with their data sources. Section 4 presents results for the 1992 U.S. economy. Section 5 calculates several aggregate and normalized metrics, and finally Section 6 illustrates the application of thermodynamic input−output analysis and the additional insight it can provide by studying two electricity generation systems.

2. Approach: Thermodynamic Input−Output Analysis

This paper employs a thermodynamic approach for including contribution of ecological products and services to economic sectors via input−output analysis. A thermodynamic approach provides a common currency or a way to deal with a diverse set of units, as any system, economic or ecological, can be considered as a network of energy flows. Similarly thermodynamic methods such as ECEC analysis and emergy analysis can deal with partial information about underlying ecological networks. Money can also provide a common currency by using economic valuation methods to capture the contribution of ecosystems (*3, 10, 11*). If monetary values for the ecosystem products and services required by each economic sector were available, the approach proposed in this article may also be used to determine the monetary

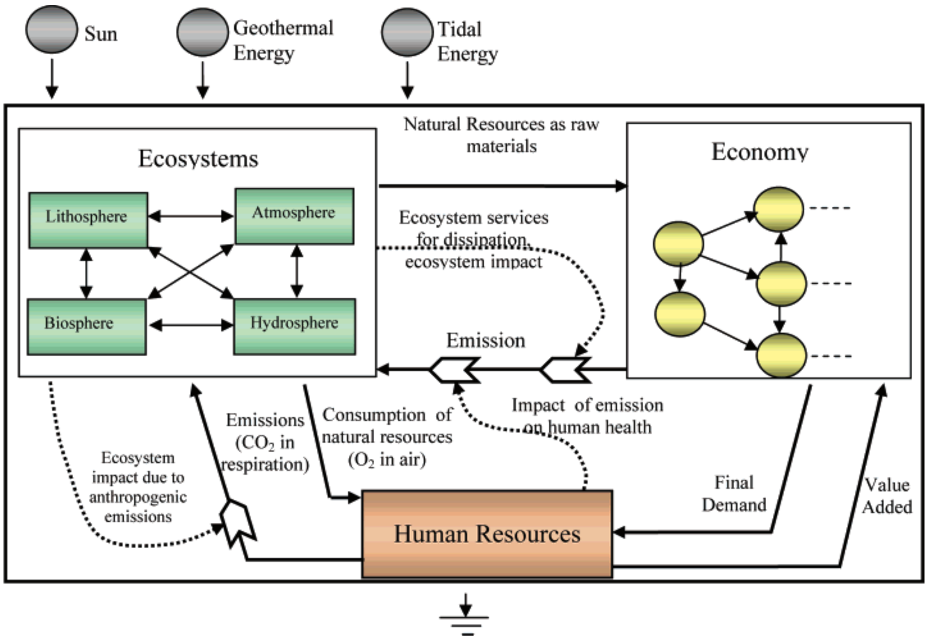


FIGURE 1. Integrated economic−ecological−human resource system (solid lines represent tangible interactions and dotted lines represent intangible interactions occurring as a consequence of emissions).

contribution of ecosystems at the sectoral level. The proposed thermodynamic approach is not meant to replace, but to complement an economic approach.

Thermodynamic input−output analysis recognizes the network structure of the integrated economic−ecological−social (EES) system shown in Figure 1. Such system is driven by three main sources of energy, namely solar radiation, tidal forces, and geothermal heat. The economy consists of a large number of industry sectors defined according to their Standard Industrial Classification codes. Ecological system consists of four conceptual ecospheres namely lithosphere (land), hydrosphere (water), atmosphere (air), and biosphere. Social sphere, also referred to as human resources, consists of consumers. Thermodynamically, the EES system is an open system with material and energy flows across system boundaries. For instance, energy enters the system from the three fundamental sources of energy and exits in the form of long wave radiation. Material enters the system in the form of imports and exits in the form of exports. Consideration of imports and exports is, however, beyond the scope of this paper. Solid lines in Figure 1 represent tangible interactions that include raw materials from and emissions to ecosystems, and human resources. Interactions shown with dotted lines in Figure 1 are less tangible and occur as a consequence of emissions. For example, the dotted line between the economy and ecosystems represents ecosystem services required for dissipating industrial emissions and the impact of emissions on ecosystems. Similarly the dotted line from human resources to economy represents impact of industrial emissions on human health. Dotted line from ecosystems to human resources represents impact of anthropogenic emissions on human health. The detailed network structure of the economic system is typically well-known, and is being used in the thermodynamic input−output analysis described in the next paragraph. Conversely, the network structure of ecological system need not be completely known as the underlying ECEC analysis can deal with partially known ecological networks using appropriate allocation rules (*31*).

The algorithm for thermodynamic input−output analysis focuses on the economic system and its interactions with ecosystems and human resources shown in Figure 1. It consists of the following three tasks.

Task 1 is to identify and quantify ecological and human resource inputs to the economic system. Such inputs include ecosystem products such as coal, wood, and water, ecosystem services such as wind, rain, and carbon sequestration, impact of emission on human health, and human resources consumed by economic activities in the form of labor employment.

Task 2 is to calculate ECEC of ecological inputs using transformities from systems ecology, and to classify inputs as additive or nonadditive to avoid double counting. In general, nonrenewable resources are additive, while renewable resources are nonadditive (*30*).

Task 3 is to allocate direct ecological and human resource inputs to economic sectors based on input−output data and the network algebra of ECEC analysis (*31*). More details about determination of ECEC of direct ecological inputs and their allocation through the economic system can be found in the Supporting Information. The network algebra of ECEC analysis is based on a static input−output representation of the economic system. Dynamic versions of input−output analysis that consider temporal changes in the economic network are also available, and will be explored in future research. Also, use of monetary data for allocation is not a limitation of the approach, but is rather caused by lack of comprehensive material or energy accounts of inter-industry interactions.

3. Data Requirements and Sources

This section describes the resources considered in this paper. All required data have been obtained from the public domain and corresponding data sources have been provided at appropriate locations in this Section and are summarized in Tables 1−3.

3.1. Transformities. ECEC of ecosystem products and services is quantified via their transformity values from the emergy analysis literature (*4*, *34*, *35*). As mentioned in Section 1, transformities as used in this analysis focus only on concurrent energy and do not include energy consumption over geological time scales. Furthermore, the concept of transformity is proved to be equivalent to the reciprocal of cumulative degree of perfection, a measure of life cycle thermodynamic efficiency (*31*). They are *not subject* to the

TABLE 1. Ecosystem Products

resource considered in this analysis	industry sector receiving direct input (SIC code)[a]	material or energy flow (F)	data source for F	ICEC flow (J/yr)[b]	transformity (τ)	data source for τ	ECEC flow $c = \tau \cdot F$ (sej/yr)
			Lithosphere				
crude petroleum field production	crude petroleum and natural gas (SIC 8)	1.31×10^{19} J/yr[c]	*36*	1.31×10^{19}	53 000 sej/J	*4*	6.95×10^{23}
iron-ore mining	metallic ores mining (SIC 5,6)	181 MMT/yr	37	1.88×10^{16}	1×10^{9} sej/g	*4*	1.81×10^{23}
nonferrous metal mining	metallic ores mining (SIC 5,6)	576 MMT/yr	*37*	4.71×10^{16}	1×10^{9} sej/g	*4*	5.76×10^{23}
crushed stone	nonmetallic minerals mining (SIC 9,10)	1118 MMT/yr	*37*, *38*	1.48×10^{17}	1×10^{9} sej/g	*4*	1.12×10^{24}
sand	nonmetallic minerals mining (SIC 9,10)	894 MMT/yr	*37*	1.18×10^{17}	1×10^{9} sej/g	*4*	8.94×10^{23}
raw coal excluding overburden	coal mining (SIC 7)	878 MMT/yr	*37*	2.56×10^{19}	1×10^{9} sej/g	*4*	8.78×10^{23}
nitrogen from mineralization	other agricultural products (SIC 2)	3 MMT/yr	*37*	1.16×10^{15}	4.19×10^{9} sej/g	*4*	1.26×10^{22}
phosphorus from mineralization	other agricultural products (SIC 2)	2 MMT/yr	*37*	9.88×10^{14}	2×10^{9} sej/g[d]	*4*	4×10^{21}
N-deposition from atmosphere[e]	other agricultural products (SIC 2)	2 MMT/yr	*37*	7.76×10^{14}	4.19×10^{9} sej/g	*4*	8.38×10^{21}
return of decomposing detritus to agricultural soil	other agricultural products (SIC 2)	-440 MMT/yr[f]	*37*	-8.91×10^{18}	2.24×10^{8} sej/g of residue[g]	*4*	-9.87×10^{22}
			Biosphere				
wood production	forestry and fishery products (SIC 3)	520 MMT/yr of roundwood	*37*	8.27×10^{18}	5.55×10^{8} sej/g[h]	*4*	2.89×10^{23}
pasture grazing	livestock and livestock products (SIC 1)	200 MMT/yr of wet grass	*37*	1.67×10^{18}	5.83×10^{19} sej/MMT of wet grass[i]	*4*	1.17×10^{22}
			Hydrosphere				
water consumption	water and sanitary services (SIC 68C)	1.47×10^{14} gallons/yr	*39*	2.73×10^{18}	7.67×10^{8} sej/gal[j]	*34*	1.13×10^{23}
			Atmosphere				
CO_2 in 24-hr net photosynthesis	other agricultural products (SIC 2)	880 MMT/yr	*37*	0[k]	6.19×10^{7} sej/g CO_2[l]	*4*	5.45×10^{22}

[a] Industry sectors and their SIC codes are given in Appendix D of the Supporting Information. [b] Details of ICEC calculations shown in Appendix C of the Supporting Information. [c] (5.953×10^{6} barrels on-shore production/day) × (30 days/month) × (12 months/yr) × (6.12×10^{9} J/barrel) $= 1.31 \times 10^{19}$ J/yr. [d] (4.6×10^{8} sej/g of P_2O_5) × (1 g of P_2O_5/0.23 g of P) $= 2 \times 10^{9}$ sej/g of P. [e] N-deposition from atmosphere is considered an input from lithosphere since nitrogenous salts enter plants through soil. [f] Negative sign indicates flow from industry sector to lithosphere. [g] (0.44 g C/g of residue) × (11 Kcal/g C) × (4186 J/Kcal) × (11068 sej/J transformity of detritus production) $= 2.24 \times 10^{8}$ sej/g residue. [h] (3.8 Kcal/g roundwood) × (4186 J/Kcal) × (34 900 sej/J) $= 5.55 \times 10^{8}$ sej/g of roundwood. [i] (0.5 MMT of dry grass/MMT of wet grass) × (10^{12} g/MMT) × (1.86×10^{11} J/ha/yr of pasture evapotranspiration) × (6962 sej/J) × (9×10^{-4} m^2/g) × (10^{-4} ha/m^2) $= 5.83 \times 10^{19}$ sej/MMT of wet grass. [j] (3785 cm^3/gallon of water) × (1 g of water/cm^3 of water) × (4.94J/g of water) × (4.1×10^{4} sej/J) $= 7.67 \times 10^{8}$ sej/gallon of water. [k] Atmospheric gases being at reference state are ignored in ICEC analysis. [l] (12 g C/44 g CO_2) × (8 Kcal/g C) × (4186 J/Kcal) × (6780 sej/J) $= 6.19 \times 10^{7}$ sej/g CO_2.

