

Thermodynamic Input-Output Analysis of Natural and Economic Capital – Implications for LCA and Supply Chain Management

Nandan U. Ukidwe and Bhavik R. Bakshi

Department of Chemical and Biomolecular Engineering, The Ohio State University, Columbus, OH 43210

1 Introduction

Ecological products and services are indispensable for any industrial, economic or social activity on earth. Examples of ecological products include coal, timber, water and atmospheric oxygen, while ecosystem services include rain, pollination, carbon sequestration and pollution abatement^[1,2,3]. Despite their obvious importance, traditional methods in engineering, economics and other disciplines have tended to ignore the role of ecosystems by considering them to be an “infinite sink” or “free”. As a result, business and policy decisions are usually made with a flawed accounting system that ignores the basic life support system for all activity. The focus of such an approach tends to be on short-term gain, while longer-term sustainability issues get ignored. Such ecologically unconscious decision-making is continuing to cause significant and alarming deterioration of global ecosystem products and services^[4,5].

The importance of accounting for the contribution of ecosystems to economic activity is being slowly recognized in both, academia and industry^[6]. Approaches such as Total Cost Assessment^[7] and Life Cycle Assessment (LCA) are being standardized and adopted by many corporations to obtain more holistic and complete information about the impact of their products and processes on the environment. However, these approaches focus mostly on the emissions from industrial processes and their impact and on consumption of nonrenewable resources. They do not account for the contribution of ecosystems to industrial activity. A variety of techniques have attempted to quantify the contribution of ecosystems to economic activity. All techniques face common challenges of combining information represented in a diverse set of units, uncertain knowledge and lack of adequate data about ecosystems. These techniques may be broadly categorized as preference-based and biophysical methods. *Preference* based methods assign a monetary

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- 1 Costanza, R.; d’Agre, R.; de Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; O’Neil, R. V.; Raruelo, J.; Raskin, R. G.; Sutton, P.; van der Belt, M. *The value of the world’s ecosystem services and natural capital*; Nature 1997, 387, 253
 - 2 Odum, H.T.; *Environmental Accounting: Emergy and Environmental Decision Making*; John Wiley & Sons: New York, NY, 1996
 - 3 Tilman, D.; Cassman, K.G.; Matson, P.A.; Naylor, R.; Polasky, S. *Agricultural sustainability and intensive production practices*; Nature 2002, 418, 671
 - 4 WRI. World Resource Institute. *World Resource 2000-2001: People and Ecosystems: The Fraying Web of Life*; WRI: Washington D.C., 2000; available at <http://www.wri.org/wr2000> (accessed May 2004)
 - 5 WWF. *Living planet Report 2000*; available at <http://panda.org/livingplanet/lpr00/> (accessed May 2004)
 - 6 Holliday, C.O. Jr.; Schmidheiny, S.; Watts, P. *Walking the Talk: A Business Case for Sustainable Development*; Berrett-Koehler Publishers Inc.: San Francisco, CA, 2002
 - 7 AIChE-Center for Waste Reduction Technologies. *Total Cost Assessment Methodology*; available at <http://www.aiche.org/cwrt/projects/cost.htm> (accessed Dec 2002)

value to ecosystem products and services by relying on human valuation. A significant advantage of these methods is that using a single unit permits ready comparison across economic and ecological contributions. However, valuation methods are often controversial and rely on knowledge about the role of each ecological product and service. Such information, along with satisfaction of scientific laws may be provided by biophysical methods. *Biophysical* methods rely on biological and physical principles to account for the role of ecosystems and can be summarized as follows;

