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Industrial and ecological cumulative exergy consumption of the United States via the 1997 input–output benchmark model

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Abstract

This paper develops a thermodynamic input–output (TIO) model of the 1997 United States economy that accounts for the flow of cumulative exergy in the 488-sector benchmark economic input–output model in two different ways. Industrial cumulative exergy consumption (ICEC) captures the exergy of all natural resources consumed directly and indirectly by each economic sector, while ecological cumulative exergy consumption (ECEC) also accounts for the exergy consumed in ecological systems for producing each natural resource. Information about exergy consumed in nature is obtained from the thermodynamics of biogeochemical cycles. As used in this work, ECEC is analogous to the concept of emergy, but does not rely on any of its controversial claims. The TIO model can also account for emissions from each sector and their impact and the role of labor. The use of consistent exergetic units permits the combination of various streams to define aggregate metrics that may provide insight into aspects related to the impact of economic sectors on the environment. Accounting for the contribution of natural capital by ECEC has been claimed to permit better representation of the quality of ecosystem goods and services than ICEC. The results of this work are expected to permit evaluation of these claims. If validated, this work is expected to lay the foundation for thermodynamic life cycle assessment, particularly of emerging technologies and with limited information.

Keywords: Exergy; Cumulative exergy; Emergy; Ecosystem goods and services; Input–output models; US economy

1. Introduction

Knowledge about the flow and transformation of exergy is proving to be useful for evaluating and understanding the behavior of industrial and ecological systems. The most common use of exergy analysis has been for the identification and reduction of sources of inefficiency in manufacturing processes and equipment [1], and in evaluating the trade-off between exergy consumption and capital cost [2,3]. More recent efforts have attempted to quantify the impact of emissions via exergy analysis. This includes exploration of the relationship between the exergy of emissions to their impact [4,5], calculating the exergy of abatement for different pollutants [6], and converting the results of life cycle impact assessment into exergetic terms [7]. Exergy analysis and other thermodynamic methods have also been popular for the modeling and assessment of ecological systems [8].

Thermodynamic methods have also been developed to consider systems at scales larger than individual equipment or process. Cumulative exergy consumption (CEC), considers the exergy consumed in industrial processes in the supply chain all the way to natural resources [1]. Exergetic life cycle assessment (LCA) combines cumulative exergy consumption and LCA by also considering exergy consumption in the demand chain [9]. Extended exergy analysis (EEA) quantifies the contribution of labor via a corresponding ratio of cumulative exergy to money [10]. Emergy analysis quantifies the contribution of ecosystem goods and services by representing global energetic inputs in terms of solar equivalents, and calculating their contribution to different natural products and services [11]. Like EEA, emergy also accounts for the contribution

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of labor and economic resources via an emergy to money ratio. The relationship between many of these methods has been described via the concepts of industrial cumulative exergy consumption (ICEC) and ecological cumulative exergy consumption (ECEC) [12]. ICEC is analogous to Szargut's cumulative exergy consumption and only focuses on exergy consumption in industrial systems. In contrast, ECEC also accounts for exergy consumption in labor and capital, like Sciubba's EEA, exergy loss due to impact of emissions, and exergy consumed in ecosystems for creating the ecosystem goods and services consumed by industrial activities.

Each of these approaches is usually applied to a few selected processes in the value chain or life cycle. Such an approach has also been standardized in ISO 14000 for "Process LCA". Since the life cycle is usually a large and complicated network of processes, including only the most important ones can entail a large truncation error [13]. Instead of selecting processes in a narrow boundary, many studies have analyzed sectors in an entire national economy. These sectors lack the detail of individual processes, due to aggregation of constituent processes. Thermodynamic analysis of nations has been popular due to its potential for providing useful insight about the efficiency of different countries, constituent economic sectors and specific technologies. Early efforts such as net energy analysis focused on the use of energy resources [14–16], but ignored material streams and the second law. Subsequent efforts accounted for material and energy use along with the second law via exergy analysis [17–21]. A recent analysis of the Norwegian economy accounts for selected emissions and labor by using Sciubba's EEA approach [22]. Many of these efforts have resulted in exergy efficiencies of specific economic sectors based on accounting for the direct and indirect cumulative exergy consumption and the exergy of products. Most of the existing efforts for national thermodynamic accounting focus mainly on the consumption of natural resources, their flow through economic sectors and the resulting products. Nevertheless, most efforts focus on a small number of economic sectors such as energy, transportation, waste, manufacturing, etc. and lack the extent of detail commonly available in economic models. Input–output analysis permits the consideration of direct and indirect effects in a complicated network and has been popular for monetary as well as thermodynamic analysis at the scale of economic sectors. Data about natural resource consumption of sectors are usually available in government statistics and can be used to calculate the exergy consumed by each sector. However, information about the exergy of products from each sector is often more challenging to find, particularly for sectors that are further along the economic chain such as advanced manufacturing and service industry. Other shortcomings of many thermodynamic analyses at the national scale are that they ignore aspects such as the emission of pollutants and their impact, contribution of human labor and capital, and of ecological goods and services.

Ignoring the contribution of ecosystem goods and services, or Natural Capital, can be a significant shortcoming for methods that aim to encourage environmentally conscious or sustainable decision making. This is because ecological resources constitute the basic support system for all activity on earth. These resources include products such as air, water, minerals and crude oil and services such as carbon sequestration and pollution dissipation [11,23–25]. However, traditional methods in engineering and economics often fail to account for the contribution of ecosystems despite their obvious importance. The focus of these methods tends to be on short-term economic objectives, while long-term sustainability issues get shortchanged. Even techniques from industrial ecology such as LCA ignore ecosystems. Such ignorance of ecosystems is widely believed to be one of the primary causes behind a significant and alarming deterioration of global ecological resources [26–29].

Thermodynamic methods have been used for quantifying the contribution of natural capital to economic activity. Costanza and Herendeen [30] considered the contribution of sunlight to agrarian and forestry sectors in proportion to their land area, but ignored material inputs and the second law. Hannon [16] presents a framework for including the contribution of ecosystems in an economic input–output model in mixed units. However, application to a specific national or regional system is missing. Among biophysical methods for quantifying natural capital, emergy analysis stands out as being the most comprehensive approach that incorporates knowledge about the contribution of global biogeochemical cycles to natural resources. A benefit of considering the exergetic contribution of natural capital is claimed to be its superior ability to capture the quality and versatility of different natural resources. However, the data for evaluating this claim have not been available as yet. Emergy analysis is often misunderstood, faces quantitative and algebraic challenges, and its broad claims about ecological and economic systems have been controversial [31–34]. Besides, emergy analysis is usually applied for the most important processes in a short supply chain, with contribution of inputs from the economy captured via a coarse economy-wide emergy to money ratio.

This paper presents the thermodynamic input–output analysis (TIOA) of the 1997 US economy via the economic input–output benchmark model. This analysis is performed in the following two ways: without considering the contribution of natural capital, and with the contribution of natural capital. In both cases, the use of input–output algebra permits consideration of direct and indirect exergy consumption. The first approach only considers industrial processes and corresponds to ICEC analysis [12]. The contribution of ecosystem goods and services is considered by expanding ICEC to include ecological processes, which results in ECEC analysis [12]. ECEC analysis extends ICEC analysis to include exergy losses in the industrial as well as ecological stages of a production chain. Hau and Bakshi have shown that under certain conditions, ECEC becomes equivalent to emergy. In addition, ECEC *does not* rely on the controversial aspects of emergy such as the use of prehistorical emergy, maximum empower principle and claims about emergy being a substitute for economic valuation since it only relies on the thermodynamics of direct inputs from ecosystems to economic sectors and only on flow of current energy. The partitioning or allocation of emergy between multiple outputs is another challenging aspect of emergy. ECEC takes a different view of allocation from emergy analysis and like LCA, treats it as a subjective decision. As described in more detail by Hau and Bakshi, this view sheds new light on the allocation approach of emergy analysis and connects it with the standardized approach in LCA.

TIOA builds upon ECEC analysis by providing it with a formal algorithm to evaluate flows in linear static networks. TIOA combines existing approaches from life cycle analysis, exergy engineering, emergy analysis, and economic input–output analysis to formulate such an algorithm. TIOA has many unique features that distinguish it from other contemporary thermodynamic methods and their application to nations. Some of these are listed below.

- TIOA combines exergy analysis of industrial systems with the ability of emergy analysis and systems ecology to account for ecosystems, and input–output analysis to consider direct and indirect effects in networks.
- TIOA acknowledges the economic network and provides industry-specific results. Such results are more accurate in appreciating the differences between industry sectors than a single aggregate metric for the entire economy like that of Odum [11] and Sciubba [35].
- TIOA can accommodate a wide variety of ecological products and services, human resources and impact of emissions, making it a holistic approach. This approach is used for ICEC and ECEC analysis in this article, but can be readily modified to other methods such as net energy analysis and EEA.

In the past, TIOA has been applied to study contribution of ecological resources to a 91-sector 1992 US economy [7]. Such analysis, though better than a completely aggregate analysis of the entire economy, can still be improved by using more detailed models of the US economic system. For instance, whereas the 91-sector 1992 model aggregates all agricultural activity into a single sector, namely the sector of other agricultural products (SIC 2), the 1997 benchmark model separates agricultural activity into 10 sub-sectors (NAICS 1111A0-1119B0). Naturally the 1997 benchmark model is more detailed than the 91-sector 1992 model, and likely to provide more accurate results. 1997 US industry benchmark model is the most recent representation of the US economic system at that level of disaggregation yet available. More recent benchmark models are being compiled by the Bureau of Economic Analysis, but are not yet available for public use.

The results of TIOA include total ICEC and ECEC requirements of industry sectors. Total ECEC requirement captures the thermodynamic basis of industrial operations and is analogous to the concept of ecological cost. The analysis also calculates ECEC/money ratio to juxtapose thermodynamic basis of an industrial operation with corresponding monetary activity, and captures the discrepancy between thermodynamic work and the willingness of people to pay for a good or service. Such discrepancy is believed to be the root cause behind lack of internalization of ecological resources into classical economics [36,37]. Industry-specific ECEC/money ratios quantify the magnitude of such discrepancy and may be useful for macroeconomic policy decisions such as determination of pro-ecological taxes. However, this work *does not* aim to connect thermodynamics with economic value. Furthermore, the TIO model may be useful for evaluating the claim made by emergy analysts that using an analysis boundary that includes ecosystems is better at capturing differences in quality of resources such as their scarcity and renewability.

The rest of the paper is organized as follows: Section 2 discusses the background and methodological aspects of TIOA. Section 3 discusses data requirements and sources for applying TIOA to 488-sector 1997 benchmark model of the US economy. Section 4 presents selected direct and indirect ICEC and ECEC values of individual streams, while Section 5 presents aggregate results and metrics including total ECEC requirements and ECEC/money ratios for individual industry sectors. Applications based on this model are described in Ukidwe and Bakshi [38] and Ukidwe [39].

2. Background: cumulative exergy and input–output analysis

2.1. Industrial and ECEC

While exergy analysis successfully captures quality differences between material and energy streams, it focuses only on the process under investigation while ignoring its production chain. This hinders its use for environmentally conscious decision making that requires consideration of the entire life cycle. Cumulative Exergy Consumption Analysis [1] overcomes this shortcoming by considering exergy requirements in the process as well as its supply chain. Hau and Bakshi [12] refer to this as Industrial Cumulative Exergy Consumption (ICEC) to convey its emphasis on industrial processes. Extensions such as Exergetic LCA [9] and Extended Exergy Accounting [10] incorporate the exergy consumption in the demand chain and due to labor in ICEC. However, ICEC analysis completely ignores exergy consumption in the ecological stages of the production chain and, consequently, cannot distinguish quality differences between ecological products and services. This shortcoming is addressed in ECEC analysis.

ECEC was developed by expanding the boundary of ICEC analysis to include the contribution of ecological goods and services [12]. Ecological functions may be in the form of natural resources such as coal, petroleum, timber and water that are used as raw materials by industrial processes or ecosystem services that are responsible for pollution dissipation, climate regulation etc. Knowledge about the exergy consumed in ecological and natural processes is available from a variety of sources and has been compiled by Szargut [40], Chen [41], Odum [42], Hermann [43] and others. Such analysis extends the supply chain all the way to the three main fundamental sources of energy, namely sunlight, geothermal heat and gravitation forces. Hau and Bakshi prove that ECEC can become equivalent to emergy if the following are identical for both methods: (i) analysis boundary, (ii) approach for combining global energy inputs, and (iii) allocation method. Furthermore, if the approach suggested in emergy synthesis is used for the above three items, transformity [11] is proved to be equivalent to the reciprocal of the cumulative degree of perfection (CDP) [1]. The second and third items have been sources of confusion, since emergy analysis has unique approaches for combining global energy inputs and for partitioning the emergy of inputs between multiple outputs. These approaches aim to account for quality differences between solar, crustal and tidal energy, and between multiple products from a system. Similar challenges are commonly encountered in LCA, and methods such as sensitivity analysis are recommended to evaluate the effect of different approaches. The relationship between ECEC and emergy shows that the most controversial claims of emergy such as, the emergy theory of value, reliance on unknowable prehistoric energy flows, and maximum empower principle that have hindered wider use of emergy analysis, are not essential for using the information about biogeochemical cycles compiled by ecologists and natural scientists. Consequently ECEC analysis has a sound and established basis in engineering thermodynamics. Additional details are available in Hau and Bakshi [12,32].

2.2. Methodology for thermodynamic input–output analysis

TIOA recognizes the network structure of the integrated economic-ecological-social (EES) system shown in Fig. 1. It combines models of each subsystem and connects them via the common currency of exergy flow. The economy is represented via an input–output model, which represents the flow of money between a variety of economic sectors [44,45]. Such models are available for many countries. This information is used in allocating cumulative exergy flows between industry sectors. The ecological system is represented via four conceptual ecospheres that encompass land (lithosphere), water (hydrosphere), air (atmosphere) and living flora and fauna (biosphere). Such classification assists categorization of vast number of ecological resources into smaller groups, and is by no means critical to the applicability of TIOA. Any other user-defined classification scheme would also work as long as renewable and non-renewable resources are distinguished. Information about the contribution of human resources and emissions from various sectors is available from government data.

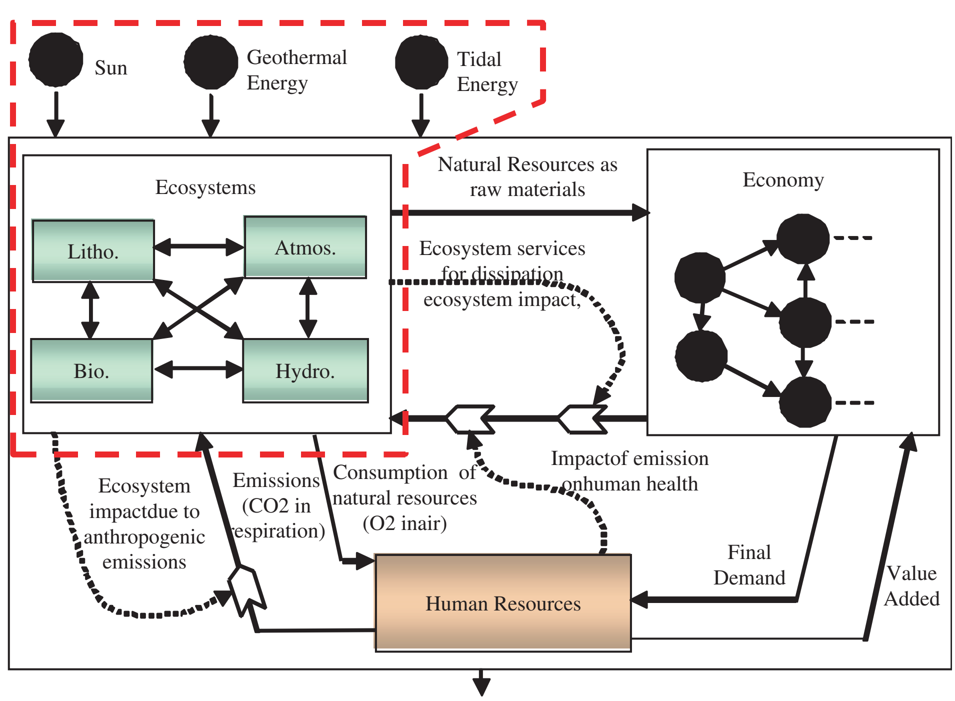

Fig. 1. Integrated economic-ecological-human resource system. ECEC analysis considers all subsystems, while ICEC analysis ignores exergy consumption in ecosystems (bounded by dashed box). Solid connecting lines represent tangible interactions and dotted lines represent intangible interactions occurring as a consequence of emissions.

Conversion of the impact of emissions in exergetic terms is accomplished via methods developed for life cycle impact assessment. Details about sources of data used in this work for the US are provided in Section 3.