TABLE 2. Ecosystem Services

ecosystem service	sector receiving direct input (SIC code)	energy or material flow (F)	data source for F	ICEC flow (J/yr)	transformity (τ) (sej/J)	data source for τ	ECEC flow ($C = F \cdot \tau$) (sej/yr)
sunlight for photosynthesis	other agricultural products (SIC 2)	2.26×10^{22} J/yr	*40*, *41*	2.26×10^{22}	1	*4*	2.26×10^{22}
	forestry and fishery products (SIC 3)	1.19×10^{22} J/yr	*41*, *42*	1.19×10^{22}	1	*4*	1.19×10^{22}
hydropotential for power generation	electric services (utilities) (SIC 68A)	9.11×10^{17} J/yr	*43*	9.11×10^{17}	27764	*4*	2.52×10^{22}
geothermal heat for power generation	electric services (utilities) (SIC 68A)	5.83×10^{16} J/yr	*43*	5.83×10^{16}	6055	*4*	3.53×10^{20}
wind energy for power generation	electric services (utilities) (SIC 68A)	1.02×10^{16} J/yr	*43*	1.02×10^{16}	1496	*4*	1.52×10^{19}
fertile soil	other agricultural products (SIC 2)	37.04×10^{8} ton/yr	*12*, *13*	3.35×10^{18}	4.43×10^{4}	*35*	1.48×10^{23} [a]
	new construction (SIC 11)	36.59×10^{8} ton/yr	*12*, *13*	3.31×10^{18}	4.43×10^{4}	*35*	1.47×10^{23}

[a] (37.04×10^{8} ton/yr topsoil loss) × (4% organics in soil) × (5.4 Kcal/g energy content of organic soil) × (4186 J/Kcal) × (4.43×10^{4} sej/J) = 1.48×10^{23} sej/yr; transformity adjusted to 1996 base of 9.44×10^{24} sej/yr.

TABLE 3. Pollutants, Immediate Destination of Emission, and Impact Category

pollutant	immediate destination of emission	impact category considered	DALY/kg of emission[a]	ECEC/kg of emission (sej/kg)
SO_2	air	respiratory disorders	5.46×10^{-5}	1.86×10^{12} [b]
NO_2	air	respiratory disorders	8.87×10^{-5}	3.03×10^{12}
PM10	air	respiratory disorders	3.75×10^{-4}	1.28×10^{13}
CO_2	air	climate change[c]	2.1×10^{-7}	7.17×10^{9}
methanol	air	respiratory disorders	2.81×10^{-7}	9.59×10^{9}
ammonia	air	respiratory disorders	8.5×10^{-5}	2.90×10^{12}
toluene	air	respiratory disorders	1.36×10^{-6}	4.64×10^{10}
1,1,1-TCE	air	ozone layer depletion	1.26×10^{-4}	4.30×10^{12}
styrene	air	carcinogenic effect	2.44×10^{-8}	8.33×10^{8}
styrene	water	carcinogenic effect	1.22×10^{-6}	4.16×10^{10}
styrene	soil	carcinogenic effect	2.09×10^{-8}	7.13×10^{8}

[a] DALY values are based on hierarchist perspective. [b] Human health impact of emission per kg of SO_2 emission = (5.46×10^{-5} DALY/kg of SO_2 emission) × (365 days/yr) × (9.35×10^{13} sej emergy associated with unskilled labor/workday) = 1.86×10^{12} sej/kg; Emergy of unskilled labor is obtained from emergy literature (*4*), and is obtained by dividing total emergy budget of the U.S. (7.85×10^{24} sej/yr) by the total population of the U.S. (230×10^{6} people). [c] Potential impacts in future (*44*).

most controversial aspects of Odum's work, such as the maximum empower principle and the emergy theory of value. Transformities used in this analysis correspond to the 1996 base of 9.44×10^{24} sej/yr (*4*).

3.2. Ecosystem Products. Ecosystem products refer to an array of ecological resources used as direct raw materials in industrial processes. They are either produced by or are a part of various ecosystem services. For example, water consumed for domestic or industrial purposes embodies constituents of the hydrologic cycle such as rain and water streams, while mineral and fossil resources are made available by the geologic cycle. Ecosystem products are always associated with corresponding material or energy flows. Crude oil in refineries and water for human consumption are some examples of ecosystem products. Table 1 shows ecosystem products considered in this analysis along with industry sectors receiving their direct inputs and corresponding data sources. The ecological products are grouped into four ecological spheres: lithosphere, biosphere, atmosphere, and hydrosphere depending on their mode of entry into the economic system.

3.3. Ecosystem Services. Ecosystem services refer to various natural functions that support economic activities. Unlike ecological products, ecosystem services need not always be associated with material or energy flows. For instance, dissipation of emissions by wind and use of geothermal heat for electricity generation are examples of ecosystem services that are associated with mass or energy flows. These are the *supply-based* services. Ecosystem services required for recreational and cultural purposes, on the other hand, are based on human valuation and are not necessarily accompanied by material or energy flows. These are the *value-*

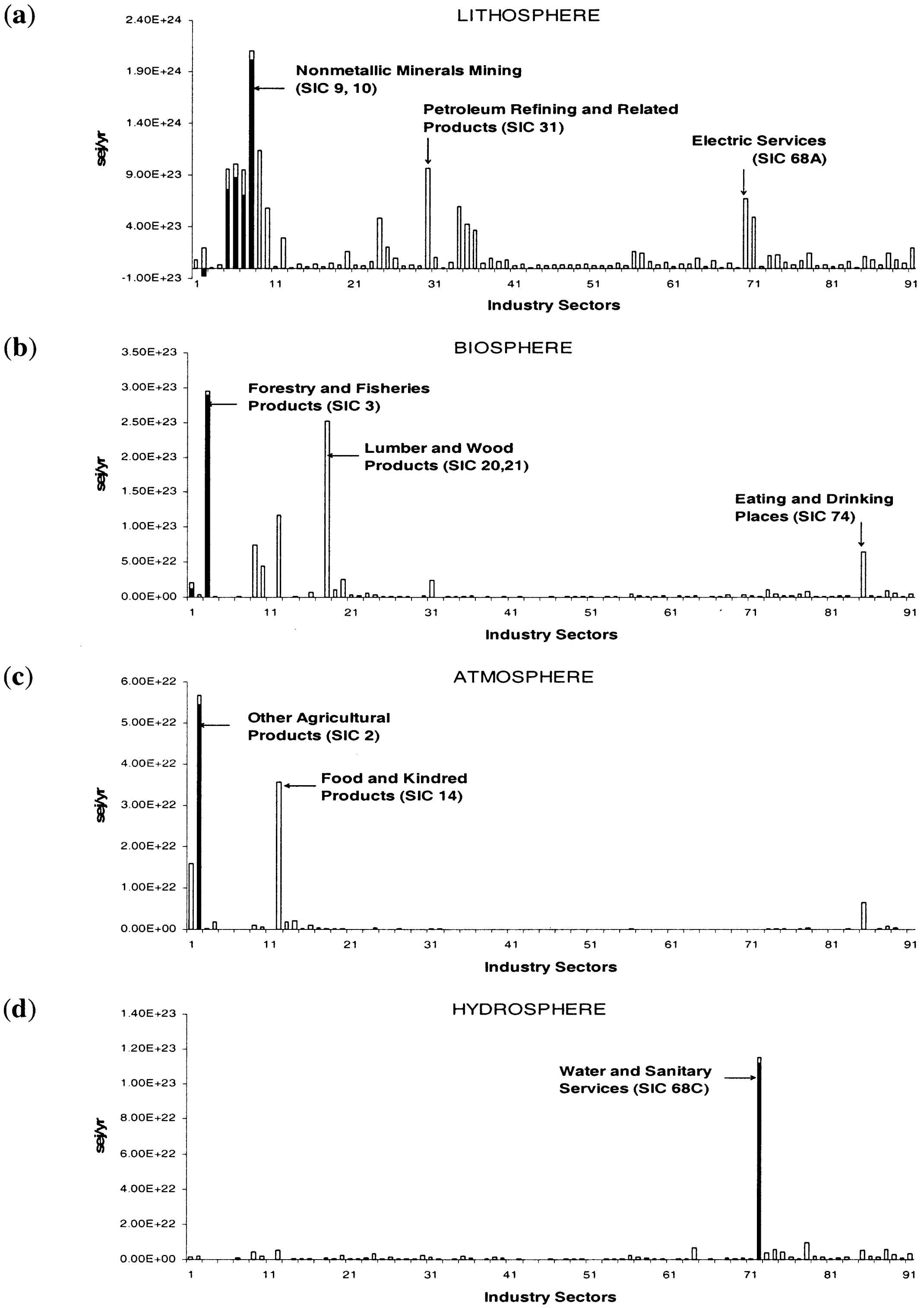


FIGURE 2. Contribution of ecological products to U.S. economic sectors from (a) lithosphere; (b) biosphere; (c) atmosphere; and (d) hydrosphere. The *y*-axis is ECEC in solar equivalent joules (sej) and *x*-axis is sector serial number (black part of each bar represents direct inputs and white part represents indirect inputs).

based services. This analysis focuses only on the supply-based services listed in Table 2. Value-based services are dealt with in refs *3* and *10*.