- *Mass* based methods have been popular to determine the physical basis of economic activity and its interaction with ecosystems ^[8,9,10]. Most of these studies are at the level of the entire economy, and disaggregation to more detailed levels is being developed. Since mass does not capture many other properties of materials, such as their energetic contribution and impact, these Material Flow Analysis (MFA) studies are of limited use by themselves. However, they can provide a good database for developing other more comprehensive methods. Furthermore, existing methods are quite limited in their incorporation of ecosystem services, which cannot be readily captured in terms of mass flow.
- *Energy* based methods such as net energy analysis and full fuel cycle analysis determine the flow of energy through various sectors of the economy ^[11,12]. They consider energy content of industrial inputs and outputs including exchanges between economic sectors and those from ecosystems to the economy. The framework of input-output analysis is used for mathematically sound analysis of energy flow in ecological and economic systems ^[13]. Like mass, energy also does not capture many aspects such as contribution of non-energetic materials, environmental impact of emissions and ignores the second law of thermodynamics.
- *Exergy* based methods satisfy the first and the second law and can capture an array of material and energy streams. They have been popular for assessing thermodynamic efficiency of industrial processes ^[14] and to analyze the behavior of ecosystems ^[15]. Exergy is the energy available to do useful work. It can capture various quality aspects of streams as indicated by their mass, energy, concentration, velocity and location. Thus, *exergy can characterize both mass and energy streams, and is the*

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 - 10 NRC. National Research Council. *Materials Count: The Case for Material Flow Analysis*; National Academies Press: Washington D.C., 2004
 - 11 Hannon, B. *The Structure of Ecosystems*; J. Theor. Biol. 1973, 41, 535
 - 12 Costanza, R.; Herendeen, R. *Embodied Energy and Economic Value in the United States Economy - 1963, 1967 and 1972*; Resources & Energy 1984, 6 (2), 129
 - 13 Hannon, B. *Ecological pricing and economic efficiency*; Ecol. Econ. 2001, 36 (1), 19
 - 14 Szargut, J.; Morris, D.R.; Steward, F.R. *Exergy Analysis of Thermal, Chemical and Metallurgical Processes*, 1st ed.; Hemisphere Pubs.: New York, 1988
 - 15 Jorgensen, S.E. *Integration of Ecosystem Theories: a Pattern*; Kluwer Academic Publishers: Boston, MA, 1997

only truly limiting resource on this planet ^[16,17]. Various extensions of exergy analysis such as Industrial Cumulative Exergy Consumption (ICEC) analysis ^[14] and Exergetic LCA ^[18] have been developed in the past to analyze industrial systems. ICEC analysis considers cumulative exergy consumption in the industrial links of a production chain, and has a strong basis in engineering thermodynamics. However, exergy based methods ignore the contribution of ecosystems, and the impact of emissions. *Furthermore, exergy analysis at the level of economic sectors is not yet available.* Other studies that account for the contribution of ecosystems are at the scale of the entire national or global economy, and rely on economic valuation ^[1] or material flow analysis ^[4]. Studies at the level of economic sectors are available in energy analysis ^[19], but these are not as comprehensive as the study presented in this paper, and may violate the second law. Exergy analysis has also been used to analyze societies ^[20,21], but the focus is mainly on comparing exergetic efficiencies of economic sectors, and neither the impact of emissions nor contribution of ecosystems are included.

- *Emergy* based methods developed by systems ecologists have also been used to analyze ecological and economic systems. Emergy is the available energy used directly or indirectly to make any product or service, and is measured in solar equivalent joules (sej) ^[2]. The key strength of emergy analysis is that it *does* account for the contribution of ecological products and processes. However, emergy analysis is often misunderstood, faces quantitative and algebraic challenges, and its broad claims about ecological and economic systems are quite controversial ^[22,23]. Besides, emergy analysis has not been done at the economic input-output scale.
- *Ecological Cumulative Exergy Consumption (ECEC)* is an extension of Industrial Cumulative Exergy Consumption to include ecosystems. ECEC provides insight into emergy analysis by exposing its thermodynamic underpinning, and its close relationship with ICEC analysis. Under conditions of identical analysis boundary, allocation method and approach for combining global exergy inputs, emergy is shown to be identical to ECEC, with transformities ^[2] being equivalent to the reciprocal of the cumulative degree of perfection (CDP), a measure of global efficiency in ICEC analysis. Very importantly, ECEC is free from all the controversial aspects of emergy analysis such as the maximum empower principle and the emergy theory of value that have hindered its use. Thus, ECEC combines the scientific rigor of exergy analysis