Fig. 1 also shows the interactions between economic, ecological and societal systems. Interactions represented by solid lines arise on account of resource consumption and emissions, whereas those represented by dotted lines are intangible interactions indicating impact of emissions on human and ecosystem health. For instance, the dotted arrow between the economy and ecosystems represents ecological services required for dissipating industrial emissions and their impact on ecosystem health. The solid arrow from ecosystems to the economy, on the contrary, represents tangible interactions that include consumption of ecological resources as raw materials by the economic activity. If interactions between ecospheres and their conversion of solar, crustal and tidal energy are ignored, then Fig. 1 represents ICEC analysis. These processes are shown within the dashed region and represent the key difference between the systems considered in ICEC and ECEC. In this case, the contribution from ecosystems is represented via the exergy content of the natural resource, and exergy consumption for producing that resource in ecological systems is ignored.

The approach used for partitioning the cumulative exergy of inputs among multiple products is as follows [12]. If the structure of the network and its products are known, then allocation is done in proportion to the exergy content or monetary value of the output streams, depending on which information is available. For the economic input–output model, only monetary information is available. For this allocation method, the cumulative exergy of different streams is *additive*. Streams representing cumulative exergy at vastly different time periods are also additive. In contrast, if the structure of the network and its products are not known, then allocation is avoided by assigning the entire cumulative exergy of inputs to each output. When such streams are combined, they cannot be added to avoid double counting, and only the maximum value of the streams is used. Such streams are *non-additive*. This is analogous to the approach used in emergy analysis for allocation among coproducts. In this work, for ICEC analysis, all streams are additive, while for ECEC analysis, renewable resources are non-additive, and non-renewable resources are additive. Thus, if there are r_1 non-additive resources and r_2 additive resources, throughput vectors for each resource can be written using the following equations:

$$\mathbf{C}^{R_{1,i}} = (\mathbf{I} - \boldsymbol{\gamma}^{\mathrm{T}})^{-1} \cdot \mathbf{C}_n^{R_{1,i}}, \quad \forall i = 1, \ldots, r_1, \tag{1}$$

$$\mathbf{C}^{R_{2,j}} = (\mathbf{I} - \boldsymbol{\gamma}^{\mathrm{T}})^{-1} \cdot \mathbf{C}_n^{R_{2,j}}, \quad \forall j = 1, \ldots, r_2. \tag{2}$$

Here $\mathbf{C}_n^{R_{1,i}}$ and $\mathbf{C}_n^{R_{2,j}}$ are direct input vectors for the ith non-additive resource and the jth additive resource respectively and $\boldsymbol{\gamma}$ is the allocation matrix, which in the case of TIOA, is the monetary inter-industry transaction matrix. The separately calculated cumulative exergy consumption values are combined for each stream according to whether they are additive or not. In general, the maximum contribution from non-additive resources is added to the sum of contributions from all additive resources as

$$\mathbf{C}^{\mathrm{total}}(k) = \max_{i=1,\ldots r_1}\left\{\mathbf{C}^{R_{1,i}}(k)\right\} + \sum_{j=1}^{r_2} \mathbf{C}^{R_{2,j}}(k) \quad \forall k = 1, \ldots, n. \tag{3}$$

Here n represents the number of industry sectors. The detailed algorithm for ECEC analysis is available in [12].

The algorithm of TIOA can be summarized as the following three tasks. Details about the sources of data and methods are in Section 3.

1. *Identify and quantify ecological and human resource inputs to the economic system*. Ecological inputs include ecosystem products such as crude oil and ecosystem services such as wind and fertile soil. Human resources include employment of labor for economic activities. Emissions and their impact on human and ecosystem health may also be included.
2. *Calculate CEC of direct ecological inputs* using transformity values from systems ecology for ECEC or exergy of inputs (unit transformities) for ICEC. For ECEC, these inputs are classified as additive or non-additive to be consistent with the network algebra rules used in emergy analysis [11,12]. In general, non-renewable resources are additive, while renewable resources are non-additive.
3. *Allocate direct inputs to economic sectors using input–output data and the network algebra of ECEC analysis* [45]. 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 are currently being explored. Also, use of monetary data for allocation is not a limitation of the approach, but is rather caused by a lack of comprehensive material or energy accounts of inter-industry interactions. ECEC analysis as used in this work does not rely on the track-summing algorithm to calculate ECEC flows in the economic network [11], but rather on simultaneous solution of a system of linear equations establishing cumulative exergy balance on each system component as well as the overall system. The effect of different allocation methods on the results is currently under investigation.

2.3. Illustrative example

The following example illustrates the TIOA methodology discussed in the previous section. The system under consideration resembles a hypothetical economy comprising three sectors. Fig. 2 shows the economic input–output structure for this network and Table 1 shows the corresponding inter-industry transaction coefficient matrix, γ.

$$\gamma = \begin{bmatrix} 0.5 & 0.1 & 0.2 \\ 0.25 & 0.0625 & 0.5 \\ 0.133 & 0.2 & 0.067 \end{bmatrix}. \quad (4)$$

This matrix is derived by normalizing the output from sector i to sector j by the total output from sector i.

The next step is identification and quantification of natural and human resource inputs to the economic system. This is shown in Fig. 3. Two different renewable resources, Ra_1 and Rb_2, one non-renewable resource, NR_1, human resource, HR_3, emission, E_2, and impact of emission on human health, IM_2, have been considered in this hypothetical example. In each case, the subscript represents the sector that gets the direct input of that particular resource.

The flows depicted in Fig. 3 are subsequently converted into a consistent thermodynamic unit of ICEC or ECEC, as shown in Table 2. Calculation of ICEC of direct inputs assumes a uniform transformity of unity and does not include human resources or impact of emission on human health. Additional methodological details about how ecological and human resource inputs and emissions and their impact can be converted into ECEC and ICEC terms can be found in Ukidwe [39]. To determine total ECEC and ICEC throughputs of the three sectors, the direct inputs need to be allocated through the economic network according to the allocation approach and equations described in Section 2.2. This is done by first calculating the throughput vectors, $\mathbf{C}_y^{NR_1}, \mathbf{C}_y^{Ra_1}, \mathbf{C}_y^{Rb_2}, \mathbf{C}_y^{HR_3}, \mathbf{C}_y^{IM_2}$ for individual resources as per Eqs. (1) and (2). ICEC analysis traditionally ignores human resources and impact of emissions on human health and only considers NR_1, Ra_1, Rb_2, whereas ECEC analysis does not ignore human resources and impact of emissions on human health and considers NR_1, Ra_1, Rb_2, HR_3 and IM_2. Subsequently, to determine total ECEC throughput vector, $\mathbf{C}_{\mathrm{ECEC}}^{total}$, throughput vectors for individual resources are added according to Eq. (3).

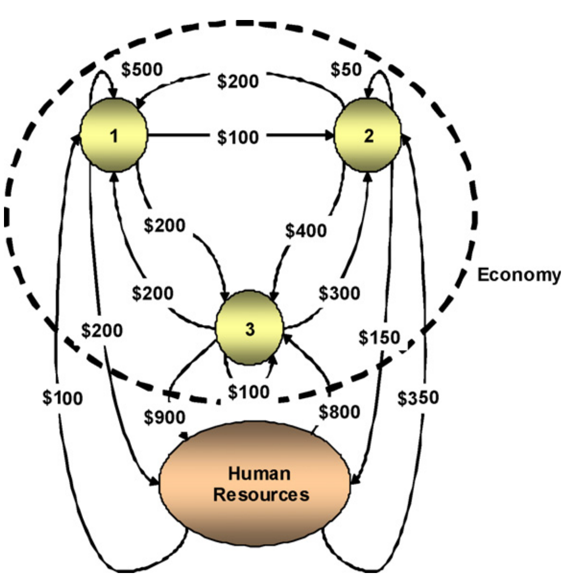

Fig. 2. Network representation of the hypothetical 3-sector economy.

Table 1
Allocation matrix for hypothetical 3-sector economy shown in Fig. 2

	To	1	2	3	FD/HR	To
From						
1		0.5	0.1	0.2	0.2	1
2		0.25	0.0625	0.5	0.1875	1
3		0.133	0.2	0.067	0.6	1
VA/HR		0.08	0.28	0.64		1

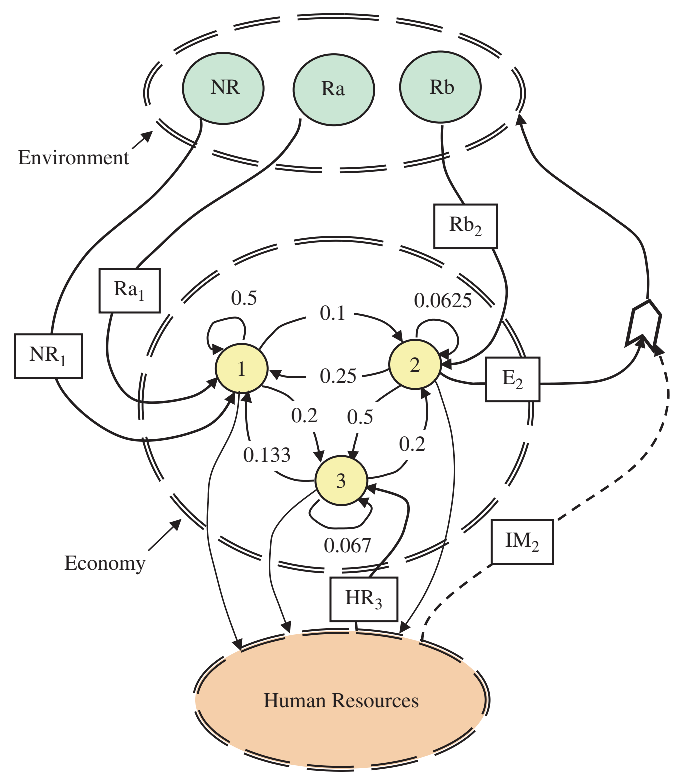

Fig. 3. Augmented system showing ecological and human resource inputs to economic sectors.

Figs. 4(a) and (b) depict direct and indirect ECEC and ICEC throughput vectors for individual resources as well as the total throughput vectors in graphical form. A similar conceptual methodology has been used in deriving the results for 488-sector 1997 US economic system in Section 4 of this paper. Based on the results presented in Fig. 4 several performance metrics can be evaluated. These performance metrics are listed in Table 3 along with their definitions, which do not rely on knowledge of the exergy content of the outputs from each sector, since such information is not readily available via the input–output model. Yield ratio indicates the proportion of the total ECEC requirement of a process or product that is derived from the economy. A process that derives a larger portion

Table 2
Ecological and human resource inputs in Fig. 3 and corresponding ECEC flows

Stream number	Type	Physical data	Transformity (sej/J)	Direct ECEC Input (sej/d)	Direct ICEC Input (J/d)
NR_1	Non-renewable	10 J/d	100.000	1,000,000	10
Ra_1	Renewable	50 J/d	20.000	1,000,000	50
Rb_2	Renewable	10 J/d	10.000	100,000	10
HR_3[a]	Human resource	50 h/d	5.000	250,000	—
E_2	Emission	2 kg/d	—	—	—
IM_2[b]	Impact on human health	2 kg/d	1.000	1,752,000	—

[a]Man hours employed, $h_i = 50$ h/d, average annual payroll for selected sector, $P_i = \$80$/d, minimum average annual payroll, $P_{\min} = \$16$/d, Transformity of unskilled labor, $\tau^{\text{unskilled}} = 1000$ sej/h, $C = h_i \cdot (P_i/P_{min}) \cdot \tau^{\text{unskilled}} = 250{,}000$ sej/d.
[b]Mass flow rate of emission, $m = 2$ kg/d, Disability Adjusted Life Year, $DALY = 0.1$ yr/kg, $\tau = 1000$ sej/h $C = m \cdot DALY \cdot$ (365 day/yr). (24 h/day). $\tau = 1{,}752{,}000$ sej/d.

of its inputs directly from ecosystems has a higher yield ratio and vice-versa. Loading ratio (LR) indicates the relative reliance of a process or product on non-renewable resources. The ratio of YR to LR, called yield-to-loading ratio, is defined in emergy analysis as the index of sustainability. According to this ratio, a process that relies on ecosystems but has lower reliance on non-renewable resources is considered to be more sustainable. Furthermore, impact per value added indicates the ratio of human health impact of emissions to some measure of value added, such as profitability or productivity. These performance metrics are easy to calculate and provide useful insight into the environmental implications of industrial products and processes. These metrics are similar to those used in emergy analysis [11,46]. The main 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 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 performance metrics for the illustrative example shown in Fig. 3 are calculated in Table 4.

3. Data sources for 1997 US industry benchmark model

This section describes the resources considered in this analysis, along with their data sources. All required data have been obtained from non-proprietary public-domain databases.

3.1. Transformities

ICEC and ECEC values of direct ecological inputs and human resources are determined via their transformity values [11,47,48]. Transformities can also be viewed as reciprocals of global exergetic efficiencies of ecological resources. Since ICEC analysis does not consider ecological stages of a production chain, it implicitly assumes cumulative exergy of direct natural resource inputs to be equal to their standard exergy values. This is tantamount to using a uniform transformity or thermodynamic efficiency of unity for all natural resources.

For ECEC calculation, as discussed in Section 2, transformities, as used in this analysis, are not subject to the controversial aspects of Odum's work such as maximum empower principle, emergy theory of value or energy consumption over geological time scales. The numbers used in this analysis correspond to the 1996 base of 9.44×10^{24} sej/yr [11]. Furthermore TIOA only uses transformities of direct inputs from nature and derived transformities of economic goods and services are not required. The transformities used in this work are listed in Tables 5 and 6.

3.2. Ecosystem products

Ecosystem products refer to the natural raw materials consumed for economic activities. These raw materials are extracted by basic infrastructure activities such as mineral mining, coal mining, petroleum and natural gas extraction, and logging and timber tract harvesting. Table 5 lists the ecosystem products considered in this analysis, their flows in the 1997 US economic model, the industry sectors that receive their direct inputs and corresponding data sources. These data sources were also used for the TIOA of the 91-sector 1992 US economy [7]. Furthermore, the analysis presented in this paper expands the scope of the previous analysis of 1992 US economy by incorporating data about gold mining and natural gas consumption. The inputs to agricultural activities were adjusted using data about number of farms and their average size during 1992 and 1997. Currently work is underway to expand the scope further by including material and energy flow information about additional ecosystem products.

3.3. Ecosystem services

This paper focuses only on supply-based services as their contribution can be quantified independent of human valuation. Supply-based services are always accompanied

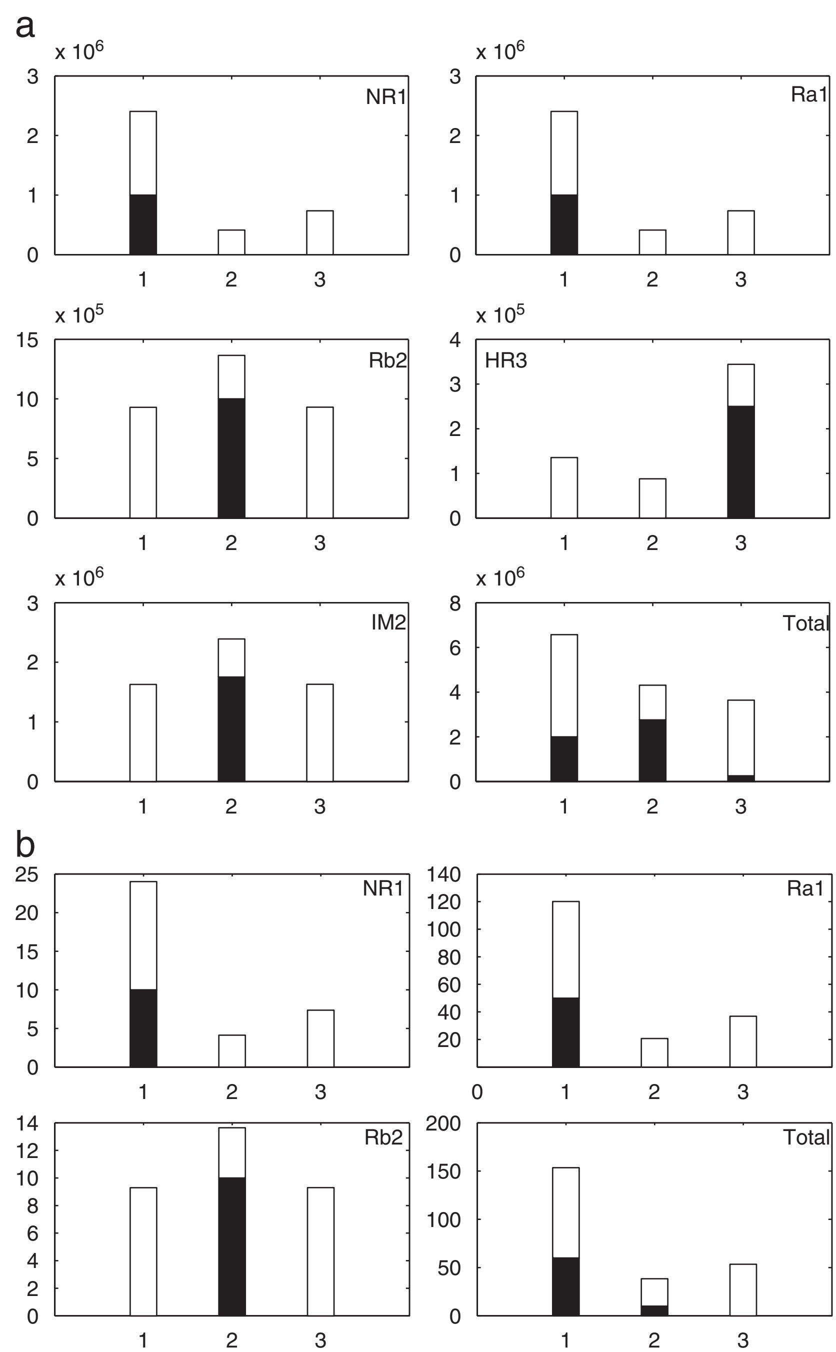

Fig. 4. Throughput vectors for individual resources and total throughput vector for the network in shown in Fig. 3 (a) ECEC analysis (b) ICEC analysis. (*X*-axis: sector number, *Y*-axis: ECEC flow in sej/d or ICEC flow in J/d; black region is the direct input, white region is indirect input).