3.4. Impact of Emissions. Once emitted to the environment every pollutant is diluted to some base concentration by ecosystem services such as wind and water streams. Several spatial and temporal factors such as dispersion, diffusion, and atmospheric chemistry become important in determining this base concentration. If the base concentration is more than a certain threshold value the corresponding emission causes human and ecosystem health impact. The impact itself depends on fate of pollutants in ecosystems, their exposure to people, and their effect on human anatomy. There are several established procedures for calculating the impact associated with emissions. The approach employed in this analysis uses eco-indicator 99 (*44, 45*). This work only focuses on impacts on human health as measured by disability adjusted life years (DALY). Table 3 lists various

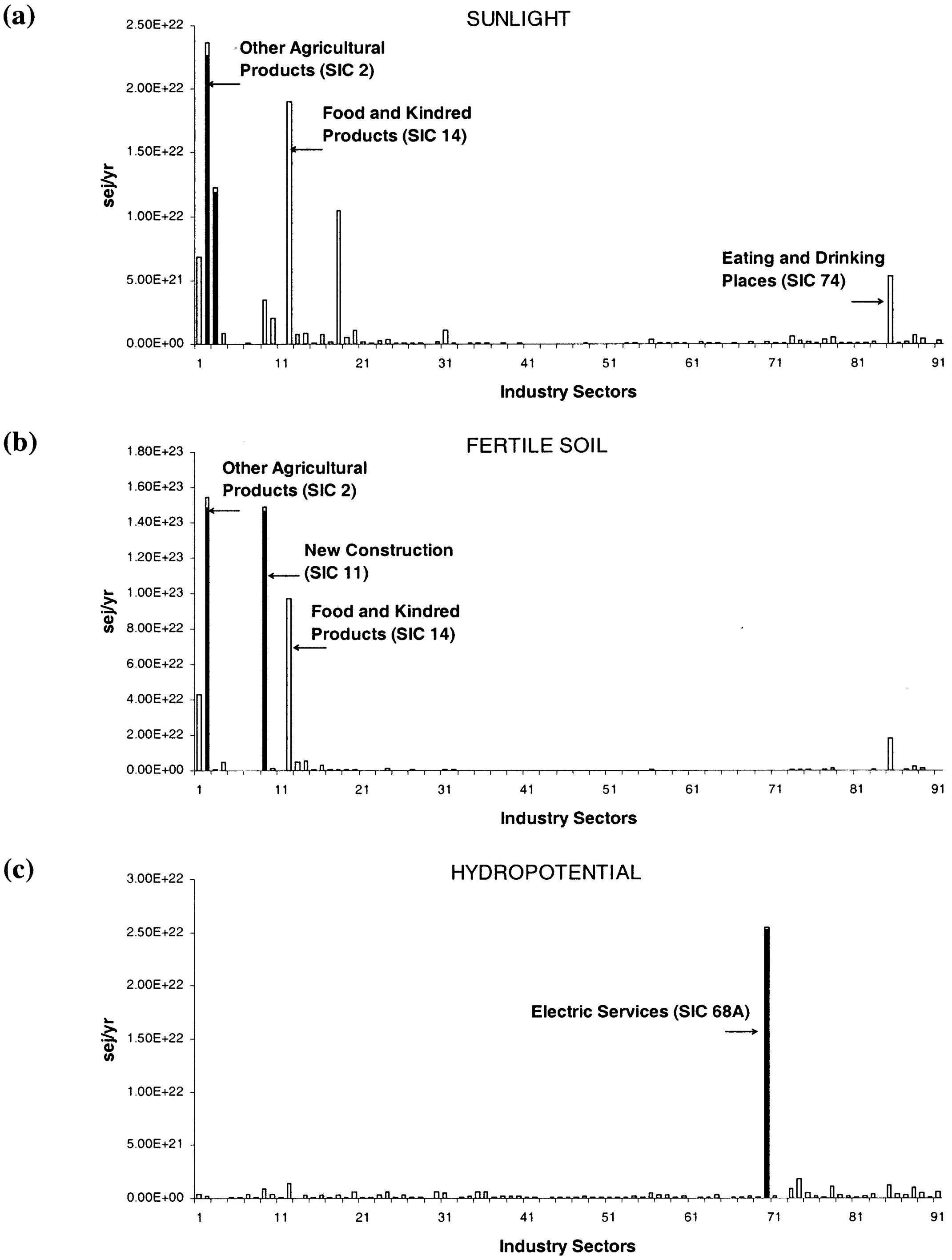


FIGURE 3. Contribution of direct ecosystem services from (a) sunlight; (b) fertile soil; and (c) hydropotential (black part of each bar represents direct inputs and white part represents indirect inputs).

pollutants considered in this work, the impact categories to which they belong, and the corresponding DALY values per kg of emission. Data on emissions are gathered from the U.S. Environmental Protection Agency's Toxics Release Inventory (TRI) which is published on a periodic basis (*46*). DALY values have been obtained from eco-indicator 99. The approach for converting DALY to ECEC is discussed in Appendix A of the Supporting Information. Work toward including more pollutants in this analysis is in progress.

3.5. Human Resources and Inter-Industry Allocation Matrix. Industry sectors consume human resources in the form of labor. Amount of human resources consumed is a function of number of individuals employed and the skill-level (quality) of the labor. In this paper, average annual payroll is chosen as a measure of the quality of labor. Data about number of people employed and their average annual payroll are available from U.S. Department of Labor's Bureau of Labor Statistics (*47*).

This paper uses a monetary allocation matrix to represent inter-industry interactions. This matrix is the inter-industry transaction coefficient matrix defined in economic input–output literature and compiled in the U.S. by the Bureau of Economic Analysis. Tables of direct requirements and transaction coefficients for the U.S. economy are readily available (*48*). This paper uses the 1992 U.S. inter-industry input–output tables, as most of the natural resource consumption data are available for the early 1990s. If the "materials count" initiative undertaken by the National

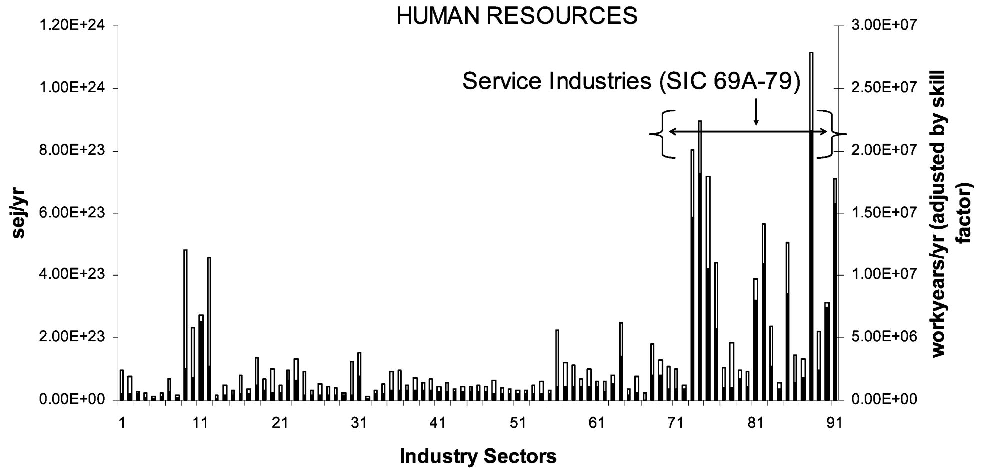


FIGURE 4. ECEC requirements from human resources (black part of each bar represents direct inputs and white part represents indirect inputs).

Research Council (*15*) materializes, more accurate data could be used for inter-industry allocation (*49*).

4. Results

4.1. Ecosystem Products. Figure 2 shows the contribution of ecological products listed in Table 1 to the 91 sectors of the 1992 U.S. economy. The sector names, SIC codes, and serial numbers of the economic sectors are shown in Appendix D of the Supporting Information.

Lithosphere. Figure 2a shows ECEC requirements of industry sectors from the lithosphere. Sectors of metallic ores mining (SIC 5, 6), coal mining (SIC 7), crude petroleum and natural gas (SIC 8), and nonmetallic minerals mining (SIC 9, 10) receive direct inputs from lithosphere. The sector of other agricultural products (SIC 2) has a direct output to the lithosphere on account of return of detrital matter to agricultural soil. This is shown by a small negative peak for SIC 2. However, SIC 2 consumes other products from the lithosphere indirectly and, as a result, has a net positive requirement. Other sectors such as petroleum refining and related products (SIC 31), stone and clay products (SIC 36), electric services (SIC 68A), gas production and distribution (SIC 68B), and industrial and other chemicals (SIC 27A) also have prominent peaks on account of indirect consumption.

Biosphere. Figure 2b shows ECEC from the biosphere. Sectors of livestock and livestock products (SIC 1) and forestry and fishery products (SIC 3) get direct inputs from the biosphere due to pasture harvesting and timber harvesting, respectively. Sectors of new construction (SIC 11), maintenance and repair construction (SIC 12), food and kindred products (SIC 14), and lumber and wood products (SIC 20, 21) also have prominent peaks because of indirect consumption. The sector of eating and drinking places (SIC 74) also has a substantial indirect requirement from biosphere.

Atmosphere. Figure 2c shows ECEC from the atmosphere. This graph shows prominent peaks for sectors of other agricultural products (SIC 2) and food and kindred products (SIC 14). Materials handling machinery and equipment (SIC 46), nonmetallic minerals mining (SIC 9, 10), and engines and turbines (SIC 43) are the sectors with the lowest requirements from atmosphere. As mentioned in Table 1, only CO_2 consumed during 24-hour photosynthesis has been considered in this analysis. Other atmospheric gases such as N_2 and O_2 have not been considered because their transformity values are unresolved in emergy analysis. Determining transformities of N_2 and O_2 is a nontrivial task because of their presence in several geo−bio−chemical cycles. For instance, O_2 is an integral part of nitrogen, sulfur, carbon, and phosphorus cycles, all of which are interconnected. Currently work is underway in systems ecology to evaluate these transformities, and they will be included in future publications as they become available.

Hydrosphere. Figure 2d shows ECEC requirements from hydrosphere. Only the sector of water and sanitary services (SIC 68C) has direct inputs from hydrosphere. None of the other sectors have any prominent peaks, indicating that dependence of other sectors on SIC 68C is relatively uniform. This is in contrast to graphs of other ecospheres where a handful of embedded sectors depend more heavily on peripheral sectors than others. This paper concentrates on water bodies such as lakes and rivers that supply water to the sector of water and sanitary services (SIC 68C). Hydrosphere also includes other elements such as rain and its services to economic sectors through climate regulation and cleansing of air. Such elements have not been considered in this analysis.