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- 17 Sciubba, E. *Beyond thermoeconomics? The concept of Extended Exergy Accounting and its application to the analysis and design of thermal systems*; Exergy Int. J. 2001, 1, 68
- 18 Cornelissen, R.L.; Hirs, G.G. *Exergetic Optimization of a Heat Exchanger*; Energy Conver. Mgmt. 1997, 38 (15-17), 1567
- 19 Costanza, R. *Embodied Energy and Economic Valuation*; Science 1980, 210 (4475), 1219
- 20 Ertesvag I.S. *Society exergy analysis: a comparison of different societies*; Energy 2001, 26, 253
- 21 Wall, G.; Sciubba, E.; Naso, V. *Exergy Use in Italian Society*; Energy 1994, 19 (12), 1267
- 22 Brown, M.T.; Herendeen, R.A. *Embodied energy analysis and EMERGY analysis: a comparative view*; Ecol. Econ. 1996, 19 (3), 219
- 23 Hau, J.L.; Bakshi, B.R. *Promise and Problems of emergy Analysis*; Ecol. Modeling, special issue in honor of H. T. Odum, 2004, accepted

with the ability of energy analysis to account for ecological products and services without relying on any of the controversial aspects of energy analysis. Additional details about ECEC can be found in ^[24]. ECEC analysis is at the basis of Thermodynamic Input-Output Analysis discussed in the next section.

The rest of the paper is organized as follows. Section 2 introduces Thermodynamic Input-Output Analysis algorithm and briefly describes the significance of total ECEC requirements, ECEC/money ratios and ECEC/ICEC ratios. Section 3 illustrates the application of Thermodynamic Input-Output Analysis as a tool for environmental decision making by comparing two electricity generation systems. Finally, Section 4 applies TIOA to compare six transportation sectors.

2 Thermodynamic Input-Output Analysis

This paper employs a thermodynamic approach for including contribution of ecological products and services to economic sectors via input-output analysis. A thermodynamic approach provides a common currency or a way to deal with a diverse set of units, as any system, economic or ecological can be considered as a network of energy flows. Similarly thermodynamic methods such as ECEC analysis and energy analysis can deal with partial information about underlying ecological networks. Money can also provide a common currency by using economic valuation methods to capture the contribution of ecosystems ^[1]. If monetary values for the ecosystem products and services required by each economic sector were available, the approach proposed in this article may also be used to determine the monetary contribution of ecosystems at the sectoral level. The proposed thermodynamic approach is not meant to replace, but to complement an economic approach.

Thermodynamic Input-Output Analysis recognizes the network structure of the integrated Economic-Ecological-Social system. The detailed network structure of the economic system is typically well-known, and is being used in the Thermodynamic Input-Output Analysis. Conversely, the network structure of ecological system need not be completely known as the underlying ECEC analysis can deal with partially-known ecological networks using appropriate allocation rules ^[24]. The algorithm for Thermodynamic Input-Output Analysis focuses on the economic system and its interactions with ecosystems and human resources. It consists of following three tasks.

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

Task 2 is to calculate ECEC of ecological inputs using transformity values from systems ecology, and to classify inputs as additive or non-additive to avoid double counting.

24 Hau, J.L.; Bakshi, B.R. *Expanding Exergy Analysis to account for Ecological Products and Services*; Environ. Sci. Technol. 2004, accepted; available on internet at <http://www.che.eng.ohio-state.edu/~bakshi/ecec.pdf>

In general, non-renewable resources are additive, while renewable resources are non-additive^[2].

Task 3 is to *allocate direct ecological and human resource inputs to economic sectors* based on economic input-output analysis and the network algebra of ECEC analysis^[24]. Economic Input-Output Analysis is a static, general equilibrium representation of the economic system and comprises a set of simultaneous, linear, algebraic equations. Dynamic versions of input-output analysis that consider temporal changes in the economic network are also available, and will be explored in future research. Also, use of monetary data for allocation is not a limitation of the approach, but is rather caused by lack of comprehensive material or energy accounts of inter-industry interactions.