Table 3
Performance metrics using thermodynamic input–output analysis and their definitions

Metric	Definition
Yield ratio (YR)	Total throughput/input from economy
Loading ratio (LR)	Throughput from non-renewable resources/throughput from renewable resources
Yield-to-loading ratio (YLR)	Yield ratio/loading ratio
Impact per value added	Impact of emissions on human health/ value added

by concomitant material and energy flows, and hence can be readily included in TIOA. This analysis considers sunlight for 24-h photosynthesis, fertile soil and wind, geopotential and hydropotential for electricity generation. Other ecosystem services such as the geological cycle and water cycle are considered in the transformity calculations for mineral resources and water, respectively, as shown in Table 5. Additional supply-based services such as those involved in pollination, carbon sequestration and dissipation of pollutant streams can also be included in TIOA, but would entail a more thorough understanding of their

Table 4
Performance metrics for illustrative example shown in Fig. 3

	Sectors		
	1	2	3
ECEC Analysis			
Yield ratio	1.44	2.77	1.07
Loading ratio	1	0.3	0.79
YLR	1.44	9.23	1.35
Impact per value added	1.63×10^4	6.83×10^3	2.04×10^3
ICEC Analysis			
Yield ratio	1.64	1.35	1
Loading ratio	0.19	0.12	0.16
YLR	8.84	11.23	6.26

geo-bio-chemical mechanisms. Unlike supply-based services, the value-based services cannot be measured using biophysical principles only. Examples of value-based services include those for recreational and cultural purposes. They depend on how people perceive them, and are dealt with in the environmental economics literature [25,49].

3.4. Human resources

Industry sectors consume human resources in the form of labor. Amount of human resources consumed is a function of number of individuals employed and their skill-level. 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 US Department of Labor's Bureau of Labor Statistics [50]. In this analysis, human resources are considered to be exogenous to the economic model representing inter-industry interactions. Therefore, in the absence of a single input–output model integrating industry sectors and societal sectors, interactions between economy and human resources need to be considered independently. This approach is an approximation and may be improved via more integrated accounting of human consumption and economic sectors. Contribution of human resources is determined via the transformity of unskilled labor, obtained from Odum [11], and calculated as the ratio of the total emergy budget to the total population of the US. Odum assumes that the total emergy input to the US economy is passed on to human resources via final demand which represents sale of economic goods and services to consumers, and consumers, in turn, feed the emergy flow back to the economy via value added which includes employment of labor. Hence, human resources incorporate natural capital flows between economy and human resources. Moreover, the per capita emergy budget of the US can be used to represent unskilled labor as only half the US population was employed in 1997. The remaining half comprised of minors, retirees and unemployed people. This approach may also be used to include the contribution of human resources while ignoring ecosystems via the ICEC to money ratio, which makes it similar to Extended Exergy Accounting [10]. Relevant calculations are in Section 4.2.

3.5. Impact of emission on human health

Industrial emissions affect human health in myriad ways. The actual impact depends on the fate of a pollutant in the natural environment and its effect on human well being. The fate itself depends on numerous physico-chemical phenomena such as dispersion, diffusion and atmospheric chemistry. There are several established procedures for calculating the impact of emissions on human health. The approach employed in this analysis represents the impact of several common pollutants on human health in terms of disability adjusted life years (DALY). This is an end-point impact assessment methodology that considers several impact categories including respiratory disorders, photochemical smog formation, ozone layer depletion, climate change and carcinogenicity [51,52]. Table 7 lists pollutants considered in this work, the impact categories they belong to and corresponding DALY values per kg of emission. Emissions data were gathered from the US Environmental Protection Agency's Toxics Release Inventory (TRI) [53]. The approach for converting DALYs to ECEC has been discussed in Ukidwe and Bakshi [7]. Currently work towards including more pollutants in this analysis is in progress. Relationship between DALY and ECEC is linear, and 1 DALY/day of human health impact corresponds to 9.35×10^{13} sej/day of impact in ECEC terms. Furthermore, conversion of DALY into ECEC is necessary only if it is desired to have a single numeraire for comparing diverse flows of ecosystem goods and services, human resources and emissions and their impact on human health. If a single metric is not required, it may be better not to convert DALY into ECEC giving rise to multiple streams in disparate units that would have to be considered in a multiobjective framework. The analysis presented in this paper does not consider ecosystem impact of emissions, but the general approach could be applied for it if exergy loss due to ecosystem impact could be quantified. A similar approach could be used to represent the impact of emissions in terms of ICEC, but is not considered in this work.

3.6. Allocation matrix for inter-industry interactions

This analysis uses a monetary, inter-industry transaction coefficient matrix to represent the US economic system. Such a matrix is compiled periodically by the US Department of Commerce's Bureau of Economic Analysis. More specifically, results presented in Section 4 are based on the 488-sector 1997 US inter-industry benchmark model [54]. Similar results have been published in the past for the 91-sector 1992 model which is a more concise and aggregated representation of the US economy [7]. An allocation matrix based on material or energy interactions between industry sectors may be more accurate than a monetary transaction matrix, but is not available at present. The "materials count" initiative undertaken by National Research Council [55] is an example of efforts that strive to compile a biophysical transaction matrix for the US economy. If this initiative materializes, more accurate data could be used for inter-industry allocation.

4. Results for individual inputs and outputs

The TIOA methodology can be applied to determine direct and indirect ECEC and ICEC requirements of individual industry sectors. The following subsections focus mainly on ECEC requirements of individual sectors. Similar ICEC plots may be readily generated, but most of them are not shown in the interest of brevity. Section 5 presents aggregate results based on both ICEC and ECEC.

4.1. Ecosystem products

Figs. 5–7 show the total contribution of ecological products listed in Table 5 to the industry sectors in 1997 US industry benchmark model. Figs. 5 and 6 show lithosphere resources calculated as Industrial and Ecological CEC, while Fig. 7 shows the rest of the inputs as ECEC. These figures also show direct and indirect inputs to each industry sector. The sector names, NAICS codes and serial numbers of the economic sectors are shown in Appendix A of the Supporting Information. These results are in general agreement with those obtained from the analysis of the 91-sector 1992 US economy. The differences between the two analyses are noted at appropriate locations in this section.

4.1.1. Lithosphere

Fig. 5 shows ECEC requirements of industry sectors from the lithosphere. Sectors of stone mining and quarrying

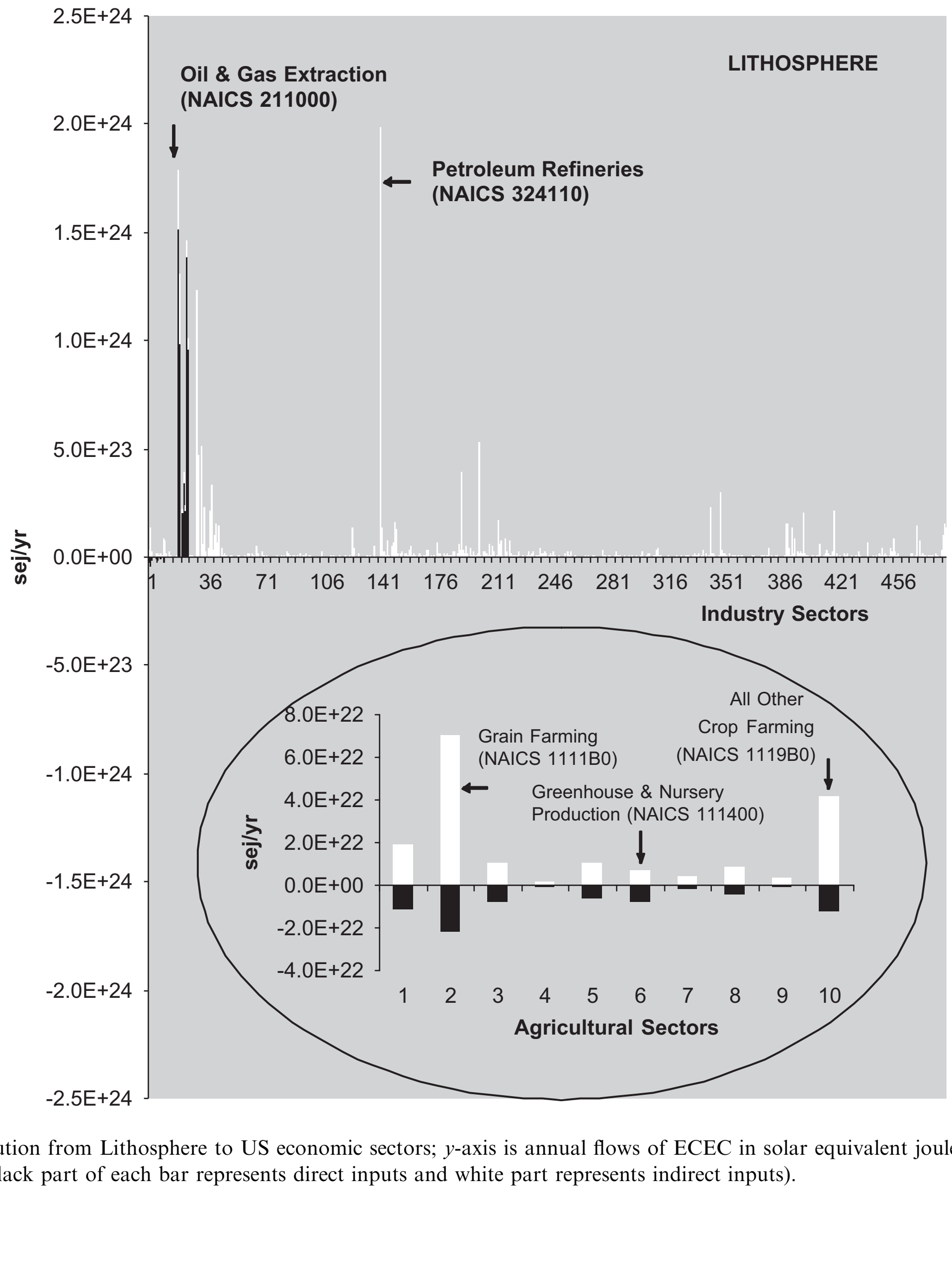

Fig. 5. ECEC Contribution from Lithosphere to US economic sectors; y-axis is annual flows of ECEC in solar equivalent joules (sej/yr), and x-axis is sector serial number (black part of each bar represents direct inputs and white part represents indirect inputs).

Table 5
Data for ecosystem product inputs to 1997 US economy

Resource considered in this analysis	Industry sector receiving direct input and its NAICS code	Material or energy flow (*F*)	Data source for *F*	ICEC flow (J/yr)	Transformity (τ)	Data source for τ	ECEC flow, $c = \tau F$ (sej/yr)
Lithosphere							
Crude petroleum field production	Oil and Gas Extraction (NAICS 211000)	1.06×10^{19}J/yr[a]	[68]	1.06×10^{19}	53000 sej/J	[11]	5.61×10^{23}
Natural gas	Oil and Gas Extraction (NAICS 211000)	18.9MMCuF/yr	[69]	1.99×10^{19}	48000 sej/J	[11]	9.58×10^{23}
Iron-ore mining	Iron ore mining (NAICS 212210)	202 MMT/yr	[70]	2.08×10^{16}[b]	1×10^{9} sej/g	[11]	2.02×10^{23}
Copper mining	Copper, nickel, lead and zinc mining (NAICS 212230)	342 MMT/yr[c]	[70]	2.80×10^{16}[d]	1×10^{9} sej/g	[11]	3.42×10^{23}
Gold mining	Gold, silver and other metal mining (NAICS 2122A0)	217 MMT/yr[e]	[70]	5.63 × 1016[f]	1×10^{9} sej/g	[11]	2.17×10^{23}
Crushed stone	Stone mining and quarrying (NAICS 212310)	1390 MMT/yr	[70]	1.83×10^{17}[g]	1×10^{9} sej/g	[11]	1.39×10^{24}
Sand	Sand, gravel, clay and refractory mining (NAICS 212310)	961 MMT/yr	[70]	1.27×10^{17}[h]	1×10^{9} sej/g	[11]	9.61×10^{23}
Raw coal excluding overburden	Coal mining (SIC 212100)	988 MMT/yr	[70]	5.73×10^{19}[i]	1×10^{9} sej/g	[11]	9.88×10^{23}
Nitrogen from mineralization	Agricultural sectors (NAICS 1111A0-1119B0)	2.96 MMT/yr[j]	[71]	1.15×10^{15}[k]	4.19×10^{9} sej/g	[11]	1.24×10^{22}
Phosphorous from Mineralization	Agricultural sectors (NAICS 1111A0-1119B0)	1.97 MMT/yr[l]	[71]	9.75×10^{14}[m]	2×10^{9} sej/g[n]	[11]	3.94×10^{21}
N-Deposition from atmosphere[o]	Agricultural sectors (NAICS 1111A0-1119B0)	1.97 MMT/yr[p]	[71]	7.76×10^{14}[q]	4.19×10^{9} sej/g	[11]	8.25×10^{21}
Return of decomposing detritus to agricultural soil	Agricultural sectors (NAICS 1111A0-1119B0)	−433 MMT/yr[r]	[71]	-8.77×10^{18}[s]	2.24×10^{8} sej/g of residue[t]	[11]	-9.70×10^{22}
Biosphere							
Wood production	Logging (NAICS 113300)	520 MMT/yr of roundwood	[71]	8.27×10^{18}[u]	5.55×10^{8} sej/g[v]	[11])	2.90×10^{23}
Pasture Grazing	Cattle Ranching and Farming (NAICS 112100)	200 MMT/yr of wet grass	[71]	1.67×10^{18}[w]	5.83×10^{19} sej/MMT of wet grass[x]	[11]	1.17×10^{22}
Hydrosphere							
Water consumption	Water, sewage and other systems (NAICS 221300)	1.47×10^{14} gallons/yr	[72]	2.73×10^{18}[y]	7.67×10^{8} sej/gallon[z]	[48]	1.13×10^{23}
Atmosphere							
CO_2 in 24-h net photosynthesis	Agricultural sectors (NAICS 1111A0-1119B0)	867 MMT/yr[α]	[71]	0[β]	6.19×10^{7}sej/g CO_2[γ]	[11]	5.37×10^{22}

[a] $(4.803 \times 10^6$ barrels on-shore production/day$) \times (30$ days/month$) \times (12$ months/yr$) \times (6.12 \times 10^9$ J/barrel$) = 1.06 \times 10^{19}$ J/yr.

[b] Iron ore mining: mass flow rate $(F) = 202$MMT/yr; exergy of Fe_2O_3 $(b) = 103$ J/g [1]; ICEC Flow $= F \times b = 2.08 \times 10^{16}$ J/yr.

[c] Copper Mining: (2.07MMT/yr 1997 mine production) × (297MMT/yr 1993 domestic ores input)/(1.79MMT/yr 1993 mine production) = (342MMT/yr 1997 domestic ores input); assuming flotation, concentration, smelting and refining technologies and ratio of domestic to imported concentrates unchanged between 1993 and 1997.

[d] Copper mining: 342MMT/yr domestic ores input (*F*); exergy of CuO $(b) = 82$J/g [1]; ICEC flow $= F \times b = 2.80 \times 10^{16}$ J/yr.

[e] Gold Mining: (325tons/yr 1997 gold production) × (221MMT/yr 1993 domestic gangue)/(331tons/yr 1993 gold production) = (217MMT/yr 1997 domestic gangue); assuming flotation, concentration, smelting and refining technologies and ratio of domestic to imported concentrates unchanged between 1993 and 1997.

[f] Gold Mining: 217MMT/yr domestic ores input (*F*); exergy of Au_2O_3 $(b) =$ (114.7KJ/mol)/(441.93g/mol of Au_2O_3) [1]; ICEC flow $= F \times b = 5.63 \times 10^{16}$J/yr.

[g] Crushed Stone: Mass Flow Rate $(F) = 1390$MMT/yr; exergy of SiO_2 $(b) = 132$J/g [1]; ICEC Flow $= F \times b = 1.83 \times 10^{17}$J/yr.

[h] Sand: Mass Flow Rate $(F) = 961$MMT/yr; exergy of SiO_2 $(b) = 132$J/g [1]; ICEC Flow $= F \times b = 1.27 \times 10^{17}$J/yr.