4.2. Ecosystem Services. Figure 3 shows the direct ECEC inputs of ecosystem services listed in Table 2.

Sunlight. Figure 3a shows the contribution of sunlight. Sectors of other agricultural products (SIC 2) and forestry and fisheries products (SIC 3) are the direct recipients of sunlight, whereas sectors of food and kindred products (SIC 14), livestock and livestock products (SIC 1), and eating and drinking places (SIC 74) also have prominent peaks on account of indirect consumption.

In this paper, sunlight is assumed to enter the U.S. economy through SIC 2 and SIC 3 in proportion to their relative land areas (*40, 42*). This is similar to the assumption made by Costanza who considered solar energy inputs to the U.S. economy to calculate embodied energy intensities of industry sectors (*26*). However, as recognized by Costanza, the approach in (*26*) was quite crude as it did not consider indirect routes of solar inputs to industry sectors. Such indirect routes include various bio−geo−chemical cycles such as the hydrologic cycle and atmospheric circulation that are driven by solar energy. The approach proposed in this paper overcomes this shortcoming as it is able to capture some of these indirect routes via the use of transformity values. Transformity, by definition, captures solar, tidal, and geothermal energy embodied in ecosystem products and services. As a result, the approach presented in this paper not only considers direct solar inputs to agricultural, forestry, and related activities but also indirect solar inputs embodied in ecosystem products and services.

Fertile Soil. Figure 3b shows ECEC content of topsoil lost due to erosion. Sectors of other agricultural products (SIC 2) and new construction (SIC 9) are directly responsible for the loss of top organic soil. The sector of food and kindred

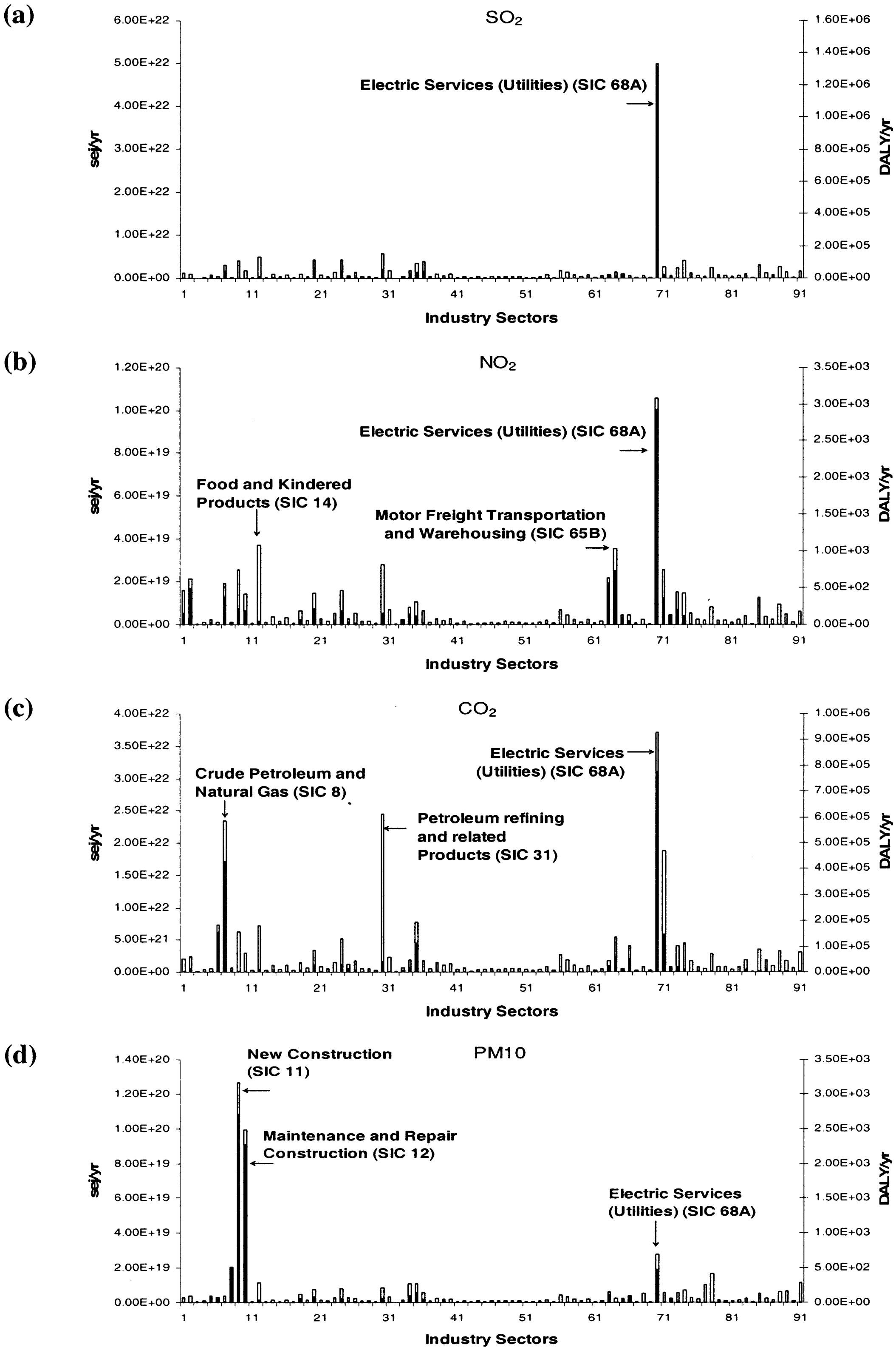
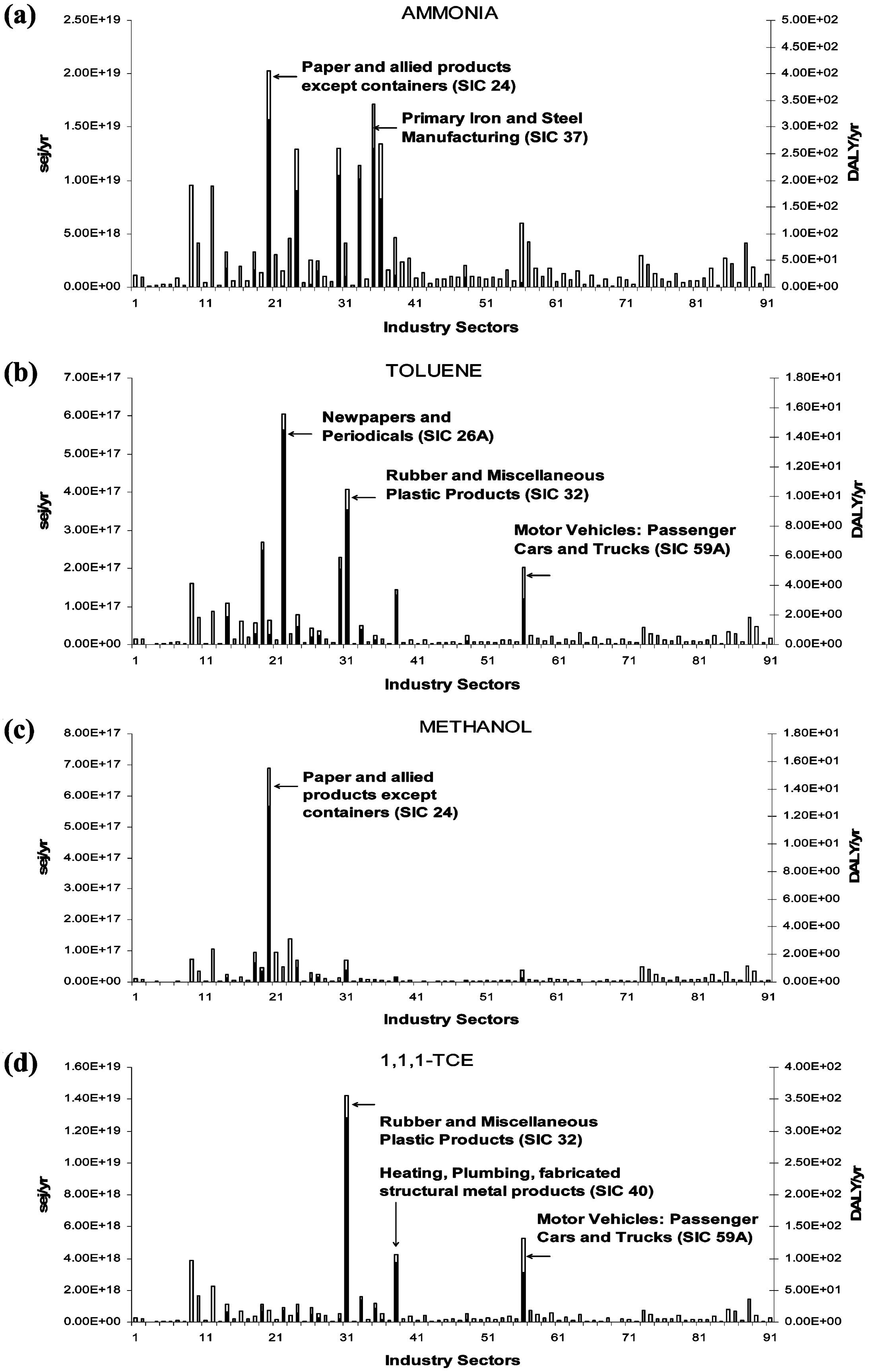


FIGURE 5. Impact of emissions in terms of ECEC from (a) SO_2; (b) NO_2; (c) CO_2; and (d) PM10 (black part of each bar represents direct inputs and white part represents indirect inputs).

products (SIC 14) also causes substantial loss indirectly. Contribution of fertile soil is significantly larger than that of sunlight because top organic soil is a more concentrated form of resource than sunlight. This is also reflected in a higher transformity value for topsoil in Table 2.