Thermodynamic Input-Output Analysis has been applied to study ecosystem contribution to 91-sector 1992^[25] and 491-sector 1997 U.S. economies. Such analyses provide a unique insight into the reliance of economic sectors on ecosystems for obtaining their inputs and for dealing with their outputs. The analysis considers a variety of ecological products, ecosystem services, human resources and impact of emission on human health. It calculates *total ECEC requirements* of industry sectors by aggregating results for individual resources. Such aggregation is facilitated by the fact that results for individual resources are expressed in a single consistent thermodynamic unit of solar equivalent joules (sej). Total ECEC requirement is similar to the concept of *ecological cost*^[26] and is potentially useful in calculating *industry-specific pro-ecological tax* as proposed by Szargut and others^[27].

The analysis also calculates *ECEC/money* ratio to demonstrate the discrepancy between the thermodynamic work required to produce an ecological resource and peoples' willingness to pay for it. Such discrepancy could lead to a suboptimal allocation of ecological resources through the economic system^[28]. *ECEC/money* ratio does not support or debunk any theory of value, but is rather meant to compare ecological and economic throughputs of industry sectors. Moreover, industry-specific *ECEC/money* ratios provide a more accurate alternative to a single *emergy/money* ratio^[2] or *exergy/money* ratio^[17] currently being used in *emergy* and *exergy* analysis. They are particularly useful in hybrid thermodynamic LCA of industrial systems^[29] and in constructing hierarchical thermodynamic metrics of sustainability^[30].

Moreover, the analysis also calculates *ECEC/ICEC* ratio to demonstrate the extent to which existing thermoeconomic analysis underestimates the contribution of ecosystems.

25 Ukidwe, N. U.; Bakshi, B. R. *Thermodynamic Accounting of Ecosystem Contribution to Economic Sectors with Application to 1992 US Economy*. Env. Sci. Tech., 2004, accepted; available on internet at <http://www.che.eng.ohio-state.edu/~bakshi/tio2.pdf>

26 Szargut, J. *Depletion of the unrestorable natural exergy resources as a measure of the ecological cost*; Proceedings of ECOS'99 1999, 42

27 Szargut, J. *Application of exergy for the determination of the pro-ecological tax replacing the actual personal taxes*; Energy 2002, 27 (4), 379

28 Ayres, R.U. *The price-value paradox*; Ecol. Econ. 1998, 25, 17

29 Suh, S.; Lenzen, M.; Treloar, G. J.; Hondo, H.; Horvath, A.; Huppes, G.; Jolliet, O.; Klann, U.; Krewitt, W.; Moriguchi, Y.; Munksgaard, J.; Norris, G. *System Boundary Selection in Life-Cycle Inventories using Hybrid Approaches*; Environ. Sci. Technol. 2004, 38 (3), 657

30 Yi, H.; Hau, J. L.; Ukidwe, N. U., Bakshi, B. R. *Hierarchical Thermodynamic Metrics for Evaluating the Sustainability of Industrial Processes*, submitted to Env. Progress, 2004

This ratio does reflect quality differences between ecological resources including their renewable or non-renewable nature. Economic input-output LCA ^[31] is similar to the proposed approach in its use of the toxic release inventory data to determine the emissions from each sector. However, unlike previous approaches, the work described in this paper also accounts for ecological inputs, and uses end-point methods for impact assessment, with exergy as the common thermodynamic unit. ICEC/money ratios enable consideration of the economic stages of a product's or process' life cycle, whereas, ECEC/money ratio enables consideration of economic *and* ecological stages of a product's and processes' life cycle

Following sections illustrate the application of these ratios in environmental decision making with the help of two case studies. The first case study compares two electricity generation systems, whereas the second compares different transportation modes.