[i] Raw Coal Excluding Overburden: Mass Flow Rate $(F) = 878$MMT/yr; exergy of coal $(b) = 29000$J/g [1]; ICEC Flow $= F \times b = 2.56 \times 10^{19}$J/yr.

[j]Nitrogen from mineralization: (3MMT/yr 1993 Nitrogen flux from mineralization) × (1.91×10^6 farms in 1997) × (487acres average size of farm in 1997)/(1.93×10^6 farms in 1993)/(491acres average size of farm in 1993) = 2.96MMT/yr 1997 Nitrogen flux from mineralization.

[k]Nitrogen from mineralization: Mass Flow Rate (F) = 2.96MMT/yr; exergy of $Mg(NO_3)_2$ (b) = 387J/g [1]; ICEC Flow = $F\times b = 1.15\times10^{15}$J/yr.

[l]Phosphorous from mineralization: (2MMT/yr 1993 phosphorous flux from mineralization) × (1.91×10^6 farms in 1997) × (487acres average size of farm in 1997)/(1.93×10^6 farms in 1993)/(491acres average size of farm in 1993) = 1.97MMT/yr 1997 Phosphorous flux from mineralization.

[m]Phosphorous from mineralization: Mass Flow Rate (F) = 1.97MMT/yr; exergy of $Mg_3(PO_4)_2$ (b) = 495J/g [1]; ICEC Flow = $F\times b = 9.75\times10^{14}$J/yr.

[n](4.6×10^8 sej/g of P_2O_5) × (1g of P_2O_5/0.23g of P) = 2×10^9 sej/g of P.

[o]N-deposition from Atmosphere is considered is an input from lithosphere since Nitrogenous salts enter plants through soil.

[p]N-deposition from Atmosphere: (2MMT/yr 1993 N-deposition flux) × (1.91×10^6 farms in 1997) × (487acres average size of farm in 1997)/(1.93×10^6 farms in 1993)/(491acres average size of farm in 1993) = 1.97MMT/yr 1997 N-deposition flux.

[q]N-deposition from Atmosphere: mass flow rate (F) = 1.97MMT/yr; exergy of $Mg(NO_3)_2$ (b) = 387J/g [1]; ICEC Flow = $F\times b = 7.62\times10^{14}$J/yr.

[r]Return of detrital matter: (440MMT/yr 1993 flux) × (1.91×10^6 farms in 1997) × (487acres average size of farm in 1997)/(1.93×10^6 farms in 1993)/(491acres average size of farm in 1993) = 433.4MMT/yr 1997 flux, Negative sign indicates flow from industry sector to Lithosphere.

[s]Return of detrital matter: (433MMT/yr of returned detritus residue) × (0.44g C/g of residue) × (11 kcal/g C) × (4186J/kcal) = 8.77×10^{18}J/yr [11].

[t](0.44g C/g of residue) × (11kcal/g C) × (4186J/kcal) × (11068 sej/J Transformity of detritus production) = 2.24×10^8 sej/g residue.

[u]Wood Production: 520MMT/yr roundwood × 3.8 kcal/g roundwood × 4186 J/kcal = 8.27×10^{18}J/yr [11].

[v](3.8 kcal/g roundwood) × (4186 J/kcal) × (34900 sej/J) = 5.55×10^8 sej/g of roundwood.

[w]Pasture Grazing: 440MMT/yr of wet grass × 0.5 MMT of dry grass/MMT of wet grass × 10^{12} g/MMT × 1.86×10^{11}J/ha/yr of pasture evapotranspiration × 9×10^{-4} m^2/g × 10^{-4} ha/m^2 = 5.83×10^{19} sej/MMT of wet grass [11].

[x](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) = 5.83×10^{19} sej/MMT of wet grass.

[y]Water Consumption: 1.47×10^{14}gallons/yr × 3785 cm^3/gallon of water × 1g of water/cm^3 of water × 4.94J/g of water = 2.73×10^{18} J/yr [11].

[z](3785 cm^3/gallon of water) × (1g of water/cm^3 of water) × (4.94J/g of water) × (4.1×10^4 sej/J) = 7.67×10^8 sej/gallon of water.

[α]CO_2 in 24-h photosynthesis: (880MMT/yr 1993 CO_2 flux) × (1.91×10^6 farms in 1997) × (487acres average size of farm in 1997)/(1.93×10^6 farms in 1993)/(491acres average size of farm in 1993) = 866.8MMT/yr 1997 CO_2 flux.

[β]Atmospheric Gases being at reference state are ignored in ICEC analysis.

[γ](12g C/44g CO_2) × (8 kcal/g C) × (4186J/kcal) × (6780sej/J) = 6.19×10^7 sej/g CO_2.

Table 6
Data for ecosystem service inputs to 1997 US economy

Ecosystem Service	Sector receiving direct input and corresponding NAICS code	Energy or material flow (F)	Data source for F	ICEC Flow (J/yr)	Transformity (τ) (sej/J)	Data Source for τ	ECEC flow ($C = F.\tau$) (sej/yr)
Sunlight for photosynthesis	Agricultural sectors (NAICS 1111A0-1119B0)	2.23×10^{22} J/yr[a]	[56,57]	2.23×10^{22}	1	[11]	2.23×10^{22}
	Forest nurseries, forest products and timber tracts (NAICS 113A00)	1.19×10^{22} J/yr	[56,57]	1.19×10^{22}	1	[11]	1.19×10^{22}
Hydropotential for power generation	Power generation and supply (NAICS 221100)	1.28×10^{18} J/yr	[69]	1.28×10^{18}	27764	[11]	3.55×10^{22}
Geothermal heat for power generation	Power generation and supply (NAICS 221100)	5.3×10^{16} J/yr	[69]	5.3×10^{16}	6055	[11]	3.21×10^{20}
Wind energy for power generation	Power generation and supply (NAICS 221100)	1.18×10^{16} J/yr	[69]	1.18×10^{16}	1496	[11]	1.77×10^{19}
Soil erosion	Agricultural sectors (NAICS 1111A0-1119B0)	34.49×10^8 ton/yr	[73,74]	3.12×10^{18}	4.43×10^4	[47]	1.38×10^{23}[b]
	Construction sectors (NAICS 230110-230250)	35.65×10^8 ton/yr	[73,74]	3.22×10^{18}	4.43×10^4	[47]	1.43×10^{23}

[a]Sunlight for photosynthesis: (2.26×10^{22}J/yr 1993 flux) × (1.91×10^6 farms in 1997) × (487acres average size of farm in 1997)/(1.93×10^6 farms in 1993)/(491acres average size of farm in 1993) = 2.23×10^{22}J/yr 1997 flux.
[b](34.49×10^8 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) = 1.38×10^{23} sej/yr; transformity adjusted to 1996 base of 9.44×10^{24} sej/yr.

Table 7
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 [11], and is obtained by dividing total emergy budget of the US (7.85×10^{24} sej/yr) by the total population of the US (230×10^6 people).
[c]Impacts are potential impacts in future [52].

(NAICS 212310), coal mining (NAICS 212100), sand, gravel, clay and refractory mining (NAICS 212320) and oil and gas extraction (NAICS 211000) have prominent peaks on account of direct inputs from lithosphere. Sectors of power generation and supply (NAICS 221100), petroleum refineries (NAICS 324110), iron and steel mills (NAICS 332111) and automobile and light truck manufacturing (NAICS 336110) also have prominent peaks on account of *indirect consumption* of lithospheric resources. Unlike mining sectors that extract resources from lithosphere, the agricultural sectors (NAICS 1111A0-1119B0) add to lithosphere on account of return of detrital matter to agricultural soil. Consequently, these sectors have *negative direct* ECEC requirements from lithosphere. This is shown with the aid of the embedded graph in Fig. 5. The agricultural sectors, like other sectors in the economy, still have *positive indirect* ECEC requirements on account of consumption of fuels and electricity. Furthermore, the

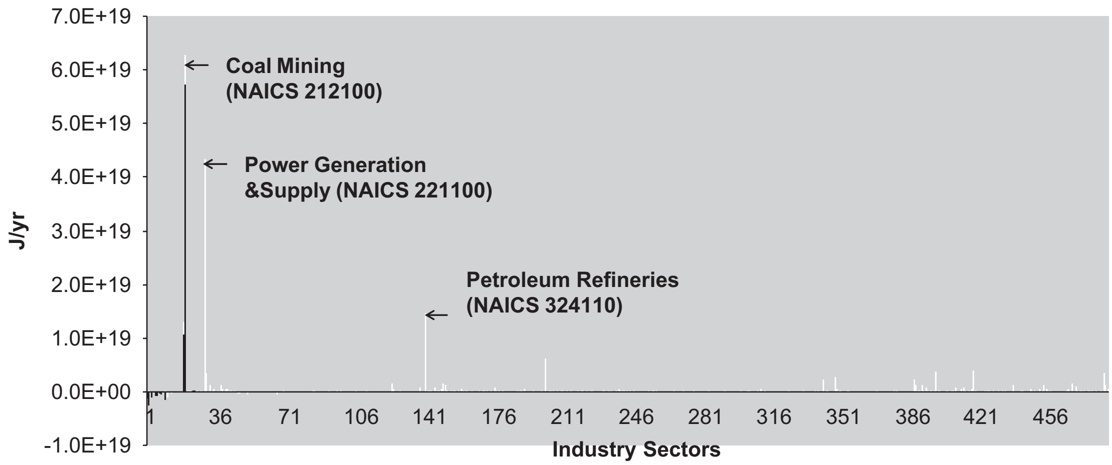

Fig. 6. ICEC Contribution from Lithosphere to US economic sectors; *y*-axis is annual flows of ICEC in J/yr, and *x*-axis is sector serial number (black part of each bar represents direct inputs and white part represents indirect inputs).

indirect requirements exceed the direct requirements making the agricultural sectors net consumers of lithospheric resources. Sector of greenhouse and nursery production (NAICS 111400) is found to be the only exception where direct requirements exceed indirect requirements, making it a net donor to the lithosphere.

Fig. 6 shows ICEC requirements of industry sectors from lithosphere. Coal mining (NAICS 212100), power generation and supply (NAICS 221100), petroleum refineries (NAICS 324191) and oil and gas extraction (NAICS 211000) have prominent peaks on account of direct inputs from lithosphere. However, comparison with Fig. 5 shows that coal mining and power generation and supply sectors have replaced petroleum refineries and oil and gas extraction as the two most significant sectors in Fig. 6. This is also supported by the data presented in Table 5 wherein the total ICEC and ECEC inputs to the sectors of oil and gas extraction are 3.05×10^{19} J/yr and 1.52×10^{24} sej/yr respectively and those for coal mining sector are 5.73×10^{19} J/yr and 9.88×10^{23} sej/yr respectively. This difference can be attributed to different transformities of coal (34,482 sej/J), natural gas (48,000 sej/J) and petroleum (53,000 sej/J) [39]. As discussed in Section 2, ICEC analysis assumes a uniform transformity of 1 J/J for all the three, and in the process suppresses the ecological consumption of exergy in natural gas and petroleum.

4.1.2. Biosphere

Fig. 7(a) shows ECEC requirements from the biosphere. Sectors of logging (NAICS 113300) and cattle ranching and agricultural (NAICS 112100) get direct inputs from the biosphere on account of timber harvesting and pasture grazing respectively. Sectors of sawmills (NAICS 321113), paper and paperboard mills (NAICS 3221A0), veneer and plywood manufacturing (NAICS 32121A) and new residential 1-unit structures (non-farm) (NAICS 230110) also have prominent peaks on account of indirect consumption. Sectors of all other petroleum and coal products manufacturing (NAICS 324199), military armored vehicles and tank part manufacturing (NAICS 336992) and ground or treated minerals and earths manufacturing (NAICS 327992) have the lowest ECEC inputs from the biosphere.

4.1.3. Atmosphere

Fig. 7(b) shows ECEC from the atmosphere. The agricultural sectors (NAICS 1111A0-1119B0) get direct inputs from atmosphere on account of CO_2 consumption during 24-h photosynthesis. As a result, Fig. 7(b) shows prominent peaks for the agricultural sectors as well for those sectors that directly rely on agricultural sectors for their operations. This includes food and fabric manufacturing sectors (NAICS 311111-313240) and the sector of food services and drinking places (NAICS 722000). Sectors of industrial pattern manufacturing (NAICS 332997), military armored vehicles and tank part manufacturing (NAICS 336992) and saw blade and handsaw manufacturing (NAICS 332213) have the lowest requirements from atmosphere. As mentioned in Table 5, only CO_2 consumed during 24-h photosynthesis has been considered in this analysis. Oxygen and nitrogen have not been considered because their transformity values are unresolved in emergy analysis [7]. Calculation of transformities of O_2 and N_2 is a non-trivial task as it entails a thorough understanding of the interwoven carbon, nitrogen, and sulfur cycles.

4.1.4. Hydrosphere

Fig. 7(c) shows ECEC requirements from the hydrosphere. Only the sector of water, sewage and other systems (NAICS 221300) that uptakes water from rivers and lakes is assumed to have a direct input from hydrosphere. Other sectors with prominent peaks in Fig. 7(c) are real estate (NAICS 531000), retail trade (NAICS 4A0000) and wholesale trade (NAICS 420000). Sectors of software reproducing (NAICS 334611), industrial pattern manufacturing (NAICS 332997) and secondary processing of copper (NAICS 331423) have the lowest ECEC

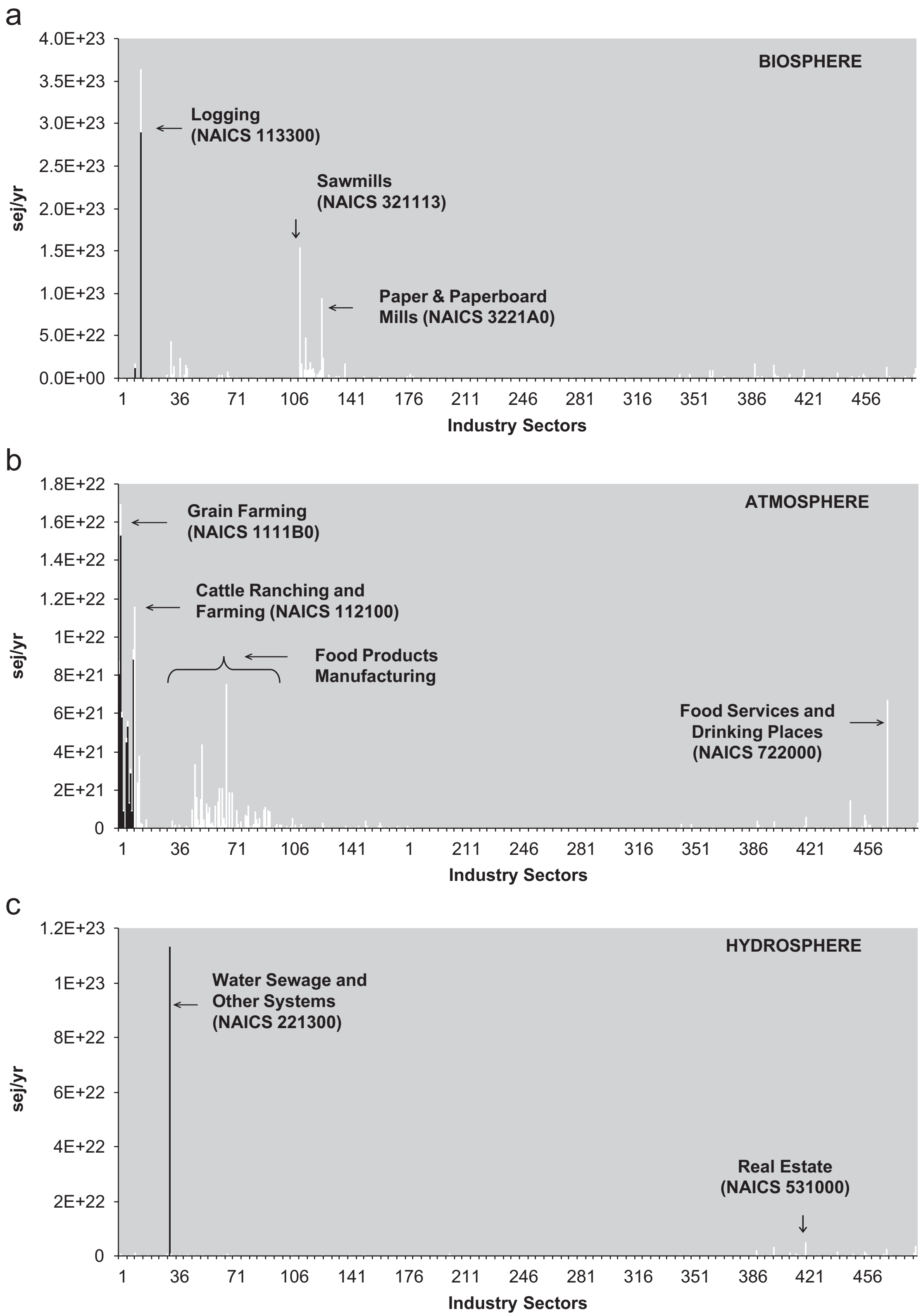

Fig. 7. Contribution of ecological products US economic sectors from (a) biosphere; (b) atmosphere; (c) hydrosphere; *y*-axis is annual flows of ECEC in solar equivalent joules (sej/yr), and *x*-axis is sector serial number (black part of each bar represents direct inputs and white part represents indirect inputs).

requirement from hydrosphere. Other functions of hydrosphere such as climate regulation and cleansing of air have not been considered in this analysis.