Hydropotential. Figure 3c shows the contribution of hydropotential to industry sectors. Hydropotential refers to the potential energy in water streams that is first converted to kinetic energy and then to electrical energy in hydroelectric power plants. Naturally the sector of electric services (SIC 68A) is the only sector with direct input. There are no other prominent peaks suggesting that other sectors depend on SIC 68A evenly. However, the service sectors (SIC 72–77B) have higher indirect ECEC requirements. Especially the sector


(a)
AMMONIA
Paper and allied products except containers (SIC 24)
Primary Iron and Steel Manufacturing (SIC 37)
sej/yr
DALY/yr
0.00E+00
5.00E+18
1.00E+19
1.50E+19
2.00E+19
2.50E+19
0.00E+00
5.00E+01
1.00E+02
1.50E+02
2.00E+02
2.50E+02
3.00E+02
3.50E+02
4.00E+02
4.50E+02
5.00E+02
1
11
21
31
41
51
61
71
81
91
Industry Sectors
(b)
TOLUENE
Newpapers and Periodicals (SIC 26A)
Rubber and Miscellaneous Plastic Products (SIC 32)
Motor Vehicles: Passenger Cars and Trucks (SIC 59A)
sej/yr
DALY/yr
0.00E+00
1.00E+17
2.00E+17
3.00E+17
4.00E+17
5.00E+17
6.00E+17
7.00E+17
0.00E+00
2.00E+00
4.00E+00
6.00E+00
8.00E+00
1.00E+01
1.20E+01
1.40E+01
1.60E+01
1.80E+01
1
11
21
31
41
51
61
71
81
91
Industry Sectors
(c)
METHANOL
Paper and allied products except containers (SIC 24)
sej/yr
DALY/yr
0.00E+00
1.00E+17
2.00E+17
3.00E+17
4.00E+17
5.00E+17
6.00E+17
7.00E+17
8.00E+17
0.00E+00
2.00E+00
4.00E+00
6.00E+00
8.00E+00
1.00E+01
1.20E+01
1.40E+01
1.60E+01
1.80E+01
1
11
21
31
41
51
61
71
81
91
Industry Sectors
(d)
1,1,1-TCE
Rubber and Miscellaneous Plastic Products (SIC 32)
Heating, Plumbing, fabricated structural metal products (SIC 40)
Motor Vehicles: Passenger Cars and Trucks (SIC 59A)
sej/yr
DALY/yr
0.00E+00
2.00E+18
4.00E+18
6.00E+18
8.00E+18
1.00E+19
1.20E+19
1.40E+19
1.60E+19
0.00E+00
5.00E+01
1.00E+02
1.50E+02
2.00E+02
2.50E+02
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81
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Industry Sectors

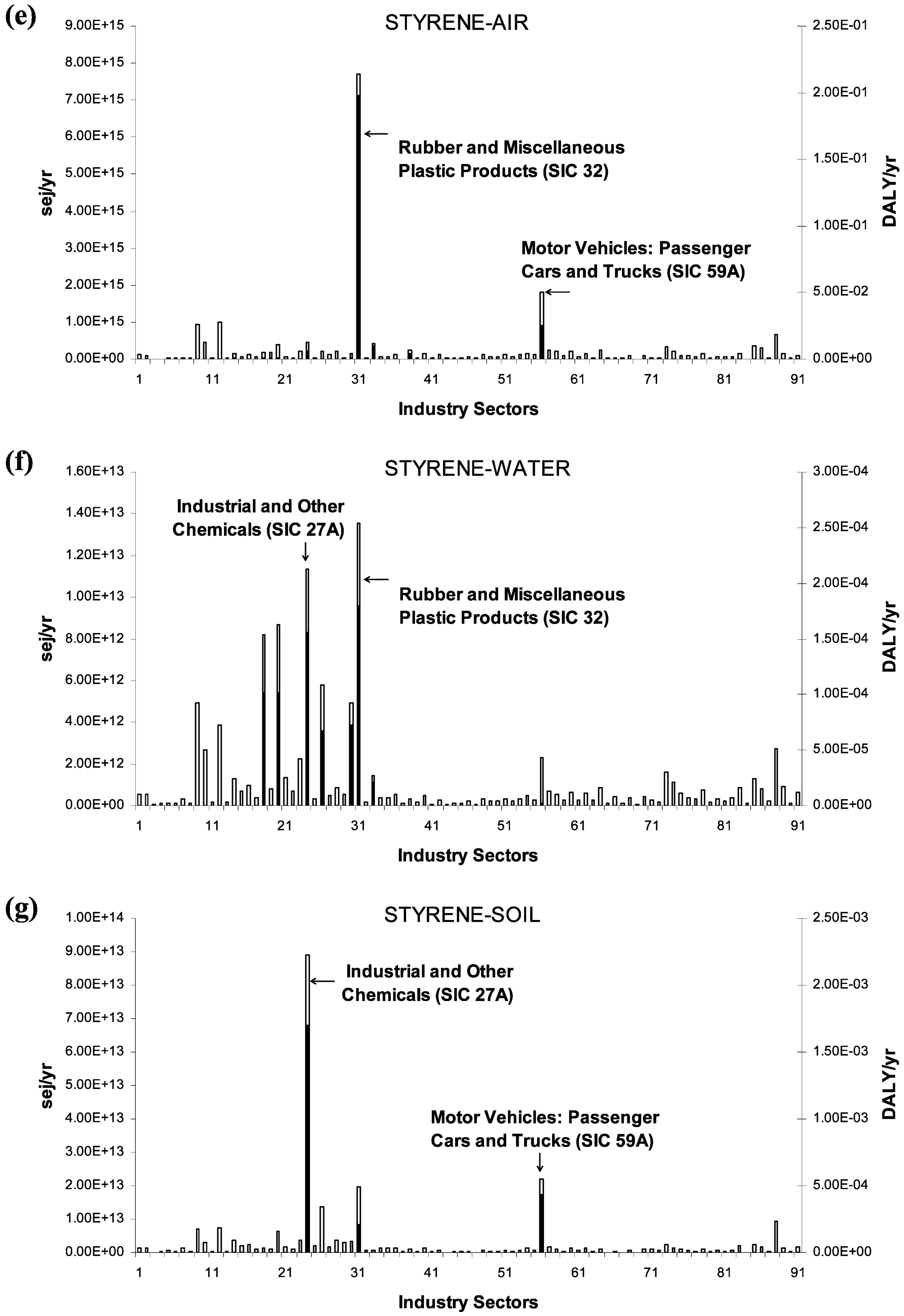

FIGURE 6. Impact of nonbulk pollutants (a) ammonia; (b) toluene; (c) methanol; (d) 1,1,1-trichloroethane; (e) styrene emission to air; (f) styrene emission to water; and (g) styrene emission to soil (black part of each bar represents direct inputs and white part represents indirect inputs).

of retail trade (SIC 69B) has higher indirect contribution from SIC 68A than any other sector. This can be explained by the dominant position of service industry in the U.S. economy. Service sectors generate 66% of all economic activity in the United States, and consequently have high electricity requirements.

The contribution of wind energy and geothermal energy is also calculated but not shown because it is qualitatively identical to that of hydropotential shown in Figure 3c. In all three cases the sector of electric services (SIC 68A) is the only direct recipient. Moreover, the inter-industry allocation matrix used in determining indirect requirements of other industry sectors is also the same. The only difference is in the *y*-axis magnitude. Contribution from hydropotential is nearly 3 orders of magnitude higher than that from wind energy.

4.3. Human Resources. Figure 4 shows ECEC requirements of industry sectors from human resources. Unlike previous graphs, every sector in Figure 4 has direct inputs of human resources, since every sector employs labor. Service sectors (SIC 69A−77B) have higher direct inputs than the manufacturing sectors (SIC 14−64). The sector of health services (SIC 77A) has the highest consumption of human resources. Sectors of retail trade (SIC 69B), wholesale trade (SIC 69A), and state and local government enterprises (SIC 79) are other major consumers of human resources. Sectors of new construction (SIC 11), maintenance and repair construction (SIC 12), and food and kindred products (SIC 14) also have high consumption of human resources on account of indirect inputs.

4.4. Human Impact of Bulk Pollutants. Figure 5 shows the human health impact of the four bulk pollutants considered in this paper. These are SO_2, NO_2, PM10, and CO_2. As discussed in Section 3.4 and the Supporting Information, each plot is proportional to the DALY of the corresponding pollutant based on a hierarchist perspective (*44*).

Sulfur Dioxide. Figure 5a shows the impact associated with SO_2. Power plants are the major emitters of SO_2. Petroleum refining and related products (SIC 31), food and kindred products (SIC 14), and paper and allied products except containers (SIC 24) are other sectors with significant impact due to SO_2 emission.

Nitrogen Oxides. Figure 5b shows impact associated with NO_2 emissions. Power plants (SIC 68A) are the major emitters of NO_2. Food and kindred products (SIC 14), motor freight transportation and warehousing (SIC 65B), and petroleum refining and related products are other sectors with prominent peaks. Agriculture and livestock sectors (SIC 1, 2) also have significant peaks due to high usage of nitrogenous fertilizers, the production of which is a source of NO_x.

Carbon Dioxide. Figure 5c shows impact associated with CO_2 emission. CO_2 is emitted in combustion processes such as furnaces and internal combustion engines, and affects human health through climate change and global warming. Sectors of electric services (SIC 68A), petroleum and refining related products (SIC 31), and crude petroleum and natural gas mining (SIC 8) have major impact due to CO_2 emission. These sectors are directly involved in extraction and consumption of fossil fuels. Impact of CO_2 emissions, as reported in eco-indicator 99, is the potential impact in future (*44*).

Particulate Matter. Figure 5d shows impact associated with emission of PM10. PM10 is primarily responsible for respiratory disorders. Sectors of new construction (SIC 11), maintenance and repair construction (SIC 12), electric services (SIC 68A), and ordnance and accessories (SIC 13) are major emitters of particulate matter. Some service industries such as owner occupied dwellings (SIC 71A), real estate and royalties (SIC 71B), and state and local government enterprises (SIC 79) also have noticeable peaks due to indirect effects. Among the bulk pollutants, impact associated with SO_2 and CO_2 is 2 orders of magnitude higher than that for NO_2 and PM10.

4.5. Human Impact of Non-Bulk Pollutants. Figure 6 shows impact associated with selected nonbulk pollutants. Their immediate destinations and the impact categories to which they belong are listed in Table 3.