3 Case Study 1: Electricity Generation Systems

The purpose of this case study is to demonstrate how accounting for ecosystem contribution in thermodynamic analysis offers a different perspective than the existing methods such as emergy analysis, exergy analysis and Industrial Cumulative Exergy Consumption (ICEC) analysis. The electricity generation systems considered in this case study have been studied in emergy analysis ^[32] allowing comparison of results obtained in this study with those obtained in the past.

For the purpose of this case study, data were obtained for two electricity generation systems in Italy ^[32]. The first was a geothermal facility at Castelnuovo V.C., Pisa, and the second was a conventional coal-fueled, thermoelectric facility at Vado Ligure, Savona. Data included direct environmental inputs, direct human resource inputs and economic inputs during construction and operation phases. Data were also obtained for process outputs including net electricity production and emissions during operation phase. All inputs were expressed on a yearly basis by dividing total amount of fixed capital equipment, buildings etc. by their estimated useful life of 25 years. For the purpose of this analysis, electricity generation systems in Italy were assumed to be technologically similar to their American counterparts so that results obtained for the US economy could be used. Information about transformity values of direct ecological inputs were obtained from the systems ecology literature, whereas, data about exergy content of ecological and purchased inputs were obtained from Szargut et al ^[14]. Data about prices of purchased inputs were obtained from various government databases. Since details of machineries used during the construction and the operation phases were not available, prices of machineries were assumed to be those of the metals from which they were made. ICEC/\$ ratios were used to perform a traditional ICEC Analysis, whereas, ECEC/\$ ratios were used to account for ecosystem contribution. The ICEC and ECEC flows associated with purchased inputs were calculated by assigning the purchased input to appropriate industry sector, determining the monetary transaction by multiplying purchased quantity by

31 EIOLCA. Economic Input-Output LCA, Green Design Initiative: Carnegie Mellon University; available at <http://www.eiolca.net> (accessed Apr 2004)

32 Ulgiati, S.; Brown, M.T. *Quantifying the environmental support for dilution and abatement of process emissions - The case of electricity production*; Journal of Cleaner Production 2002, 10 (4), 335

market price, and finally multiplying the monetary transaction by ICEC/\$ and ECEC/\$ ratios for the previously chosen industry sector. For the inputs purchased from the Sector of Petroleum Refining and Related Products the ratios were augmented by a factor of 2.1 to account for imports of crude oil, since in 1992, total consumption of refinery products in the U.S. was 2.1 times the domestic production of crude oil. Table 1 shows different metrics for the two alternatives based on exergy analysis, ICEC analysis and ECEC analysis.

As seen from Table 1, accounting for ecosystem contribution gives a different perspective on thermodynamic efficiencies of industrial processes. For instance, according to exergy analysis and ICEC analysis, the thermoelectric alternative is more efficient than the geothermal alternative, but according to ECEC analysis it is the other way around. The primary reason for this is the *ability of ECEC analysis, and the failure of exergy analysis and ICEC analysis, to incorporate exergy expended in ecological processes*. Geothermal Heat being a renewable resource is readily available to industrial activity, whereas coal being a non-renewable resource requires significant contribution from ecosystems. Because of this ability to account for ecosystem products and services, ECEC analysis is a more suitable technique for environmental decision making than the existing thermodynamic techniques such as exergy analysis and ICEC analysis.

Table 1: Comparison of the two electricity generation Systems

	Geothermal	Coal-fueled Thermoelectric
Annual electricity production (J/yr)	3.28×10^{14}	2.44×10^{16}
Total Emergy Cost (sej/yr) (0)	4.83×10^{19}	3.23×10^{21}
Total ECEC requirement (sej/yr)	3.85×10^{19}	3.18×10^{21}
<i>Efficiencies</i>		
Exergetic Efficiency	1.38×10^{-1}	2.20×10^{-1}
Industrial Cumulative Degree of Perfection (ICDP)	1.36×10^{-1}	2.09×10^{-1}
Ecological Cumulative Degree of Perfection (ECDP) (J/sej)	8.52×10^{-6}	7.59×10^{-6}
<i>Metrics</i>		
Yield Ratio (Total ECEC requirement/(ECEC inputs from economy))	11.5	1.1
Loading Ratio (ECEC from Non-renewable resources/ECEC from Renewable Resources)	0.08	52
Yield Ratio/Loading Ratio (YLR)	145.3	0.02
Impact/Value Added (ECEC of human health impact/annual electricity production) (sej/J)	7.53×10^2	1.15×10^4