4.2. Ecosystem services

Fig. 8 shows the direct ECEC inputs of ecosystem services listed in Table 6.

4.2.1. Sunlight

Fig. 8(a) shows the contribution of sunlight. The agricultural sectors (NAICS 1111A0-1119B0) and the sector of forest nurseries, forest products and timber tracts (NAICS 113A00) are the direct recipients of sunlight. Sectors of sawmills (NAICS 321113) and food services and drinking places (NAICS 722000) have prominent peaks in Fig. 8(a) on account of indirect consumption. In this paper, solar inputs to the group of agricultural sectors and to the sector of forest nurseries, forest products and timber tracts are determined by multiplying average solar flux per unit area in the continental US by the total land area of the two [56,57]. To allocate solar inputs within the group of agricultural sectors, economic data were used. If data about land areas in individual agricultural sectors were available, it could have been used for allocation as well. Furthermore, the use of transformity values in this analysis ensures consideration of indirect routes of solar inputs to industry sectors. These indirect routes include bio-geochemical cycles such as the hydrologic cycle and atmospheric circulation that are driven by solar insolation. In that regard, the analysis presented in this paper improves upon Costanza [58] who considered only direct solar inputs to the US economy to calculate energy intensities of industry sectors. In this paper, exergy of sunlight is assumed to be equal to its energy. Other approaches that assume solar radiation to have a composition similar to that of a black body are also available [40]. Such approaches require detailed knowledge about ambient temperature, level of earth's surface, sun's position and the composition of atmosphere but are unlikely to change the results presented in this paper significantly.

4.2.2. Fertile soil

Fig. 8(b) shows ECEC content of topsoil lost due to erosion. The agricultural sectors (NAICS 1111A0-1119B0) and the construction sectors (NAICS 230110-230250) are directly responsible for the loss of top organic soil. Sectors of animal, except poultry, slaughtering (NAICS 311611) and food services and drinking places (NAICS 722000) also have prominent peaks on account of indirect effects. Contribution of soil erosion is significantly larger than that of sunlight because top organic soil is a more concentrated form of resource than sunlight. Sectors with the lowest contribution from fertile soil are industrial pattern manufacturing (NAICS 332997), military armored vehicles and tank parts manufacturing (NAICS 336992) and saw blade and handsaw manufacturing (NAICS 332213). In this analysis fertile soil is assumed to be a renewable, and hence, non-additive resource. The assumption is based on the fact that the carbonaceous content of top organic soil, as used in this analysis, is regenerated from the dead biomass in a renewable fashion.

4.2.3. Hydropotential

Fig. 8(c) shows the contribution of hydropotential to industry sectors. Hydropotential refers to the potential energy in water streams that is converted to kinetic energy and then to electrical energy in hydroelectric power plants. Naturally, the sector of power generation and supply (NAICS 221100) is the only sector with direct input. Sectors of real estate (NAICS 531000), retail trade (NAICS 4A0000) and wholesale trade (NAICS 420000) also have prominent peaks on account of high electricity consumption that can be explained considering their high economic throughputs. These results also match those obtained for the 91-sector 1992 US economic system [7]. Sectors of software reproducing (NAICS 334611), industrial pattern manufacturing (NAICS 332997) and lessors of nonfinancial intangible assets (NAICS 533000) have the lowest contribution from hydropotential. Contributions of wind energy and geothermal energy are also calculated but not shown. Their graphs can be obtained by multiply the y-axis of Fig. 8(c) by 4.99×10^{-4} and 9×10^{-3}, respectively.

4.3. Human resources

Fig. 9 shows ECEC requirements of industry sectors from human resources. Unlike other resources, human resources are directly consumed by all industry sectors through employment of labor. Service sectors, in particular, have higher direct inputs than the rest of the economy. Sectors of other state and local government enterprises (NAICS S00203), retail trade (NAICS 4A0000), wholesale trade (NAICS 420000) and home health care services (NAICS 621600) have the highest consumption of human resources. These results also conform to those obtained for 91-sector 1992 US economy. Other non-service sectors with prominent peaks include automobile and light truck manufacturing (NAICS 336110), motor vehicle parts manufacturing (NAICS 336300), new residential 1-unit structures, nonfarm (NAICS 230110) and commercial and institutional buildings (NAICS 230220). In this analysis, contribution of human resources is determined from economic data that includes the number of people employed and their average annual payrolls, as discussed in Section 3.4.

A similar approach based on ICEC analysis can be used to evaluate industry-specific exergetic intensities of human labor in Sciubba's Extended Exergy Accounting (EEA) [10]. Sciubba defines exergetic intensity of human labor as total exergetic resources into a portion of the society divided by the number of working hours sustained by it. This ratio can be calculated for the aggregate US economy by dividing the ECEC of unskilled labor, 9.35×10^{13} sej/workday [11], by the average ECEC/ICEC

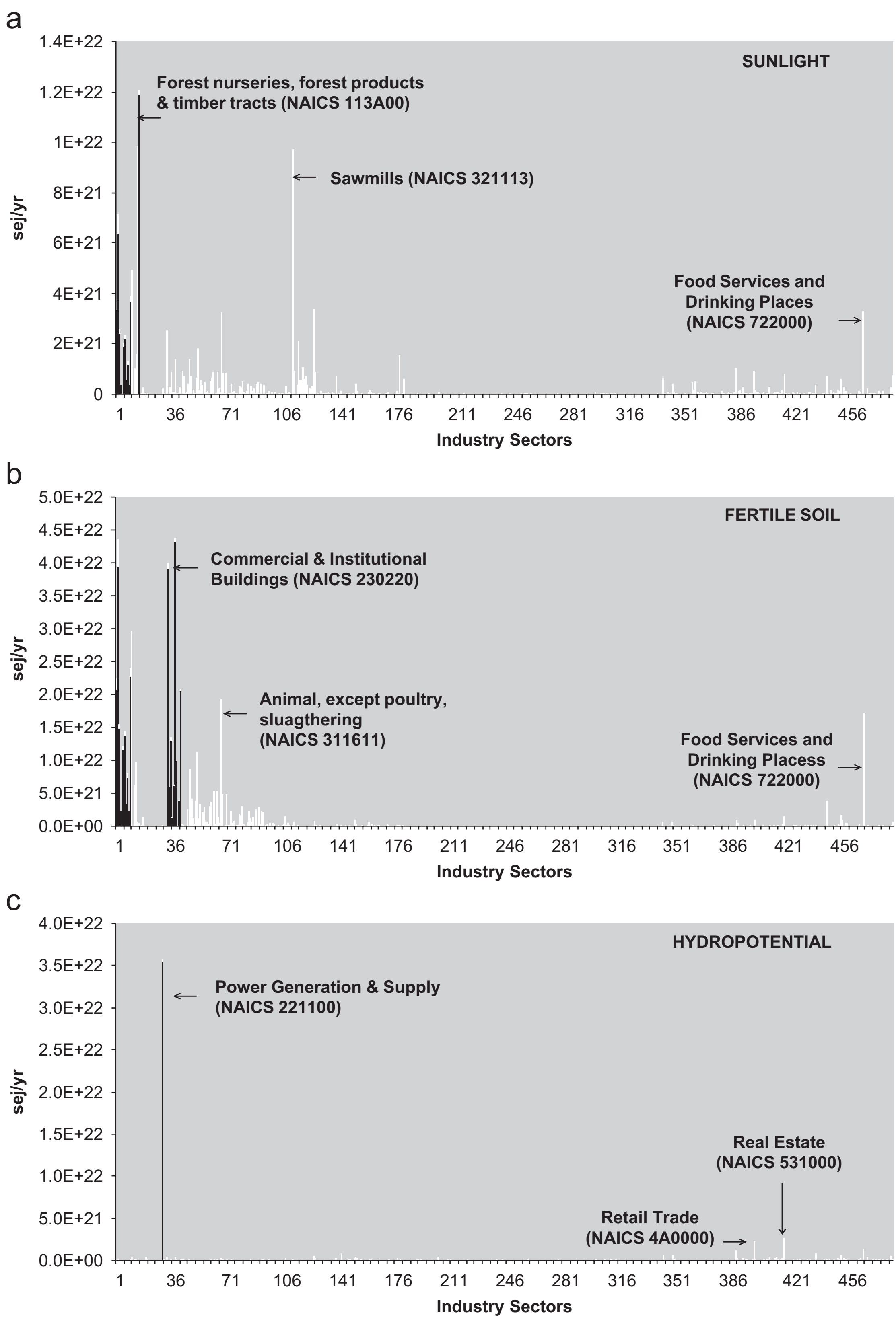

Fig. 8. Contribution of direct ecosystem services. (a) sunlight; (b) fertile soil; (c) hydropotential y-axis is annual flows of ECEC in solar equivalent joules (sej/yr), and x-axis is sector serial number (black part of each bar represents direct inputs and white part represents indirect inputs).

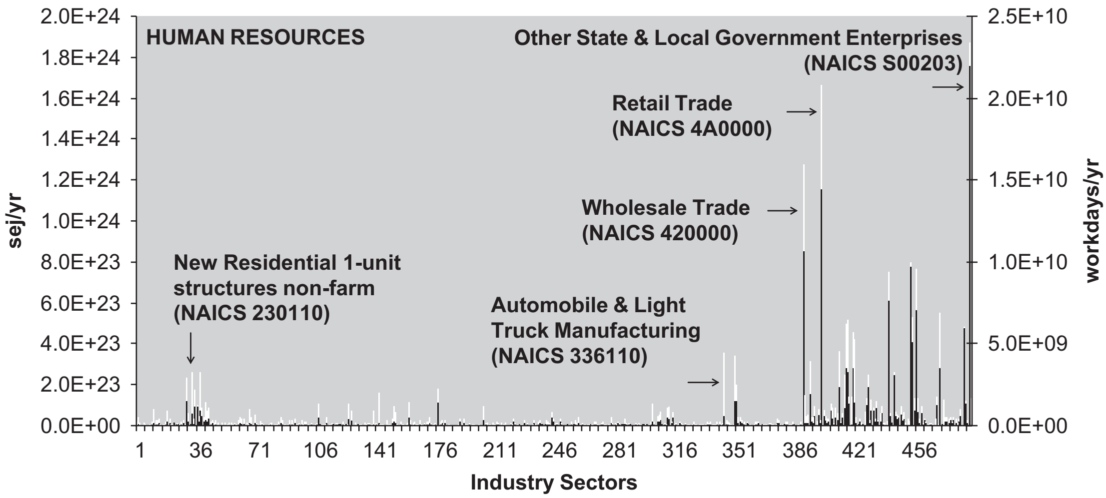

Fig. 9. ECEC requirements from human resources; *y*-axis are annual ECEC flows in sej/yr and corresponding flows in workdays/yr; *x*-axis is sector serial number (black part of each bar represents direct inputs and white part represents indirect inputs).

ratio for the 1997 US economy, 2873 sej/J. The latter ratio is discussed further in Section 5.3. This gives a value of 3.25×10^{10} J/workday that can be used in EEA. In addition industry-specific values can also be calculated using ECEC requirements of industry sectors from human resources from Fig. 9, industry-specific ECEC/ICEC ratios from Fig. 14(c) and the number of people employed in each sector [50].

4.4. Human impact of bulk pollutants

Fig. 10 shows the human health impact of the four bulk pollutants considered in this paper, namely, SO_2, NO_2, PM10 and CO_2. This figure shows human health impact in terms of DALY/yr based on a hierarchist perspective as well as corresponding ECEC values. To convert human health impact from DALY/yr to ECEC/yr, the former is multiplied by a factor of 3.42×10^{16} sej/yr [7,39]. Similar results can be obtained based on ICEC analysis using the exergetic intensity of human labor from Section 4.3. In such case, to convert human health impact from DALY/yr to ICEC/yr, the former needs to be multiplied by a factor of 1.19×10^{13} J/yr. The plots based on ICEC would be qualitatively similar to those shown in the sequel for ECEC.

4.4.1. Sulfur dioxide

Fig. 10(a) shows the impact associated with SO_2. Power plants are the major emitters of SO_2. Consequently, the sector of power generation and supply (NAICS 221100) has the most significant peak in Fig. 10(a). Other sectors with prominent peaks include petroleum refineries (NAICS 324110), real estate (NAICS 531000) and retail trade (NAICS 4A0000). Sector of petroleum refineries is one of the major suppliers to the sector of power generation and supply, whereas sectors of real estate and retail trade are major consumers of electricity due to their large economic throughputs.

4.4.2. Nitrogen oxides

Fig. 10(b) shows impact associated with NO_2 emissions. Like SO_2, power plants are also the major emitters of NO_2. Consequently, the sector of power generation and supply (NAICS 221100) has the most significant peak in Fig. 10(b). Other major emitters of NO_2 include sectors of natural gas distribution (NAICS 221200) and truck transportation (NAICS 484000). Sectors of petroleum refineries (NAICS 324110), retail trade (NAICS 4A0000), wholesale trade (NAICS 420000), food services and drinking places (NAICS 722000) and oil and gas extraction (NAICS 211000) also have prominent peaks on account of indirect effects. Some of the agricultural and husbandry sectors, namely sectors of grain agricultural (NAICS 1111B0) and cattle ranching and agricultural (NAICS 112100), also have noticeable peaks due to high usage of nitrogenous fertilizers whose production is a source of NO_2.

4.4.3. Carbon dioxide

Fig. 10(c) 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 power generation and supply (NAICS 221100) and oil and gas extraction (NAICS 211000) have the highest CO_2 emissions amongst all sectors. Other sectors with prominent peaks include natural gas distribution (NAICS 221200), petroleum refineries (NAICS 324110) and retail trade (NAICS 4A0000). These sectors are either directly involved in extraction and consumption of fossil fuels or are major consumers of electricity. Impact of CO_2 emissions, as reported in eco-indicator 99, is the potential impact in the future [52]. Among the bulk pollutants, impact associated with SO_2 and CO_2 is two orders of magnitude higher than that for NO_2 and PM10.

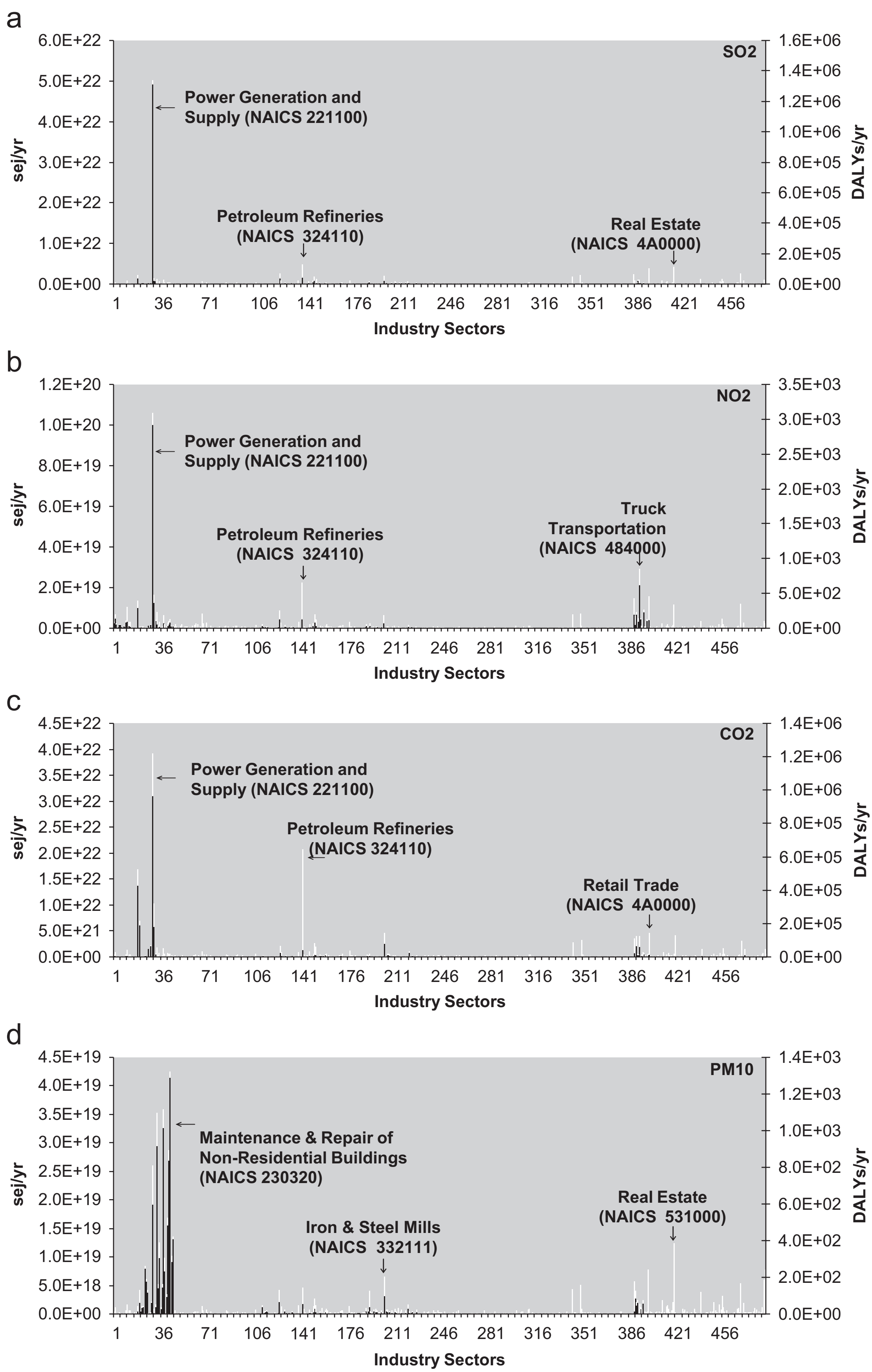

Fig. 10. Human Health Impact of Bulk-Pollutants (a) SO_2; (b) NO_2; (c) CO_2; (d) PM10; *y*-axis are annual ECEC flows in sej/yr and corresponding impact in DALYs/yr; *x*-axis is sector serial number (black part of each bar represents direct inputs and white part represents indirect inputs).