Ammonia. Figure 6a shows impact associated with emission of ammonia. Ammonia is primarily emitted by manufacturing sectors, namely paper and allied products except containers (SIC 24), stone and clay products (SIC 36), and petroleum refining and related products (SIC 31). Other sectors with prominent peaks include primary nonferrous metals manufacturing (SIC 37) and other printing and publishing (SIC 26B).

Toluene. Figure 6b shows impact associated with emission of toluene. Sectors of newspapers and periodicals (SIC 26A) and rubber and miscellaneous products (SIC 32) have the highest impact. Other sectors with significant impact are furniture and fixtures (SIC 22, 23), petroleum refining and related products (SIC 31), and motor vehicles (passenger cars and trucks) (SIC 59A).

Methanol. Figure 6c shows impact associated with emission of methanol. Paper and allied products except containers (SIC 24), lumber and wood products (SIC 20, 21), and industrial and other chemicals (SIC 27A) are some of the major emitters of methanol. Other sectors with prominent peaks include other printing and publishing (SIC 26B), food and kindred products (SIC 14), and new construction (SIC 11).

1,1,1-Trichloroethane. Figure 6d shows impact associated with 1,1,1-trichloroethane. 1,1,1-TCE plays an active role in ozone layer depletion. Rubber and miscellaneous plastic products (SIC 32), motor vehicles (passenger cars and trucks) (SIC 59A), and heating, plumbing, fabricated structural metal products (SIC 40) are some of the major emitters of 1,1,1-TCE. New construction (SIC 11) and food and kindred products (SIC 14) also have substantial impact due to indirect effects.

Styrene. Figure 6e−g show impact associated with emission of styrene. Styrene is a carcinogenic substance that is released to soil, water, and air. Depending on the immediate destination of styrene emission human health impact could be very different. This is demonstrated by Figure 6e−g. The impact of styrene emission to air is 2 orders of magnitude higher than that to water or soil. Sectors of rubber and miscellaneous plastic products (SIC 34) and motor vehicles (passenger cars and trucks) (SIC 59A) are the major emitters of styrene to air. Industrial and other chemicals (SIC 27A), paper and allied products except containers (SIC 24), and lumber and wood products (SIC 20, 21) are the primary emitters of styrene emission to water streams. The sector of health services (SIC 77A) also has appreciable impact on human health due to indirect effects.

5. Aggregate Metrics

This section presents and interprets aggregated metrics based on the results obtained in Section 4. Such aggregation is facilitated by the fact that all the results obtained in Section 4 are expressed in a single consistent thermodynamic unit of solar equivalent joule (sej). Use of a single consistent thermodynamic unit provides a systematic way of combining information available in disparate units. For instance, ecosystem products and services are typically measured in disparate units such as tonnes of coal and joules of sunlight. Moreover, ecological resources that do get expressed in the same unit cannot be combined without appreciating their quality differences. As a result, existing methods for environmental decision-making such as EIOLCA report consumption data for ecological resources and emission data for various pollutants separately. It is then the job of the user to distill these data into a smaller number of indices that are easy to use and, yet, sufficiently representative. There is no established method for combining the data expressed in disparate units, and arbitrary valuation is often employed. Thermodynamic input−output analysis is useful for addressing this issue, since it presents a systematic way of aggregating resource consumption and emission data into a smaller number of indices. Consequently, the proposed approach is potentially useful in constructing hierarchical metrics of sustainability (*50*, *51*).

Care must be taken in aggregating the results obtained in Figures 2−6 because simple, across-the-board addition may lead to double counting. The solution proposed in emergy analysis (*4*) and ECEC analysis (*31*) is to divide the resources into two groups: additive and nonadditive. This distinction is due to the allocation methods used for ecological inputs in emergy analysis to avoid double-counting. Accordingly, renewable resources are nonadditive, while nonrenewable resources are additive. In the context of this paper, inputs from atmosphere, hydrosphere, and ecosystem ser-

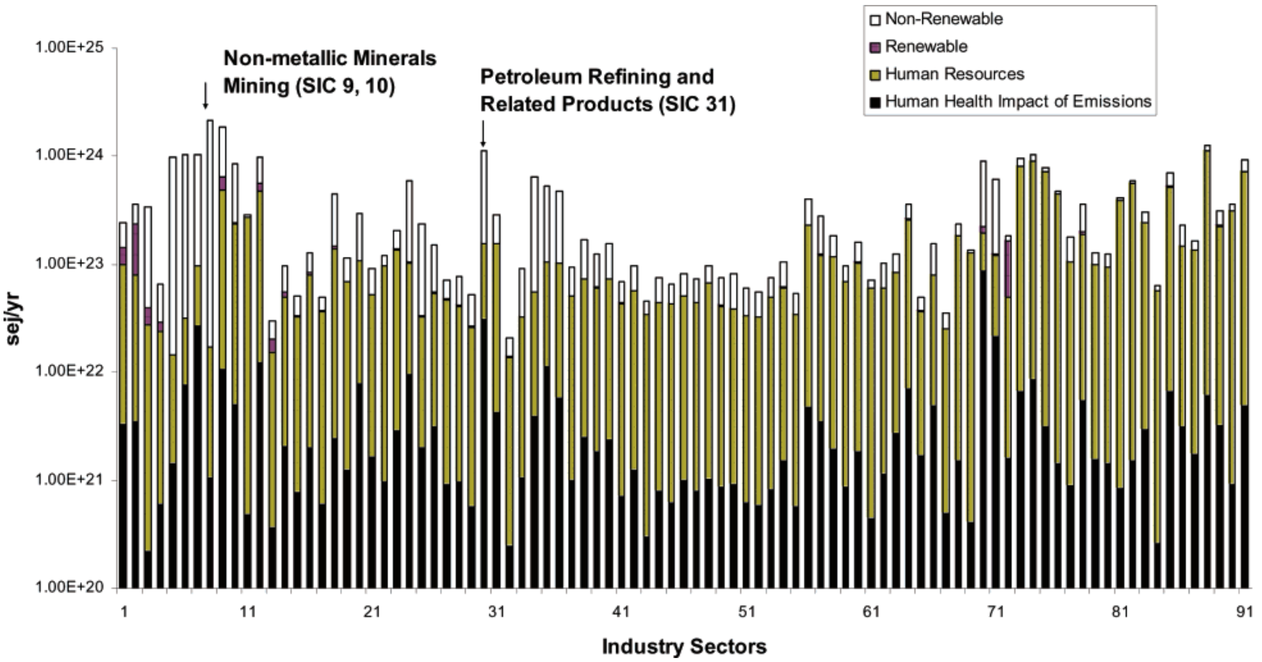

FIGURE 7. Total ECEC Requirements of Industry Sectors

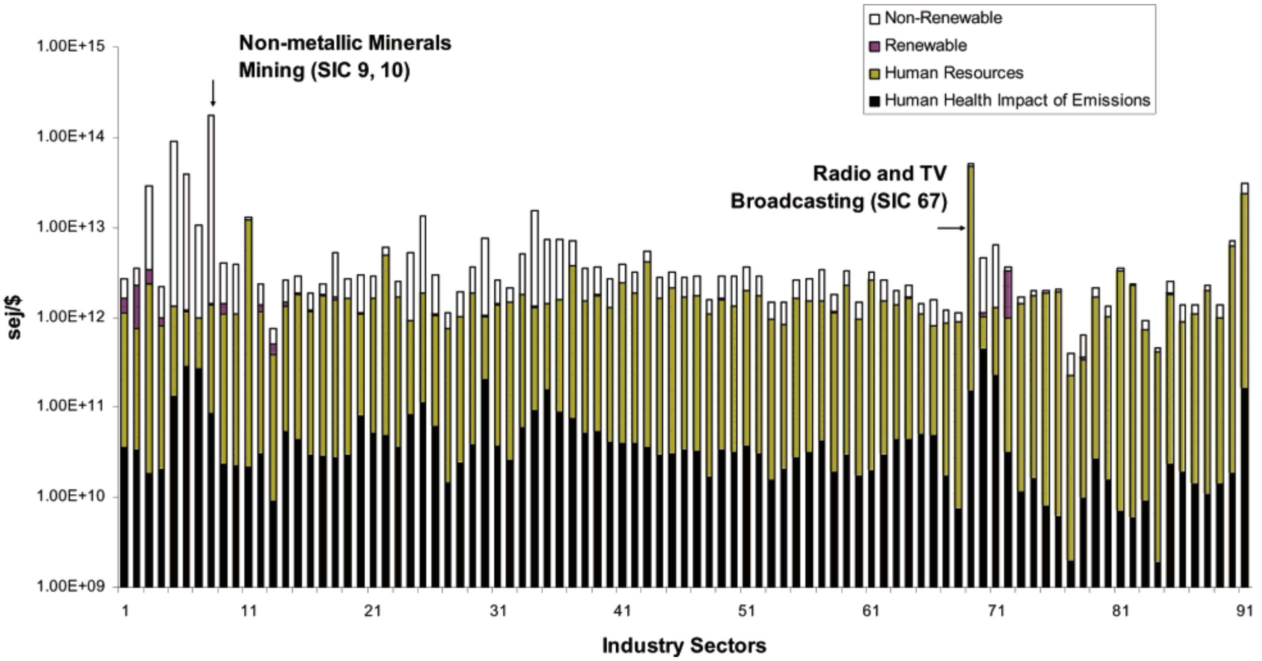

FIGURE 8. ECEC/Money Ratio for Industry Sectors

vices are nonadditive, whereas inputs from lithosphere, biosphere, human resources, and impact of emissions on human health are additive. Since the choice of allocation rules is usually subjective, the sensitivity of the results to different allocation rules should be evaluated. It may also be possible to select system boundaries that avoid allocation altogether. The application of such techniques to the analysis presented in this paper is a part of the ongoing work.

5.1. Total ECEC. Total ECEC of each industry sector is shown in Figure 7 and is also listed in Table E1 in the Supporting Information. Figure 7 is a semilog plot that shows relative contributions of renewable resources, nonrenewable resource, human resources, and human health impact of emissions to the total ECEC of each sector. The sector of nonmetallic minerals mining (SIC 9, 10) is found to have the highest ECEC. Other sectors with high ECEC values are new construction (SIC 11), health services (SIC 77A), and petroleum refining and related products (SIC 31). Sectors with the smallest ECEC are footwear, leather, and leather products (SIC 33, 34), tobacco products (SIC 15), and pipelines, freight forwarders, and related services (SIC 73D).