Table 1 also calculates metrics for comparing the two alternatives. These metrics have been defined along the lines of those used in emergy analysis^[33]. The major difference is in the way resources are categorized. For instance, unlike emergy analysis, the analysis presented in this paper does not have to distinguish between purchased inputs and direct ecological inputs.

Since the TIOA can consider the entire economic network, ecological inputs embodied in purchased inputs can also be quantified. Accordingly, direct ecological inputs in emergy analysis correspond to direct ECEC inputs in TIOA and purchased inputs in emergy analysis correspond to indirect ECEC inputs in TIOA. The higher yield

33 Ulgiati, S.; Brown, M.T.; Bastianoni, S.; Marchettini, N. *Emergy-based indices and ratios to evaluate the sustainable use of resources*; Ecol. Eng. 1995, 5 (4), 519

ratio for geothermal alternative indicates that it derives a larger portion of its ECEC inputs directly from ecosystems. Similarly a higher loading ratio for the thermoelectric alternative indicates that it consumes relatively more non-renewable resources than the geothermal alternative. As a result, the YLR, also called the index of sustainability in emergy analysis ^[33], of the geothermal option is 6919 times that of the thermoelectric alternative. Moreover, human health impact of emissions per unit electricity production is 15 times higher for the thermoelectric alternative. A significant portion of this impact arises from direct SO₂ and NO_x emissions from the thermoelectric alternative.

4. Case Study 2: Transportation Sectors

This section illustrates the application of TIOA to assess ecosystem contribution to the six transportation sectors. These sectors are listed in Table 2 along with their corresponding NAICS codes and economic sizes. These sectors were chosen for further analysis because of the undisputed significance of transportation in LCA/LCMs of numerous products and processes. The main emphasis of this case study is to compare life cycle resource consumption of renewable and non-renewable ecosystem resources, human resources and human health impact of emissions of the six transportation modes, and to study their supply chains. The results are potentially useful in incorporating environmental considerations in passenger and freight movement and in logistics of industrial products and processes. Other criteria such as cost of transportation, accessibility and availability of transportation options, durability of materials transported and safety issues are also important in choosing the appropriate mode of transportation, but have not been considered in this analysis.

Table 2: Transportation Sectors Selected for Detailed Analysis

Sector	NAICS Code	1997 Econ. Activity (\$ mil)	Sector	NAICS Code	1997 Econ. Activity (\$ mil)
Air	481000	119,445	Truck	484000	169,396
Rail	482000	37,967	Transit & ground Pass.	485000	24,625
Water	483000	24,397	Pipeline	486000	27,284

Table 3 shows resource requirements normalized by economic activity for the six transportation sectors. Resource requirements of these sectors have been aggregated into four resource categories, namely renewable, non-renewable, human resources and human health impact of emissions using Thermodynamic Input-Output Analysis discussed in Section 2. Since indirect effects were found to be of significant importance, supply chains of the six transportation sectors were also investigated. This was done by identifying the most prominent inter-industry transaction coefficients from 491-sector 1997 direct requirement matrix. Top five first order suppliers for the six transportation modes are listed in Table 4. Tables 3 and 4 lead to following notable observations;

- None of the transportation sectors has any direct input of renewable or non-renewable resources. This is so because transportation sectors do not extract natural resources themselves, but rather rely on basic infrastructure sectors such as mining and utilities for their material and energy requirements. Atmospheric O₂ required for combusting

fossil fuels could be considered a direct input. However, it has been omitted from this analysis since its transformity value is unresolved in emergy analysis.