4.4.4. Particulate matter

Fig. 10(d) shows impact associated with emission of PM10. PM10 is primarily responsible for respiratory disorders. Particulate matter is primarily emitted during construction activities. Sectors of maintenance and repair of nonresidential buildings (NAICS 230320), commercial and institutional buildings (NAICS 230220) and new residential 1-unit structures, non-farm (NAICS 230110) have prominent peaks in Fig. 10(d) on account of direct emission of particulate matter. Other sectors with prominent peaks include real estate (NAICS 531000) and iron and steel mills (NAICS 332111).

4.5. Human impact of non-bulk pollutants

Fig. 11 shows the impact associated with selected non-bulk pollutants. Their immediate destinations and parent impact category are listed in Table 7.

4.5.1. Ammonia

Fig. 11(a) shows impact associated with emission of ammonia. Ammonia is primarily emitted by the sectors of paper and paperboard mills (NAICS 3221A0) petroleum refineries (NAICS 324110) and iron and steel mills (NAICS 331111). As a result, these sectors also have the tallest peaks in Fig. 11(a). Sectors of motor vehicles part manufacturing (NAICS 336300) and automobile and light truck manufacturing (NAICS 336110) also have significant peaks on account of indirect effects.

4.5.2. Toluene

Fig. 11(b) shows impact associated with emission of toluene. Sectors of software publishers (NAICS 511200), petroleum refineries (NAICS 324110) and plastic plumbing fixtures and all other plastics products (NAICS 32619A) are the major emitters of toluene. Other sectors with prominent peaks include automobile and light truck manufacturing (NAICS 336110), newspaper publishers (NAICS 511110) and periodical publishers (NAICS 511120).

4.5.3. Methanol

Fig. 11(c) shows impact associated with emission of methanol. Sectors of paper and paperboard mills (NAICS 3221A0), coated and laminated paper and packaging materials (NAICS 32222A) and sanitary paper product manufacturing (NAICS 322291) are some of the major emitters of methanol. Other sectors with prominent peaks include other paperboard container manufacturing (NAICS 322210), commercial printing (NAICS 32311A) and retail trade (NAICS 4A0000).

4.5.4. 1,1,1-trichloroethane

Fig. 11(d) shows impact associated with 1,1,1-Trichloroethane. 1,1,1-TCE is primarily responsible for the depletion of ozone layer. Sectors of plastic plumbing fixtures and all other plastic products (NAICS 32619A), automobile and light truck manufacturing (NAICS 336110) and plastics packaging materials, film and sheet (NAICS 326110) are some of the major emitters of 1,1,1-TCE. Sectors of commercial and institutional buildings (NAICS 230220), new residential 1-unit structures, non-farm (NAICS 230110), glass and glass products, except glass containers (NAICS 32721A) and motor vehicle part manufacturing (NAICS 336300) also have substantial impact due to indirect effects.

4.5.5. Styrene

Figs. 11(e–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 Figs. 11(e–g). Impact of styrene emission to air is two orders of magnitude higher than that to water or soil. Sectors of plastic plumbing fixtures and all other plastic products (NAICS 32619A) and plastic packaging materials, film and sheet (NAICS 326110) are the major emitters of styrene to air. Sectors of automobile and light truck manufacturing (NAICS 336110) and motor vehicle parts manufacturing (NAICS 336300) also have significant peaks in Fig. 11(e). Compared to styrene emissions to air, styrene emissions to water is fairly small. Sectors of plastic plumbing fixtures and all other plastic products (NAICS 32619A) and plastic material and resin manufacturing (NAICS 325211) have the highest emission of styrene to water. Other sectors with significant styrene emissions to water include petroleum refineries (NAICS 324110) and paperboard mills. Sectors with highest styrene emissions to soil include other basic organic chemical manufacturing (NAICS 325190) and automobile and light truck manufacturing (NAICS 336110).

5. Aggregate metrics

One of the fortes of exergy analysis is its ability to represent and combine a variety of streams in a consistent way. This feature permits TIOA to provide aggregate metrics by combining separate results for each input and output category presented in Sections 4.1–4.5. Such aggregation is facilitated by the fact that all results obtained for individual resources in Section 4.1–4.5 are expressed in a single consistent thermodynamic unit, while accounting for differences in their thermodynamic quality. In this regard, TIOA can complement existing techniques such as EIOLCA [59,60] that report consumption and emission data in disparate units. It is then left to the user to distill these data into a smaller number of indices that are sufficiently representative and easy to use. In the absence of a theoretically rigorous technique for combining disparate data, arbitrary weighting is often employed. TIOA is useful in this context as it presents the type of details of other methods as well as a systematic way of aggregating resource consumption and emission data.

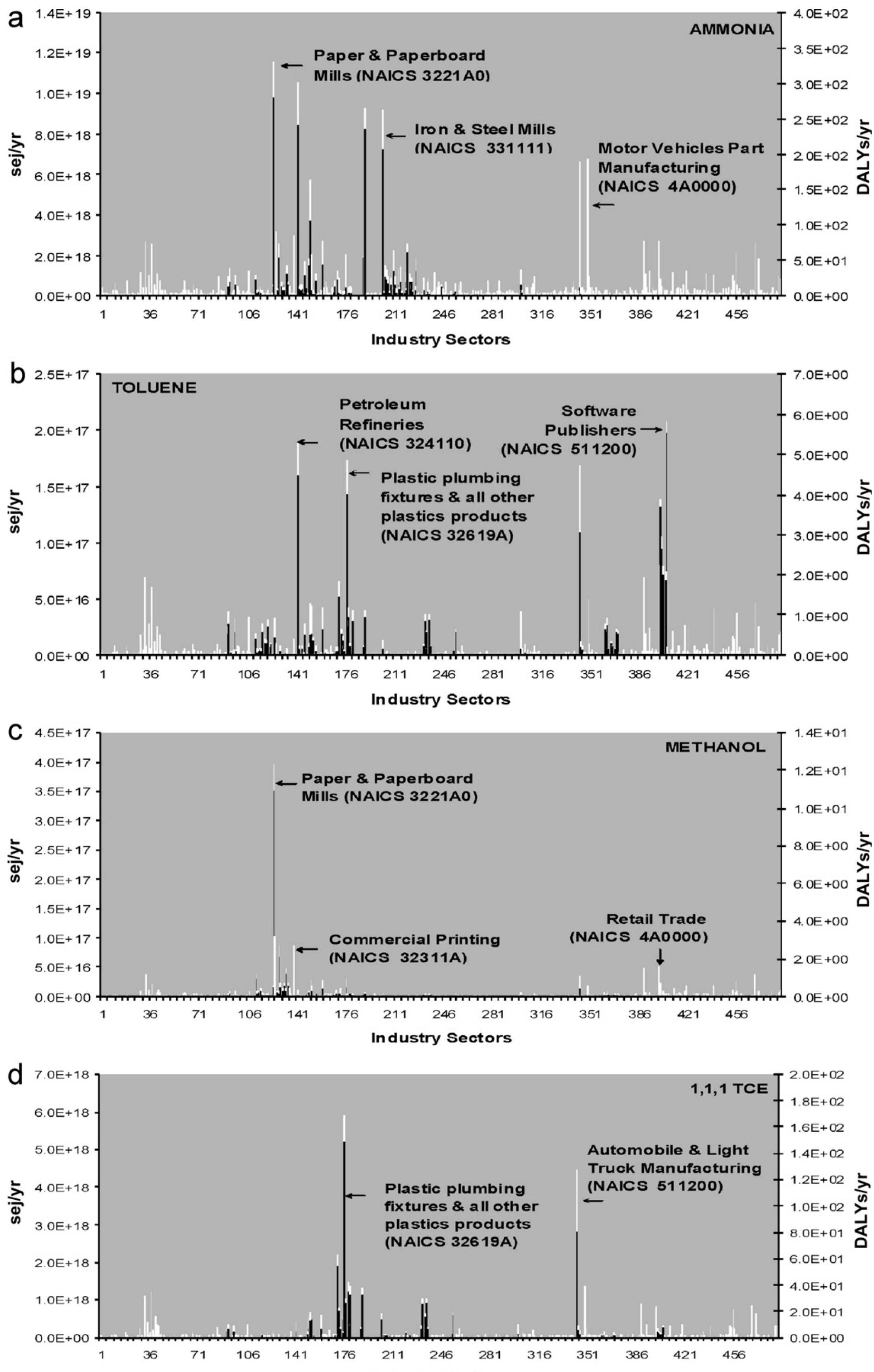

Fig. 11. Impact of non-bulk pollutants. (a) ammonia; (b) toluene; (c) methanol; (d) 1,1,1-trichloroethane (e) styrene emission to air; (f) styrene emission to water; (g) styrene emission to soil ; *y*-axis are annual ECEC flows in sej/yr and corresponding impact in DALYs/yr; *x*-axis is sector serial number (black part of each bar represents direct inputs and white part represents indirect inputs).

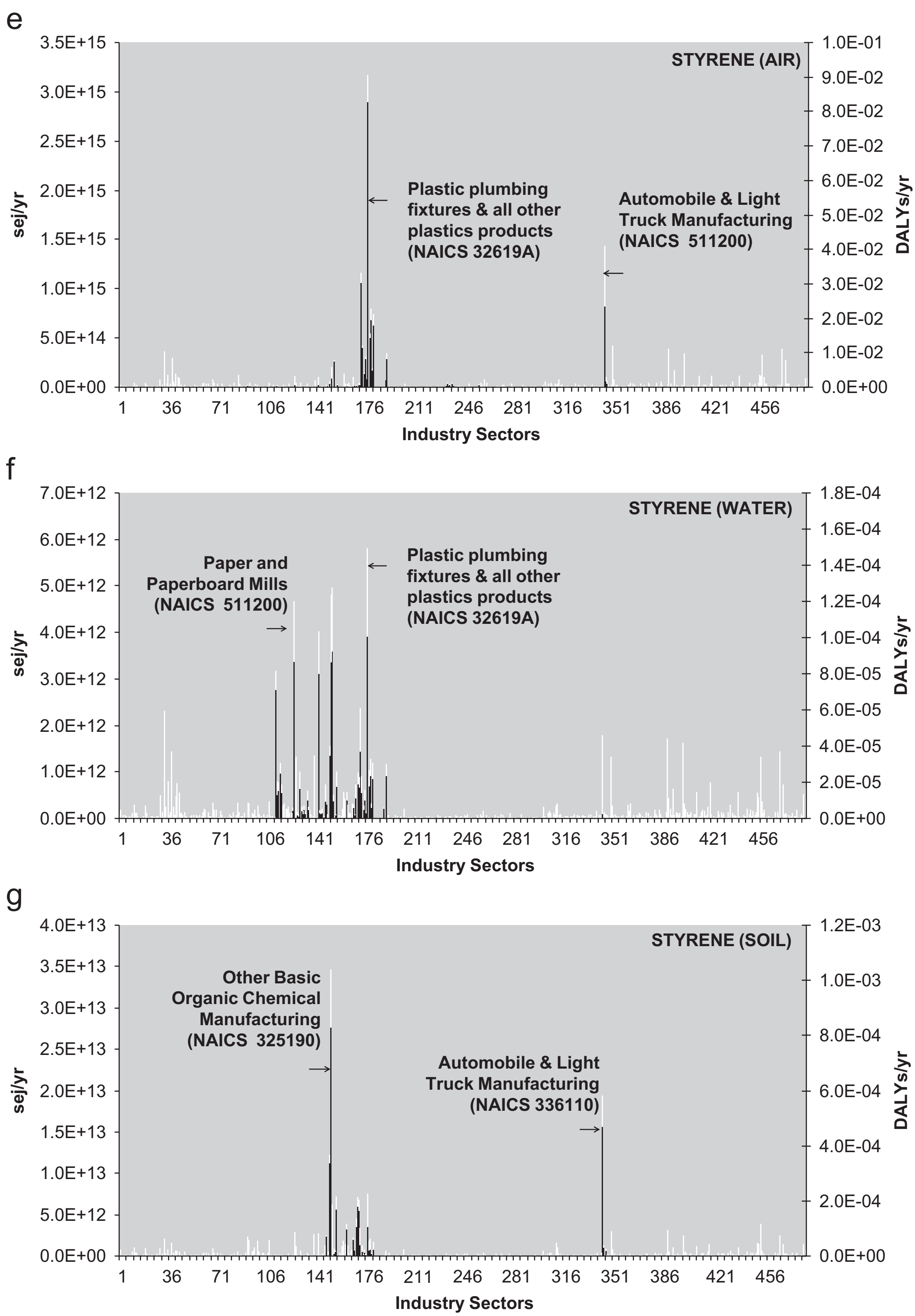

Fig. 11. (*Continued*)

Detailed information is also available and hierarchical metrics with different levels of aggregation may be easily developed [61]. For emerging technologies or at early stages of decision making, information about emissions and their impact may not even be available. Here, LCA based on the inputs to TIOA may provide a reasonable proxy for full LCA studies.

For combining results obtained in Figs. 5 and 7–11, the algorithm of ICEC and ECEC analysis, explained in

Section 2 has been used. This algorithm avoids across-the-board addition which could lead to double counting, particularly in ECEC by the approach described in Section 2.2. To calculate aggregate metrics in this paper, inputs from atmosphere, hydrosphere and ecosystem services are considered to be non-additive whereas the rest are considered to be additive. This is so because in case of non-renewable resources such as minerals and fossil fuels, allocation is possible and is typically done in proportion to their mass fraction in the earth's sedimentary cycle. In case of renewable resources, however, such allocation is more difficult as they are by-products of the same energy input to the earth system. 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 [62]. The application of such techniques to the analysis presented in this paper is a part of the on-going work. As mentioned in Section 3.4, labor is considered to be an exogenous input in TIOA, which is similar to EEA [10]. However, since the inputs to human consumption are outputs of the economy, this may not be a fair assumption, and it may be better to treat labor as a non-additive input [31].

5.1. Total ECEC and ICEC

Total ECEC of each industry sector is shown in Fig. 12(a–d), which is a semi-log plot that shows relative contributions of renewable resources, non-renewable resource, human resources and human health impact of emissions to the total ECEC of each sector. The sector of stone mining and quarrying (NAICS 212310) is found to have the highest ECEC. Other sectors with high ECEC values are coal mining (NAICS 212100), power generation and supply (NAICS 221100) and sand, gravel, clay and refractory mining (NAICS 212320). Sectors with the smallest ECEC are industrial pattern manufacturing (NAICS 332997), malt manufacturing (NAICS 311213) and tortilla manufacturing (NAICS 311830). Sectors with the smallest ECEC requirements are also among the sectors with the smallest economic activity.

Total ECEC requirement captures the cumulative exergy consumption in all the links of the production network, and in principle, is equivalent to the concept of ecological cost. Unlike ecological cost that focuses only on industrial stages of the production network and non-renewable resources, total ECEC considers renewable resources along with non-renewable resources, and exergy consumed in the ecological links along with the industrial links of a production network. Fig. 12(a) can be useful in determining industry-specific pro-ecological tax as proposed by Szargut and others [63]. ECEC by itself is of limited use for decision making. A normalized metric that compares ecosystem contribution to economic activity is more insightful, and is discussed in Section 5.2.

Fig. 13(a–c) shows ICEC inputs to individual industry sectors from renewable and non-renewable resources and their total. Agriculture and forestry sectors (NAICS 1111A0-113A00) and sectors relying on them for raw materials, such as the sector of sawmills (NAICS 321113), have some of the highest peaks in Fig. 13(c). High ICEC requirement of agricultural and forestry sectors can be explained on account of inputs of sunlight. Furthermore the sectors involved in extraction and processing of non-renewable resources such as coal mining, oil and gas extraction and petroleum refining do not appear prominently in Fig. 13(c). ICEC analysis considers a transformity of 1 sej/J for all the resources and ignores the substantial amount of exergy that needs to be expended by ecological processes to make fossil fuels and other resources available to the economic system. Consequently, ICEC analysis tends to downplay the contribution from non-renewable resources. The negative bars in Fig. 13(b) are due to the return of detrital matter to the lithosphere in agricultural sectors (NAICS 1111A0-1119B0), as explained in Section 4.1. Other sectors that rely on agricultural inputs (NAICS 311111-311310) also have negative ICEC requirements due to indirect effects.