Total ECEC requirement is similar to the concept of *ecological cost* proposed by Szargut as “the cumulative consumption of nonrenewable exergy in all links of the production network and connected with the fabrication of the considered product” (*52*). However, ECEC actually calculates this cost and also captures the cumulative consumption of exergy in all the links of the production network. It enhances ecological cost in two aspects—unlike ecological cost, total ECEC considers renewable *and* nonrenewable resources, and ECEC also accounts for the exergy consumed in the ecological links of a production network.

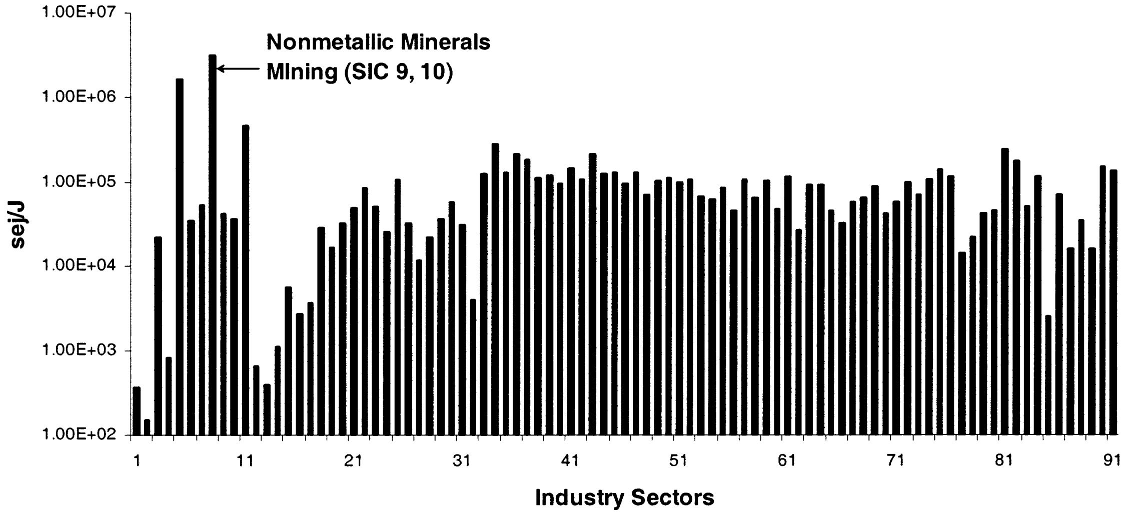

FIGURE 9. ECEC/ICEC Ratio for Industry Sectors

Figure 7 can be easily modified to represent ECEC requirements of industry sectors from nonrenewable resources alone. *Such a graph can be useful in determining industry-specific pro-ecological tax as proposed by Szargut and others* (*53*). ECEC by itself is of limited use for sustainable decision-making. A normalized metric that compares ecosystem contribution to economic activity is more insightful, and is discussed next.

5.2. ECEC/Money Ratio. This ratio compares ecological and economic throughputs of industry sectors. Figure 8 shows ECEC/money ratio of each of the 91 industry sectors on a semilog plot. It is calculated by dividing total ECEC throughput of each sector shown in Figure 7 by its total economic throughput. Similar to Figure 7, Figure 8 also shows ECEC/money ratio for renewable resources, nonrenewable resources, human resources, and human health impact of emissions separately. The ECEC/money ratio is analogous to the emergy/money ratio used in emergy analysis, and similar ratios suggested in exergy analysis (*53, 54*). However, unlike the single ratio in emergy or exergy analysis for the entire economy, Figure 8 provides a separate ratio for each sector. The variation in Figure 8 confirms the heterogeneous nature of the economy. The ratio of the direct ecological inputs to the 1992 GDP of the U.S. is 2.10×10^{12} sej/\$, which is close to the emergy/\$ ratio of 1.44×10^{12} sej/\$ obtained by Odum. The former ratio is slightly higher because it also includes the human health impact of emissions which is ignored in emergy analysis. *The ECEC/money ratio does not support or debunk any theory of value, but is rather meant to provide insight into the magnitude of discrepancy between thermodynamic work needed to produce a product or service and the willingness of people to pay for it.* ECEC/money ratios can be used to quantify ecological cumulative exergy contained in purchased inputs of industrial processes. Such industry-specific ratios provide a more accurate alternative to the single emergy/\$ ratio used in emergy analysis, and similar ad hoc procedures used in thermoeconomics. Normalization with respect to money is possible because monetary outputs of industry sectors are well-known. However, normalization with respect to exergy to determine transformity or CDP values of industry sectors is more difficult due to lack of information about exergetic outputs of industry sectors.

The ECEC/money ratio is a measure of cumulative exergy consumption in the production chain of an industry sector to generate \$1 of economic activity. Table E2 in the Supporting Information lists ECEC/money ratios for the 91 industry sectors sorted in ascending order. Some salient observations about this ratio are as follows.

(i) The ECEC/money ratio for the sectors of nonmetallic minerals mining (SIC 9, 10) and metallic ores mining (SIC 5, 6) are the highest. Sectors with the smallest ECEC/money ratios are owner-occupied dwellings (SIC 71A) and advertising (SIC 73D). The sector of radio and TV broadcasting (SIC 67) also has a high ECEC/money ratio due to high human resource inputs.

(ii) Specialized sectors such as tobacco products (SIC 15), drugs (SIC 29A), and computer and office equipment (SIC 51) have smaller ECEC/money ratios than basic sectors such as petroleum refining and related products (SIC 31) and primary iron and steel manufacturing (SIC 37).

(iii) The average ECEC/money ratio for mining sectors (SIC 5−10) is 22 times the average ECEC/money ratio for service industry sectors (SIC 69A−79).

(iv) Among peripheral sectors, or the sectors that lie at the economy−ecosystem interface, agricultural, forestry, livestock, fisheries, and water and sanitary services sectors (SIC 1−4, 68C) have an average ECEC/money ratio that is 11% of that for mining sectors (SIC 5−10).

The wide variation in ECEC/money ratio indicates the discord between natural capital and corresponding economic capital. This may be because market prices do not fully reflect the contribution of ecosystems. Since economic value is not inherent in objects but is a product of a variety of consumer judgments, the variation in this ratio may also reflect a lack of consumer awareness about ecosystem contribution toward economic activity. Thus, sectors with larger ratios seem not to appreciate or value ecosystem products and services as much as those with smaller ratios. This not only corroborates the lack of integration of the "eco-services" sector with the rest of the economy but also quantifies the magnitude of this discrepancy (*32, 55*).

Furthermore, ECEC/money ratio tends to decrease along supply chains of industrial processes. Basic infrastructure sectors that lie at the economy-ecosystem interface and the sectors that rely more heavily on nonrenewable resources have higher ECEC/money ratios. This suggests that sectors with high ECEC/money ratio consume natural capital in a manner that is disproportionate to their contribution to economic capital. These observations match other work on the relationship between environmental impact and economic value along supply chains of industrial processes (*56*), but require further analysis. Potential implications of ECEC/money ratio to outsourcing and sustainability and to adjust trade policy are currently being explored, and will be included in future publications.

ECEC/money ratio is particularly useful in hybrid thermodynamic life cycle analysis of industrial systems. A hybrid analysis integrates process models or product systems with economy-scale input–output models, and in the process, combines accurate, process-specific data with more uncertain economy-scale data (*57*). Consequently, a hybrid analysis is more powerful as it combines the two critical attributes of an environmental decision tool, specificity and a broad system boundary. ECEC/money ratio can come in handy in this context as the interactions of a product system with the rest of the economy are routinely measured in monetary terms in normal accounting procedures. The use of these ratios is illustrated in Section 6.

5.3. ECEC/ICEC Ratio. ICEC analysis determines cumulative exergy consumption in the industrial links of a production chain. However, it does not consider ecological links of the production chain at all. Consequently, ICEC analysis assumes that all ecosystem products and services are identical, and have a constant transformity of unity. This is erroneous as ecosystem products and services are known to differ widely in their quality aspects. For instance, ICEC analysis does not differentiate between 1 J of coal and 1 J of sunlight, though it is well-known that ecosystems have to perform a lot of work in producing 1 J of coal, whereas sunlight is practically free. ECEC analysis overcomes this shortcoming through the use of transformity values.

ECEC/ICEC ratio represents the degree to which ICEC analysis underestimates cumulative exergy consumption of a production chain by ignoring its ecological links. Since transformities of nonrenewable resources are higher than those of renewable resources, ECEC/ICEC ratio is also higher for industry sectors that depend more on nonrenewable resources. *Therefore ECEC/ICEC ratio is potentially useful as a proxy-indicator of "degree of nonrenewability" of industry sectors* (*58*), though a more rigorous analysis is required to propose any correlation.

As seen from Figure 9 and Table E3 in the Supporting Information the sector of other agricultural products (SIC 2) has the lowest ECEC/ICEC ratio, while the sector of non-metallic minerals mining (SIC 9,10) has the highest. The median ECEC/ICEC ratio for all the sectors is approximately 64 500 sej/J indicating that ecosystems have to expend 64 500 J of energy to make 1 J of an average ecological resource available to an average industrial activity. ECEC/ICEC ratios can be used in conjunction with ECEC/money ratios to determine ICEC/money ratios that are useful to quantify industrial cumulative exergy content of purchased inputs of industrial processes.

6. Case Study: Electricity Generation Systems

The purpose of this case study is to demonstrate how accounting for ecosystem contribution in thermodynamic analysis offers a different perspective than the existing methods such as emergy analysis, exergy analysis, and industrial cumulative exergy consumption (ICEC) analysis. This case study illustrates how results obtained in Section 5 can be used for environmental decision-making. The electricity generation systems considered in this case study have already been studied in emergy analysis (*59*) allowing comparison of results obtained in this paper with those obtained in the past.