Table 3: Direct, Indirect and Total ECEC throughputs of the six transportation sectors normalized by corresponding economic activities listed in Table 2 (ECEC/money ratios)

		Air	Rail	Water	Truck	Tran. & Ground	Pipeline
Non-Renwable (sej/\$)	Direct	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Indirect	5.97E+11	1.03E+12	3.13E+11	4.18E+11	3.15E+11	1.32E+12
	Total	5.97E+11	1.03E+12	3.13E+11	4.18E+11	3.15E+11	1.32E+12
Renewable (sej/\$)	Direct	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Indirect	4.27E+09	4.77E+09	4.83E+09	2.60E+09	3.87E+09	3.80E+09
	Total	4.27E+09	4.77E+09	4.83E+09	2.60E+09	3.87E+09	3.80E+09
Human Health Impact of Em (sej/\$) ‡	Direct	1.74E+10	1.38E+10	4.50E+10	1.35E+10	1.38E+10	4.58E+08
	Indirect	2.24E+10	1.20E+10	1.36E+10	1.67E+10	1.10E+10	4.37E+10
	Total	3.98E+10	2.58E+10	5.86E+10	3.02E+10	2.48E+10	4.41E+10
Human Res. (sej/\$) §	Direct	2.18E+11	4.80E+11	6.48E+11	7.01E+11	4.80E+11	1.54E+10
	Indirect	4.89E+11	4.46E+11	6.50E+11	4.95E+11	3.39E+11	5.34E+11
	Total	7.06E+11	9.25E+11	1.30E+12	1.20E+12	8.18E+11	5.50E+11
Total (sej/\$)	Direct	2.35E+11	4.94E+11	6.93E+11	7.15E+11	4.94E+11	1.59E+10
	Indirect	1.11E+12	1.50E+12	9.81E+11	9.32E+11	6.68E+11	1.90E+12
	Total	1.35E+12	1.99E+12	1.67E+12	1.65E+12	1.16E+12	1.92E+12

‡ To convert Human Health Impact of emissions into DALYs/yr divide by 3.42×10^{16} sej/yr

§ To convert Human Resources into workdays/yr divide by 9.35×10^{13} sej/workday

Table 4: Top five suppliers of the transportation sectors with % contributions to intermediate input

Air transportation		Truck transportation	
Total	100%	Total	100%
Travel arrangement and reservation services	18.50%	Truck transportation	23.92%
Petroleum refineries	14.10%	Wholesale Trade	8.24%
Scenic and sightseeing transportation	11.51%	Petroleum Refineries	7.19%
Food services and drinking places	9.77%	Scenic and sightseeing transportation	6.30%
Telecommunications	3.12%	Motor vehicle parts man.	5.24%
Rail transportation		Transit and ground passenger transportation	
Total	100%	Total	100%
Machinery & equipment rental & leasing	17.59%	Wholesale Trade	10.03%
Scenic and sightseeing transportation	15.90%	Insurance Carriers	8.89%
Railroad rolling stock manufacturing	6.52%	Transit Ground and Passenger	8.08%
Wholesale Trade	5.06%	Motor vehicle parts manufacturing	7.90%
Petroleum refineries	4.05%	Petroleum Refineries	7.41%
Water transportation		Pipeline transportation	
Total	100%	Total	100%
Scenic and sightseeing transportation	30.93%	Petroleum refineries	18.36%
Insurance Carriers	10.33%	Environmental and other technical consultin	10.91%
Management of companies and enterprises	5.93%	Oil and gas extraction	6.82%
Ship Building and Repairing	5.11%	Employment Services	4.89%
Other State and Local Government enterprise	4.58%	Other maintenance and repair construction	4.18%

- Human health impact caused by direct emissions from pipeline transportation is two orders of magnitude smaller than that caused by indirect emissions. On the contrary,

direct emissions from other transportation sectors are comparable to the indirect emissions from them. A plausible reason behind this could be that pipeline transportation itself does not consume fossil fuels to the same extent as other transportation sectors that burn fuels in internal combustion and other types of engines.