5.2. Ratios of ECEC/money and ICEC/money

Fig. 14(a) shows the ECEC/money ratio of each of the 488 industry sectors on a semi-log plot. It is calculated by dividing total ECEC throughput of each sector shown in Fig. 12 by its total economic throughput. The ECEC/money ratio is analogous to the emergy/money ratio used in emergy analysis, and similar ratios suggested in exergy analysis [35,63]. However, unlike the single ratio in emergy or exergy analysis for the entire economy, Fig. 14 provides a separate ratio for each sector. Variation in Fig. 14(a) captures the difference between different industry sectors. Fig. 14(a) shows that ECEC/money ratios can vary over 3 orders of magnitude with the highest ratio being 2287 times the lowest ratio. Such difference is completely ignored in emergy analysis and thermoeconomics that use a single economy-wide average.

The ECEC/money ratio is not meant to support or debunk any theory of value, but may indicate the magnitude of discrepancy between thermodynamic work needed to produce a product or service and people's willingness 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 ratios 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 thermodynamic efficiency (CDP) or transformity values of industry sectors is more difficult due to lack of information about exergetic outputs of industry sectors. The ECEC/money ratio is a

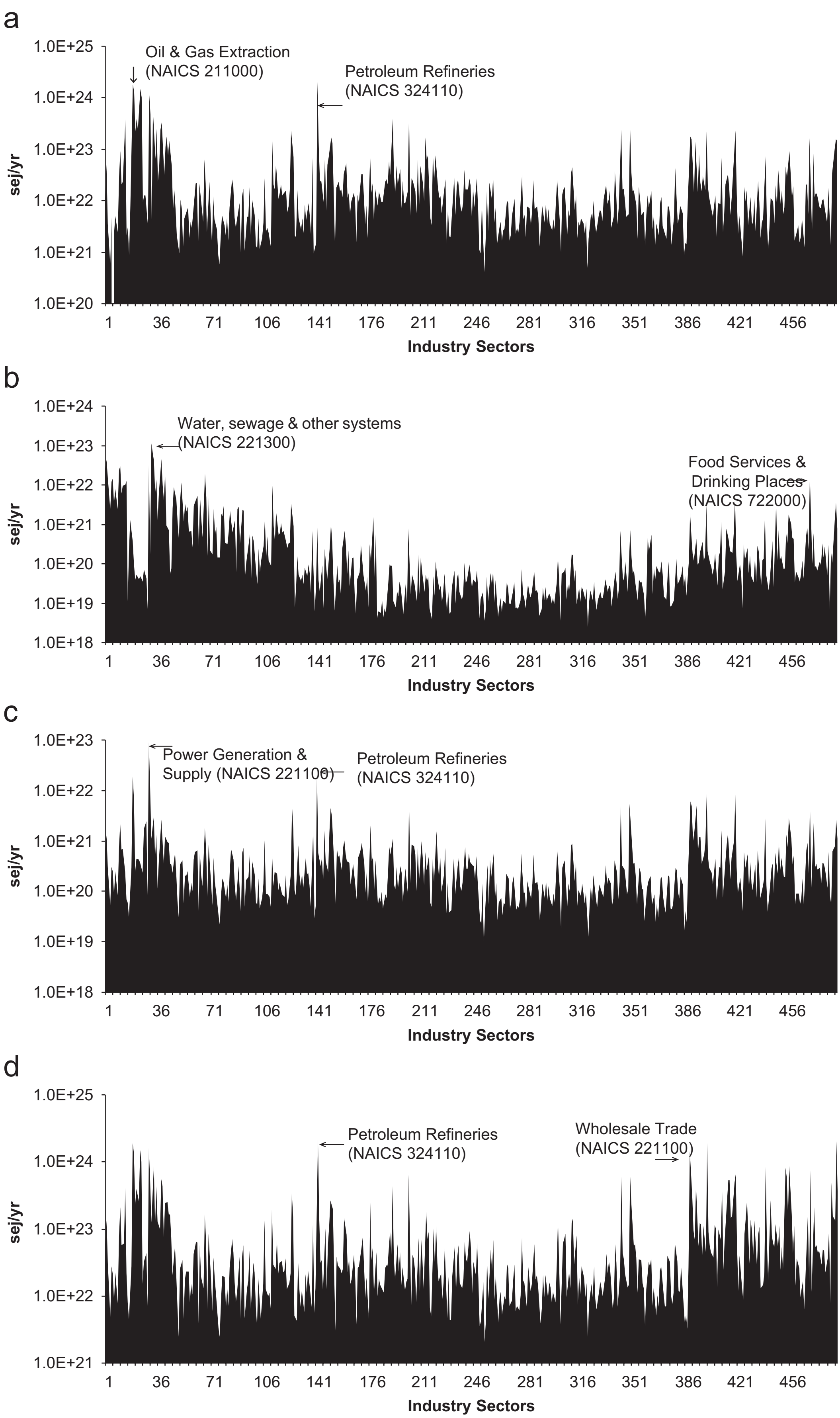

Fig. 12. ECEC requirements of industry sectors (a) non-renewable resources; (b) renewable resources; (c) human health impact of emissions; (d) total; y-axis are annual ECEC flows in sej/yr; x-axis is sector serial number.

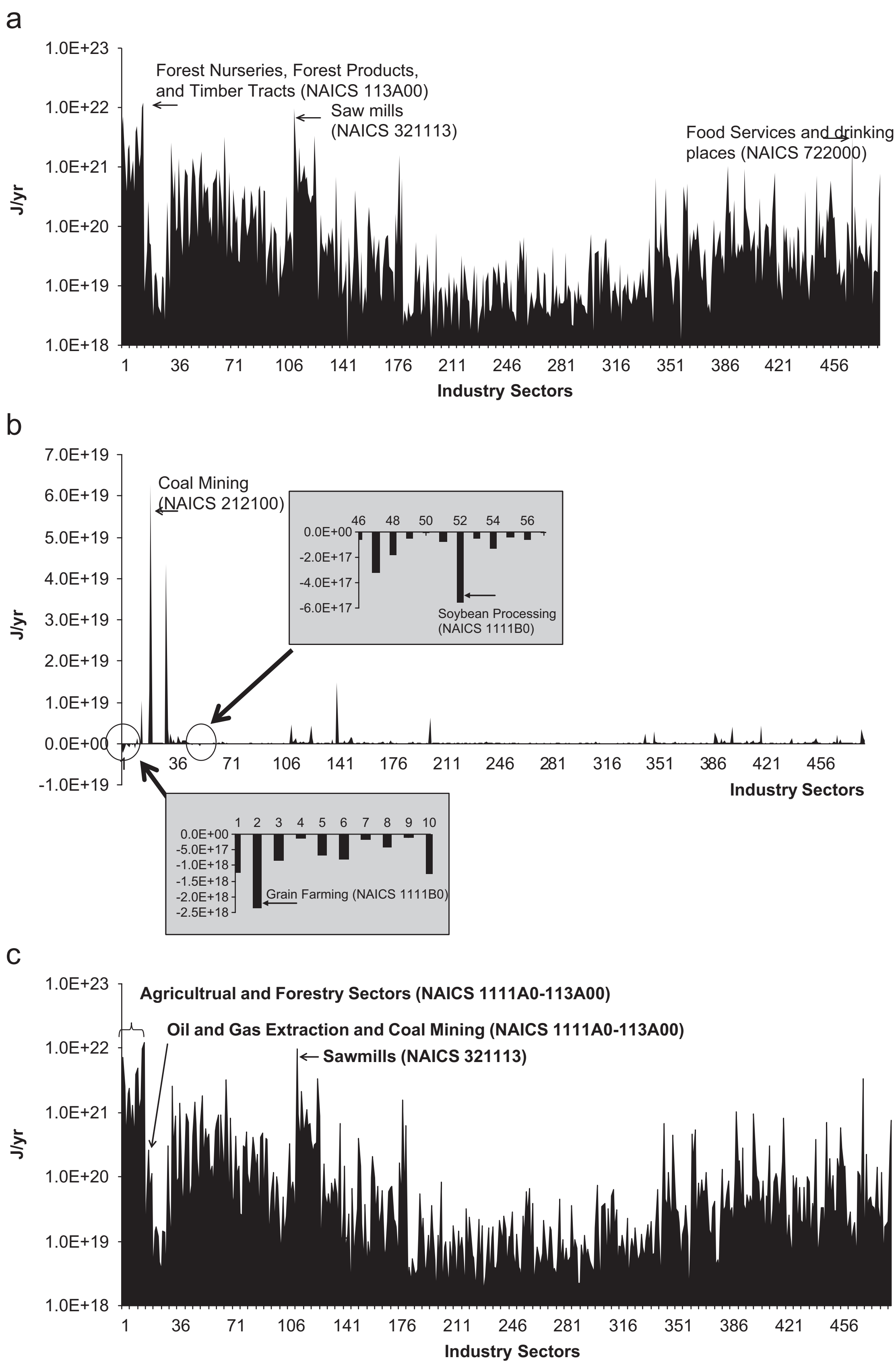

Fig. 13. ICEC requirements of industry sectors (a) renewable resources; (b) non-renewable resources; (c) total; *y*-axis are annual ICEC flows in J/yr; *x*-axis is sector serial number.

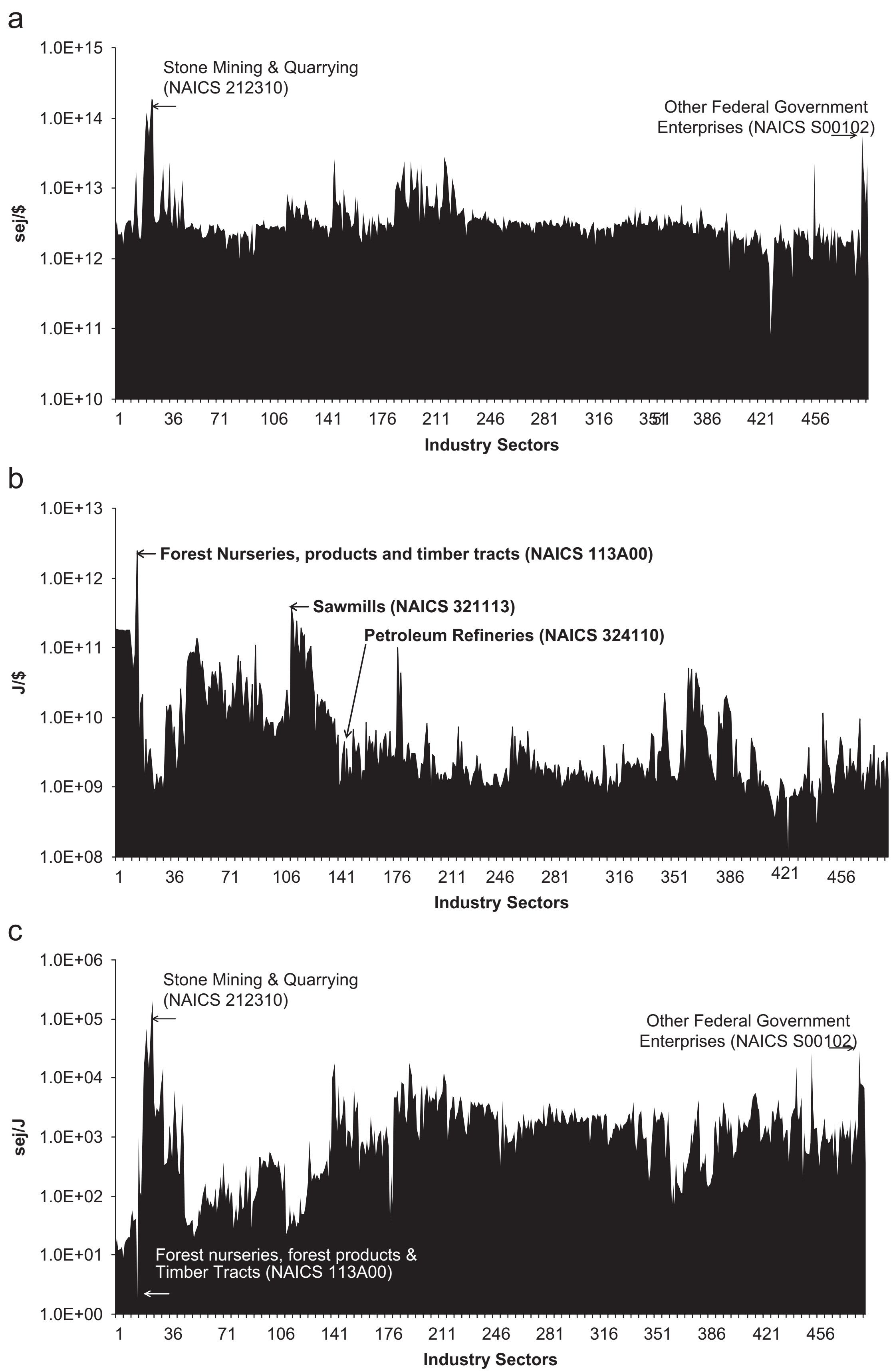

Fig. 14. (a) ECEC/money ratios; (b) ICEC/money ratios; (c) ECEC/ICEC ratios.

measure of cumulative exergy consumption in the production chain of an industry sector to generate $1 of economic activity.

As seen from Fig. 14(a), the mining sectors have the highest ECEC/money ratios. Sectors of stone mining and quarrying (NAICS 212310), sand, gravel, clay and refractory mining (NAICS 212320) and iron ore mining (NAICS 212210) have some of the highest ECEC/money ratios. Sectors with the smallest ECEC/money ratios are service sectors such as lessors of non-financial intangible assets (NAICS 533000), owner-occupied dwellings (NAICS S00800) and all other miscellaneous professional and technical services (NAICS 5419A0). Sectors such as primary smelting and refining of copper (NAICS 331411) that rely on mining sectors also have high ECEC/money ratios. In general, more specialized sectors have lower ECEC/money ratios than the basic infrastructure sectors. For instance, the median ECEC/money ratio of finance, insurance, real estate, rental and leasing sectors (NAICS 522A00-533000) is approximately 1/10th of that of mining and utilities (NAICS 211000-221300) sectors. Amongst sectors receiving direct inputs from ecosystems, agriculture, forestry, fishing and hunting sectors (NAICS 1111A0-115000) have a median ECEC/money ratio that is 14% of that of the mining and utilities (NAICS 211000-221300) sectors. Agriculture, forestry, fishing and hunting sectors also depend more on renewable resources than the mining and utilities sectors that are primarily fossil-based.

The variation in ECEC/money ratio indicates the discord between ecological activity and corresponding economic valuation. This may be because market prices do not fully reflect the cumulative exergy consumption of corresponding sectors and 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 societal preferences with limited consumer awareness about ecosystem contribution towards 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 [36,64].

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 non-renewable resources have higher ECEC/money ratios. This suggests that sectors with high ECEC/money ratios consume natural capital in a manner that is disproportionate to their contribution to economic capital. The resultant hierarchical structure of the economy resembles an ecological food chain wherein basic infrastructure industries constitute the base and are equivalent to photosynthetic tissue, whereas value-added service industry constitutes the top, and is equivalent to carnivores. These observations match other work on the relationship between environmental impact and economic value along supply chains of industrial processes [65]. These observations also provide a unique insight into sustainability of industrial supply chains from the standpoints of weak- and strong-sustainability paradigms, and other macro-economic phenomena including outsourcing, sustainable international trade and corporate restructuring [38].

Fig. 14(b) shows the ICEC/money ratios of individual industry sectors. Agriculture and forestry sectors (NAICS 1111A0-113A00), in general, have high ICEC/money ratios. Sectors with direct inputs of sunlight such as forest nurseries, forest products, and timber tracts (NAICS 113A00), logging (NAICS 113300), and sectors that rely on forest products such as sawmills (NAICS 321113) and veneer and plywood manufacturing (NAICS 32121A) have some of the highest ICEC/money ratios. These sectors rely mainly on renewable resources and are near the periphery of the economy due to relatively short supply chains. In contrast, sectors with high ECEC/money ratios rely mainly on nonrenewable resources, and also have short supply chains. Service industries including employment services (NAICS 561300), insurance (NAICS 524100 and 524200) and monetary authorities (NAICS 52A000) have some of the lowest ICEC/money ratios. This observation matches with Fig. 14(a) and can be explained based on higher economic capital generation vis-à-vis natural capital consumption of service industries. However, unlike results from Fig. 14(a), sectors involved in extraction and processing of non-renewable resources such as oil and gas extraction (NAICS 211000), ground or treated minerals and earths manufacturing (NAICS 327992) and natural gas distribution (NAICS 221200) also have low ICEC/money ratios. This again can be explained considering the ignorance of ecological processes in ICEC analysis and assumption of no exergy consumption in ecosystems.