For the purpose of this case study, data were obtained for two electricity generation systems in Italy (*59*). The first was a geothermal electricity generation system located at Castelnuovo V. C., Pisa, and the second was a conventional coal-fueled, thermoelectric generation facility located at Vado Ligure, Savona. Data included direct environmental inputs, direct human resource inputs, and economic inputs during construction and operation phases. Data were also obtained for process outputs including net electricity production and emissions during operation phase. All inputs were expressed on a yearly basis by dividing total amount of fixed capital equipment, buildings etc. by their estimated useful life of 25 years. For this analysis, electricity generation systems in Italy were assumed to be technologically similar to their American counterparts so that results obtained for the U.S. economy could be used. Information about transformity values of direct ecological inputs were obtained from the systems ecology literature (*4*), whereas data about exergy content of ecological and purchased inputs were obtained from Szargut et al. (*20*). Data about prices of purchased inputs were obtained from various government databases (*36, 38*). Detailed calculations are provided in Appendix F of the Supporting Information. Since details of machineries used during the construction and the operation phases were not available, prices of machineries were assumed to be those of the metals from which they were made. ICEC/$ ratios calculated in Section 5 were used to perform a traditional ICEC analysis, whereas ECEC/$ ratios were used to account for ecosystem contribution. The ICEC and ECEC flows associated with a purchased input were calculated by assigning the purchased input to appropriate industry sector, determining the monetary transaction by multiplying purchased quantity by market price, and finally multiplying the monetary transaction by ICEC/$ and ECEC/$ ratios for the previously chosen industry sector. For the inputs purchased from the sector of petroleum refining and related products (SIC 31) the ratios were augmented by a factor of 2.1 to account for imports of crude oil, since in 1992 total consumption of refinery products in the United States was 2.1 times the domestic production of crude oil (*60*).

Table 4 shows different metrics for the two alternatives based on exergy analysis, ICEC analysis, and ECEC analysis. Details of calculation are provided in the Supporting Information.

Geothermal Electricity Production Facility, Castelnuovo V. C., Pisa. Total annual electricity production from this facility was 3.28×10^{14} J. Total exergetic inputs, total ICEC requirements, and the total ECEC requirements of the process were 2.38×10^{15} J/yr, 2.42×10^{15} J/yr, and 3.85×10^{19} sej/yr, respectively. Total ECEC requirement calculated in this case is comparable to the total emergy cost of 4.83×10^{19} sej/yr calculated by Ulgiati and Brown. The difference between total ECEC requirement and total emergy cost may arise as the two are calculated in different ways. Total emergy cost is based on transformity values, whereas total ECEC requirements are based on economic prices and ECEC/money ratios. The second law efficiency and ICDP of this process are close because the process derives 98.9% of its exergetic requirements directly from ecosystems. These direct inputs include geothermal heat as the primary source of energy and wind for cooling towers. Direct renewable resource input to the process is 3.35×10^{19} sej/yr which is equal to that calculated by Ulgiati and Brown (*59*).

Coal-Fueled, Thermoelectric Production Facility; Vado Ligure, Savona. Total annual electricity production from this facility was 2.44×10^{16} J/yr. Total exergetic inputs, total ICEC requirements, and total ECEC requirements were 1.11×10^{17} J/yr, 1.17×10^{17} J/yr, and 3.22×10^{21} sej/yr, respectively. Unlike the geothermal facility that relies heavily on direct ecological inputs, this facility derives only 38.7% of its total exergetic inputs from ecosystems. The two primary sources of energy, namely coal and combustion oil, are purchased from the sectors of coal mining and petroleum refinery and related products, respectively. Total ECEC content of direct fuel inputs is 2.88×10^{21} sej/yr which is close to the emergy value of 3.01×10^{21} sej/yr calculated by Ulgiati and Brown (*59*). The difference is again attributable to different analyses techniques adopted in the two approaches.

As can be seen from Table 4, accounting for ecosystem contribution gives a different perspective on thermodynamic efficiencies of industrial processes. For instance, according

TABLE 4. Comparison of the Two Electricity Generation Systems

	geothermal	coal-fueled thermoelectric
annual electricity production (J/yr)	3.28×10^{14}	2.44×10^{16}
total emergy cost (sej/yr) (*59*)	4.83×10^{19}	3.23×10^{21}
total ECEC requirement (sej/yr)	3.85×10^{19}	3.22×10^{21}
Efficiencies		
exergetic efficiency	1.38×10^{-1}	2.20×10^{-1}
industrial cumulative degree of perfection (ICDP)	1.36×10^{-1}	2.09×10^{-1}
ecological cumulative degree of perfection (ECDP) (J/sej)	8.52×10^{-6}	7.59×10^{-6}
Metrics		
yield ratio (total ECEC requirement/ (ECEC inputs from economy)	11.5	1.1
loading ratio (ECEC from nonrenewable resources /ECEC from renewable resources)	0.08	52
index of sustainability (yield ratio/loading ratio)	145.3	0.02
impact/value added (ECEC of human health impact/ annual electricity production) (sej/J)	7.53×10^{2}	1.15×10^{4}

to exergy analysis and ICEC analysis, the thermoelectric alternative is more efficient than the geothermal alternative, but according to ECEC analysis it is the other way around. The primary reason for this is the *ability of ECEC analysis, and the failure of exergy analysis and ICEC analysis, to incorporate exergy expended in ecological processes*. Geothermal heat being a renewable resource is readily available to industrial activity, whereas coal being a nonrenewable resource requires significant contribution from ecosystems. Because of this ability to account for ecosystem products and services, ECEC analysis is a more suitable technique for environmental decision-making than the existing thermodynamic techniques such as exergy analysis and ICEC analysis.

Table 4 also calculates metrics for comparing the two alternatives. These metrics have been defined along the lines of those used in emergy analysis (*4, 61*). The major difference is in the way resources are categorized. For instance, unlike emergy analysis, the analysis presented in this paper does not have to distinguish between purchased inputs and direct ecological inputs. Since the thermodynamic input−output analysis (TIOA) can consider the entire economic network, ecological inputs embodied in purchased inputs can also be quantified. Accordingly, direct ecological inputs in emergy analysis correspond to direct ECEC inputs in TIOA and purchased inputs in emergy analysis correspond to indirect ECEC inputs in TIOA. The higher yield ratio for geothermal alternative indicates that it derives a larger portion of its ECEC inputs directly from ecosystems. Similarly, a higher loading ratio for the thermoelectric alternative indicates that it consumes relatively more nonrenewable resources than the geothermal alternative. As a result, the index of sustainability of the geothermal option is 6919 times that of the thermoelectric alternative. Moreover, human health impact of emissions per unit electricity production is 15 times higher for the thermoelectric alternative. A significant portion of this impact arises from direct SO_2 and NO_x emissions from the thermoelectric alternative as shown in Table F2 in the Supporting Information.

Like ECEC analysis, emergy analysis can also determine ecosystem contribution to economic activity. However, to do so it either needs to know the entire industrial network which is infinitely long and practically intractable or has to use a single emergy/$ ratio to represent the entire economy. *ECEC/$ ratios calculated in Section 5.2 and used in this case study are easier to use since the required monetary information about purchased inputs is routinely gathered by businesses for their financial accounts. Moreover, unlike emergy analysis, TIOA does consider the entire economic network through the use of economic input−output models. ECEC/$ ratios are also more accurate than a single emergy/$ ratio because they are more disaggregated and can reflect differences between industry sectors.* At this point, it is necessary to note that the use of a single emergy/$ ratio is not a theoretical limitation of emergy analysis. Emergy analysis can use different industry-specific ratios if they are available. The analysis presented in this paper is the first systematic effort to make such ratios available. ICEC/$ and ECEC/$ ratios are also particularly useful in hybrid thermodynamic analysis of industrial processes (*57*). Since the interactions of a process or a *product system* with the rest of the economy are typically measured in monetary units ICEC/$ and ECEC/$ ratios can be readily used to determine efficiencies at coarser economy and ecosystem scales, respectively.

7. Discussion

This paper presents and illustrates a novel approach for including the contribution of ecosystems to economic sectors. It synthesizes available data and methods from multiple disciplines, including studies of the contribution of ecosystems at global or national scales, economic input−output analysis, systems ecology, life cycle assessment, and engineering thermodynamics. The concept of ecological cumulative exergy consumption permits integration of inputs from ecosystems and human resources and the impact of emissions. Although transformity values from emergy analysis have been used to convert different resource flows into a consistent thermodynamic unit, they do not inherit any of the controversial aspects of Odum's work. Economic input−output data have been used to allocate inputs of ecological resources within the economic system. Application to the 1992 U.S. economy provides unique insight into the extent to which each economic sector relies on ecosystem contribution, and how each sector values its ecological inputs. The ECEC/money ratio not only clearly demonstrates but also quantifies the discrepancy between the thermodynamic work required to produce an ecological resource and human willingness to pay for it. The results are potentially useful to internalize the externalities and to devise more prudent economic policies. The value of ecosystems is also found to increase along supply chains of industry sectors, with basic extracting and manufacturing sectors valuing nature less than specialized and service sectors. The ratio of CEC with and without inclusion of ecosystems (ECEC/ICEC) illustrates the extent to which conventional thermoeconomic analyses underestimate the contribution of ecosystems. The analysis presented in this paper determines, for the first time, industry-specific ECEC/money and ECEC/ICEC ratios that are more accurate and more disaggregated than the single emergy/money ratio in emergy analysis and similar ad hoc procedures in thermoeconomics. Potential applications of the results obtained in this paper to define sustainability metrics based on natural resource consumption, replenishment, and deposits as well as critical natural capital are currently being explored and will be included in future publications.

Many avenues are available for continuing this work. More recent economic and environmental data consisting of many more sectors are available, and are being used in the ongoing research. More information about ecosystem products and services is also available (*3*, *10*), and may be incorporated in the presented approach. This work considers only human impact of emissions, but in principle, impact of emissions on ecosystems can also be considered if information about the exergy content of affected ecosystems is available. Since all data are uncertain and may contain errors, rigorous statistical methods are required to obtain reliable results. Different allocation approaches, including ways of avoiding allocation, need to be studied. Economy-scale analysis also needs to be integrated with information at other spatial and temporal scales. Results obtained may be used in defining sustainability metrics that are simple, cost-effective, robust, and protective of proprietary information (*50*, *51*). This approach is expected to add another tool to the industrial ecologist's toolbox, and encourage the industrial and economic transformation toward sustainability.

Acknowledgments

Partial financial support from the National Science Foundation (BES-9985554), availability of www.eiolca.net for obtaining part of the results, and suggestions from anonymous reviewers are gratefully acknowledged.

Supporting Information Available

Appendices A through F, including figures, tables, and calculations. This material is available free of charge via the Internet at http://pubs.acs.org.

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Received for review December 6, 2003. Revised manuscript received May 27, 2004. Accepted June 19, 2004.

ES035367T