- Pipeline transportation has the highest ECEC/money ratio for non-renewable resources whereas water transportation has the lowest. This is so because Pipeline transportation derives 25.18% of its inputs from sectors of petroleum refineries and oil and gas extraction, both of which are basic infrastructure industries with heavy reliance on non-renewable resources. Water Transportation, on the other hand, gets 47.19% of its inputs from three service industries shown in Table 4 that have relatively lower consumption of non-renewable resources.
- Water transportation has the highest human health impact of emissions per unit economic throughput. More than 75% of this is caused by direct emissions of SO₂ (3.42×10^{10} sej/yr) and CO₂ (1.06×10^{10} sej/yr).

Table 5: Thermodynamic metrics for transportation sectors

	Air	Rail	Water	Truck	Trans. & Ground	Pipeline
Yield Ratio (Total ECEC requirement/ECEC inputs from economy)	1.22	1.33	1.70	1.77	1.74	1.01
Loading Ratio (ECEC from non-renewable resources/ECEC from Renewable Resources)	140	216	65	161	81	347
Yield Ratio/Loading Ratio (YLR)	8.7	6.1	26.3	11	21.3	2.9
Impact/Value Added (ECEC/money ratio for human Health Impact) (sej/\$)	3.98E+10	2.58E+10	5.86E+10	3.02E+10	2.48E+10	4.41E+10

Table 5 calculates Yield Ratios, Loading Ratios and Yield-to-Loading Ratios (YLR) for the six transportation sectors. Yield-to-Loading Ratio is also termed as the index of sustainability in emergy literature. Based on Table 5, pipeline transportation not only has the highest loading ratio but also the lowest yield ratio. Conversely, water transportation has the highest YLR on account of its low loading ratio. However, it also has the highest human health impact per unit economic activity. Transit and Ground Passenger Transportation has a higher YLR and a lower human health impact of emissions per unit economic activity than air, rail, truck and pipeline transportation, making it a better alternative if the decision is to be made based only on these two objectives. A more rigorous multi-objective optimization analysis with YLR, human health impact of emissions and cost of transportation as the three objectives is currently underway, and the results will be included in future publications.

5 Conclusion

Thermodynamic Input-Output Analysis is a systematic framework to account for the contribution of ecological and human resources to industrial systems, as well as the impact of their emissions on human and ecosystem health. TIOA complies with the first and the second laws of thermodynamics and acknowledges the underlying network structure of economic and ecological systems. TIOA is especially useful for LCA/LCM,

as it can readily evaluate environmental implications of a product's or process' supply network. TIOA is different from other economy-wide LCA approaches as it also accounts for ecological inputs, and uses end-point methods for impact assessment, with exergy as the common thermodynamic unit.

The main emphasis of this paper is to demonstrate the application of TIOA as a tool for environmental decision making. In this context, two case studies have been presented. The first case study compares a conventional coal-fueled thermoelectric facility with a geothermal electricity generation system. The second case study compares six transportation modes that include air, rail, water, truck, transit and ground passenger and pipeline transportation. As seen from these case studies, TIOA enables calculation of life-cycle exergetic efficiencies of industrial systems at multiple spatial scales. It also enables aggregation of a diverse set of resources in a thermodynamically rigorous way into a smaller number of hierarchical metrics that can help the decision-making process. ECEC/money and ICEC/money ratios used in this analysis can be readily used in thermodynamic LCAs of other industrial products and processes, since the interactions of a product system or a process ensemble with the rest of the economy are typically captured in terms of monetary flows. ICEC/money ratios assist in thermodynamic LCA at the scale of the economy, whereas ECEC/money ratios would assist in thermodynamic LCA at the scale of the ecosystems. Such ratios have been calculated for 91-sector 1992 and 491-sector 1997 U.S. economies, and have been made available on the internet ^[34,35].

34 <http://www.che.eng.ohio-state.edu/~ukidwe/91sector1992.pdf>

35 <http://www.che.eng.ohio-state.edu/~ukidwe/491sector1997.pdf>