Over the last few decades many researchers have suggested a relationship between thermodynamic measures and money [30,31], but none has been found as yet. Recently, it has been conjectured that "if all the indirect exergy flows are taken into account, the discrepancy between diamonds and Persian carpets, on one hand, and coal on the other hand, might not be so great" [31]. This conjecture implies that cumulative exergy and money may be strongly correlated. The plots in Figs. 14(a) and (b) indicate that the correlation between ECEC and money is higher than that between ICEC and money. However, the smaller variation of the ECEC/money ratio still does not validate the conjecture, and sorting the sectors based on this ratio has some interesting interpretations [38]. Further analysis may lead to greater insight, but is outside the scope of this paper.

The two CEC to money ratios can be 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 [66].

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 such ratios for 91-sector 1992 US economy to account for ecosystem contribution to industrial activity and the additional insight they can provide in comparison with existing thermoeconomic techniques such as exergy and industrial cumulative exergy consumption analyses has been illustrated in Ukidwe and Bakshi [7] for two electricity generation systems. Other uses of these ratios are available in Ukidwe [39].

5.3. ECEC/ICEC ratio

ECEC is the cumulative exergy consumption in the industrial as well as ecological stages of a production chain, whereas ICEC only focuses on the industrial stages. Consequently, ECEC/ICEC ratio indicates the extent to which ICEC analysis underestimates the contribution of ecological resources. Fig. 14(c) depicts ECEC/ICEC ratios for industry sectors from the 1997 benchmark model of the US economy. As seen from this figure, forest nurseries, forest products and timber tracts (NAICS 113A00) have the lowest, whereas sand, gravel, clay and refractory mining (NAICS 212320) have the highest ECEC/ICEC ratio amongst all sectors. In general, agricultural and forestry sectors have lower ECEC/ICEC ratios due to their reliance on renewable resources such as sunlight, which have smaller transformity. Mining and extraction sectors, on the contrary have higher ratios due to their reliance on non-renewable resources. These results conform to those obtained for the 1992 US economy [7]. Furthermore, the average ECEC/ICEC ratio for the 1997 US economy is 2873 sej/J as against a ratio of 1860 sej/J for the 1992 US economy. This plausibly indicates that the 1997 economy had a higher reliance on non-renewable resources than the 1992 US economy. The fact that ECEC is 2 to 4 orders of magnitude higher than ICEC and variation in ECEC/ICEC ratios across industry sectors indicates that TIOA is successful in capturing quality differences between natural resources such as their renewable and non-renewable nature whereas methods like ICEC analysis and thermoeconomics cannot. Therefore TIOA would be more meaningful for generating objectives for ecologically conscious decision making than the contemporary techniques such as ICEC analysis, Extended Exergy Accounting and thermoeconomics. Illustrations and case studies to back this claim are the subject of future publications.

5.4. Performance metrics

Based on the aggregate metrics obtained in Fig. 12(a–d), various performance metrics can also be calculated. The metrics defined and calculated in this paper are meant to mainly illustrate the ability of ICEC and ECEC to combine various types of input and output streams. More research is required on the characteristics of different metrics and their appropriateness for environmentally conscious decision making.

As described in Section 2.3, the metrics in this section have been defined along the lines of those used in emergy analysis [11,46]. However, there are some marked differences due the ability of TIOA to provide more comprehensive results. Yield ratio is defined as the ratio of total inputs to purchased inputs or, alternatively, the ratio of total ECEC requirements to indirect ECEC requirements. It measures the extent to which a process or product relies on economic inputs vis-à-vis direct environmental inputs. Fig. 15(a) shows the yield ratio for the 488 industry sectors. A peripheral sector that derives a large portion of its ECEC requirements directly from ecosystems or a sector that relies more on human resources has a higher yield ratio. This is evident from Fig. 15(a) which shows high peaks for non-metallic mineral mining sectors (NAICS 212310 and 212320) and water sewage and other systems sector (NAICS 221300). Other federal government enterprises (NAICS S00102) and home health care services (NAICS 621600) also have prominent peaks due to their large and direct reliance on human resources. Sectors with lowest yield ratios include veterinary services (NAICS 541940), automotive repair and maintenance, except car washes (NAICS 8111A0) and religious organizations (NAICS 813100). These are service industries that are embedded in the economic network and have relatively lower direct reliance on ecological or human resources.

Loading ratio is defined as ratio of inputs from non-renewable resources to those from renewable resources. Fig. 15(b) shows environmental loading ratio for the 488 industry sectors. As seen from Fig. 15(b), sectors of stone mining and quarrying (NAICS 212310), asphalt paving mixture and block manufacturing (NAICS 324121) and cut stone and stone product manufacturing (NAICS 327991) have some of the tallest peaks. These are the sectors that are involved either in mining of non-metallic minerals or in their downstream processing. Sectors with the lowest environmental loading ratios are water, sewage and other systems (NAICS 221300), forest nurseries, forest products and timber tracts (NAICS 113A00), vegetable and melon farming (NAICS 111200), tree nut farming (NAICS 111335) and oilseed farming (NAICS 1111A0). These sectors along with other agricultural sectors have environmental loading ratios of less than unity indicating that they rely on renewable resources more than nonrenewable resources. All other sectors in the economy have environmental loading ratios of higher than unity due to heavy reliance on metallic and non-metallic minerals and fossil energy sources.

Fig. 15(c) shows the yield-to-loading (YLR) ratios for the 488 sectors. YLR is called the index of sustainability in emergy analysis, though it only represents the resource

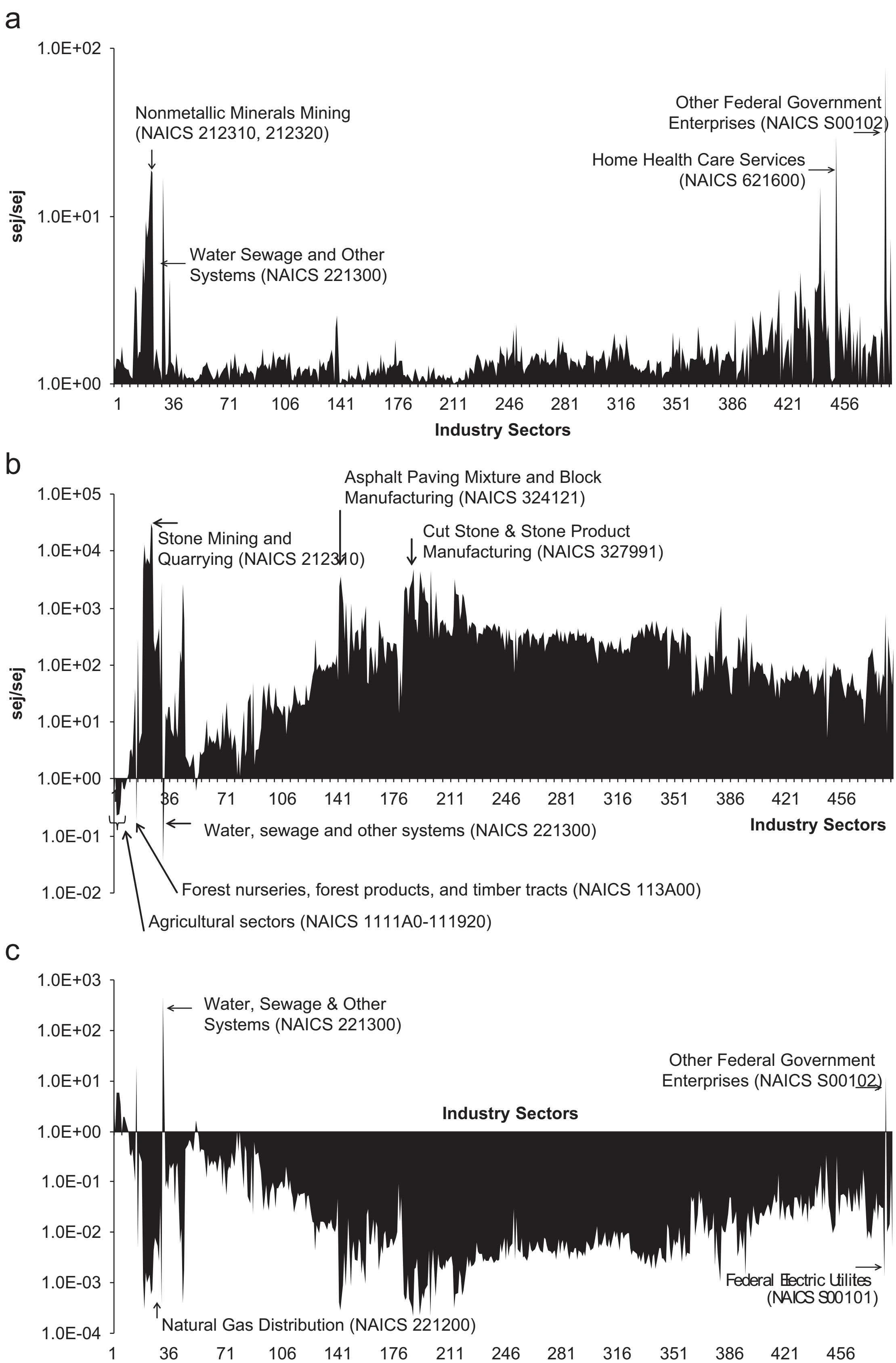

Fig. 15. Performance metrics of industry sectors (a) yield ratio; (b) environmental loading ratio; and (c) yield-to-loading ratio.

consumption side of the sustainability riddle. YLR is less than unity for all sectors of the economy except the agricultural sectors (NAICS 1111A0–1119A0), forest nurseries, forest products and timber tracts (NAICS 113A00), water sewage and other systems (NAICS 221300), soybean processing (NAICS 311222), other oilseed processing (NAICS 311223) and other federal government enterprises. Sectors with the lowest YLR are clay refractory and other structural clay products (NAICS 32712A), ready-mix concrete manufacturing (NAICS 327320) and cut stone and stone product manufacturing (NAICS 327991). Thus sectors relying on nonmetallic minerals, in general, have some the lowest YLR values.

6. Discussion

This paper has focused mainly on the development of the TIOA model and calculation of various ratios based on ICEC and ECEC. It does not aim to connect thermodynamics with economic value. Application of TIOA to the 1997 US economic model yields unique insight into the behavior of the economy. However, a natural question at this point is about the usefulness of this model, and particularly whether accounting for ecosystem goods and services, as in ECEC has any benefits over ICEC. This section attempts to answer this question by discussing some of the applications of TIOA in greater detail.

- This paper presents total ECEC requirements of industry sectors from non-renewable and renewable ecological resources, human resources and human health impact of emissions. Total ICEC and ECEC requirements define the thermodynamic basis of operations of various industry sectors, and are similar to the concept of ecological cost [1] and thermo-ecological cost [75]. Thermo-ecological cost is theoretically defined as the total consumption of non-renewable exergy appearing in all the links of the domestic technological network due to the fabrication of the considered final product, but practically focuses only on selected links of the production chain. As a result it is prone to narrow system scope and large truncation errors. Total ICEC requirement addresses this shortcoming by considering the entire economic network. Furthermore total ECEC requirement strengthens thermo-ecological cost by considering exergy losses in the ecological links of the production network.
- The analysis also presents industry-specific ECEC and ICEC to money ratios. These ratios describe the discord between thermodynamic work required for an economic sector and willingness of people to pay for it. The ratios presented in this paper could prove useful in better internalization of ecological resources into economic policies and in formulating pro-ecological taxes. The significance of pro-ecological tax has been discussed quite extensively by various authors [63,76] and use of ICEC has been suggested as a guideline in this regard. The results presented in this paper may be directly used to determine such taxes at the level of industry sectors. Furthermore, ECEC analysis would allow us to consider exergy consumption in the ecological network and may provide a more meaningful eco-centric guideline for pro-ecological taxes.
- ECEC/money ratios are fundamentally identical to emergy/$ ratios used in systems ecology. However, unlike a single emergy/$ ratio for the entire economy that is commonly used, this analysis determines a separate ratio for each industry sector. Consequently, ECEC/money ratios are not only readily applicable wherever emergy/$ are used in emergy analysis, but also provide a more accurate and disaggregate alternative to the latter. Such ratios are also expected to be useful for other approaches that wish to consider the contribution of inputs such as labor and capital in exergetic terms such as Sciubba's extended exergy accounting.
- Even though this paper is not exploring or proposing any relationship between exergy and money, such a relationship has been suggested by many researchers over the last few decades. The relevance of this work to such conjectures is discussed in Section 5.2. Rigorous statistical analysis may lead to important insight.
- Significance of techniques such as emergy analysis and extended exergy accounting has been covered extensively in literature. These techniques allow joint analysis of economic and environmental objectives of industrial systems. Methods such as Optimum LCA Performance (OLCAP) [78] and Material Intensity Per Service unit (MIPS) [79] are based on multi-criteria analysis of economic and environmental objectives. Economic factors have also been combined with exergy analysis via thermoeconomics and multiobjective optimization [80,81]. These methods use environmental objectives that suffer from the same shortcomings listed in the introductory paragraphs of this paper, that is narrow system boundary, large truncation errors, ignorance of ecological processes and non-compliance with basis biophysical principles amongst others. Use of ICEC/money and ECEC/money ratios would allow us to define these objectives more accurately, representatively and rigorously. Analysis and results presented in this paper can be used in constructing improved environmental objectives that would ultimately lead to more accurate and environmentally conscious decisions [77].
- ECEC/money ratios also provide a unique insight into natural and economic capital flows in industrial supply networks [38]. Such insight permits greater appreciation and conservation of vital ecological goods and services. These results have been studied from the standpoints of weak and strong sustainability paradigms, and their implications to corporate restructuring, green supply chain management and sustainable international trade have been discussed by Ukidwe and Bakshi [38]. TIOA can also be modified to perform net energy and material flow analyses by considering only fuel sources for the

former and material sources for the latter analysis. Research is also underway to strengthen the results by incorporating additional ecological resources and impact categories.

- ICEC/money and ECEC/money ratios can be useful for performing thermodynamic LCA at the economy and ecosystem scales, and hybrid LCA that combines the economy scale data with more detailed information at finer scales. It can also enable the application of different methods based on energy, exergy, emergy and cost, which can provide valuable information for life cycle improvement [67]. Such thermodynamic LCA can provide an approximate idea about the impact of emissions based on material and energy inputs, without requiring detailed knowledge about process emissions and their toxicological aspects, and can be especially useful in evaluating emerging technologies [82]. ICEC/money and ECEC/money ratios can also be used in constructing hierarchical thermodynamic metrics of sustainability as demonstrated by Yi et al. [61] that are easy-to-calculate, robust, stackable, communicable to diverse audiences and protective of proprietary information.

7. Conclusions and future work

This paper develops a Thermodynamic Input–output model to quantify the direct and indirect, industrial and ECEC of the 488-sector 1997 US economy. The underlying economic input–output benchmark model is the most recent representation of the US economy at that level of detail. Hence the results obtained in this paper are more accurate and current than those presented by Ukidwe and Bakshi [7] for 91-sector 1992 representation of US economy. This paper presents data about inputs of ecosystem products and services to industry sectors defined according to their North American Industrial Classification System (NAICS) codes. Data about selected bulk- and non-bulk pollutants and their impact on human health are also presented. Calculations for determining Industrial and ECECs associated with these flows are presented in detail along with the underlying assumptions at appropriate places in this analysis.

TIOA synthesizes concepts from systems ecology, engineering thermodynamics, and economic input–output analysis to evaluate direct and indirect reliance of industry sectors on ecological resources and impact of emissions from them. It treats the economic-ecological system as a network of energy flows with exergy as the common currency. Though TIOA uses knowledge from systems ecology, it is free of the controversial aspects of emergy analysis such as maximum empower principle, emergy theory of value and reliance on prehistoric energy. It also only considers the direct ecological inputs, thus avoiding the use of derived transformity values for human-made products. Thus, the model and data presented in this paper can provide the foundation for many applications and encourage the development of sustainable engineering. As discussed in Section 6, TIOA can help in calculating industry-specific ecological costs and pro-ecological taxes allowing development of environmentally conscious macroeconomic policies. TIOA can also help in juxtaposition of economic and natural capital flows in industrial supply networks shedding valuable insight into green supply chain management, and sustainable international trade. At the micro-scale, industry specific ICEC/money and ECEC/money ratios can be used in constructing hierarchical thermodynamic metrics of sustainability and also in conducting thermodynamic LCA to evaluate existing and emerging technologies. ICEC/money and ECEC/money ratios can be readily used to replace similar but aggregate metrics that are currently being used in emergy analysis and thermoeconomics as well.

There are many avenues to continue this work. Information about additional ecosystem products and services and emissions can be easily incorporated in TIOA to make it more comprehensive. Challenges pertaining to data and model uncertainty and different allocation approaches remain. Transformity values of oxygen to include combustion related activities, transformities of wind and water streams that address turbulent mixing and diffusion and not just shaft work to include ecosystem services required for pollution dissipation, transformities of human labor that not only consider material and energy inputs from the economy but also value addition via intellectual capital and average transformities to evaluate impact of emissions on ecosystem health are some of the areas where inputs from systems ecology would be very helpful. Finally, implementation of this approach and data in user-friendly software is essential for wider dissemination.

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