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Energy Intensity of Computer Manufacturing: Hybrid Assessment Combining Process and Economic Input−Output Methods

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The total energy and fossil fuels used in producing a desktop computer with 17-in. CRT monitor are estimated at 6400 megajoules (MJ) and 260 kg, respectively. This indicates that computer manufacturing is energy intensive: the ratio of fossil fuel use to product weight is 11, an order of magnitude larger than the factor of 1−2 for many other manufactured goods. This high energy intensity of manufacturing, combined with rapid turnover in computers, results in an annual life cycle energy burden that is surprisingly high: about 2600 MJ per year, 1.3 times that of a refrigerator. In contrast with many home appliances, life cycle energy use of a computer is dominated by production (81%) as opposed to operation (19%). Extension of usable lifespan (e.g. by reselling or upgrading) is thus a promising approach to mitigating energy impacts as well as other environmental burdens associated with manufacturing and disposal.

1. Introduction

Information Technology (IT) continues to change how we do business, research, and even socialize. Pundits speak of IT as a revolution as important as the adoption of electricity or the combustion engine. Given the extent to which computers have affected our daily lives, it is difficult to disagree. Technological revolutions also affect the environmental challenges faced by societies and how to respond to them. As Information Technology is concerned with moving and processing bits instead of mass, its direct environmental consequences should not be as severe as, say, adoption of the combustion engine. Nonetheless, the environmental impacts associated with the physical IT infrastructure (i.e. computers, peripherals, and communications networks) are significant. Many in rich countries use two or more computers (e.g. one for home, one for work). Rapid technological change implies that users buy new computers far more often than many other durable goods. Indeed, the problem of what to do with waste computers is of sufficient concern that regions and nations around the world are enacting legislation to mandate take-back and recycling systems, such as the European Union Directives on Waste Electrical and Electronic Equipment (WEEE) and Restriction on Hazardous Substances (RoHS) (*1*).

Environmental assessment is key in formulating appropriate societal response to the environmental impacts of IT. A recent study of semiconductors estimated that manufacture of a 2-g memory chip requires at least 630 times its weight in fossil fuels and chemicals, orders of magnitude higher than the factor of 1−2 for an automobile or refrigerator (*2*). The authors argue that the origin of this high materials intensity is due to the additional processing needed to attain the highly organized, low entropy structure of microchips. A weakness of the previous comparison, however, is that a chip is only a component. It must be integrated into a device to deliver a useful information service. It is thus desirable to upgrade the analysis to address a final end product. The desktop computer remains the workhorse of information technology and thus is chosen as the focus of the current study. There are a number of environmental issues of potential concern associated with computers, including energy use, chemical exposure to workers in high-tech factories, and health impacts on those involved in backyard computer recycling in the developing world. While broad assessment of a variety of impacts is needed to understand the full effect of computers on the environment, practical considerations constrain the current study to analysis of only energy use. In conclusion, the target is estimation of the energy consumed in the network of production processes yielding a desktop computer with 17-in. CRT monitor.

There are several existing analyses of materials and energy use in producing computers. In 1993, a consortium facilitated by a consulting firm and including many U.S. high-tech manufacturers, published a study reporting that production of a workstation requires 8300 megajoules (MJ) of electricity, 63 kg of chemical waste, and 27 700 kg of water (*3*). The European Union commissioned a 1998 study whose results include 3630 MJ of energy use and 2.6 million kg of water consumption for manufacturing a desktop computer with monitor (*4*). The latter figure for water use is an obvious overestimate as it implies world computer production in 2000 of 120 million computers requires 40% of worldwide industrial water consumption. A few other studies exist (some by computer manufacturers), but these contain even less reporting of data and assumptions than the two mentioned.

There are four main weaknesses in the existing literature. One is that studies are mainly based on proprietary or confidential data. These are not reported, and it is thus impossible to deconstruct results. Second, there is little or no critical discussion of underlying data and assumptions, nor comparison of results with existing work. Proper reporting of data and assumptions as well as comparison with existing work are two key elements of any analysis attempting to model itself on the scientific method. Third, many steps in the network of manufacturing processes have been left out, in particular those producing specialized materials supplying the electronics industry, such as silicon wafers and high-grade chemicals. The fourth issue is lack of consideration of how data might vary from facility to facility and nation to nation. These issues stand out as weaknesses not only for analyses of computers but also for many existing environmental assessments of a wide range of products and services. This study addresses these gaps in the literature with an analysis that reports *all* data and assumptions, via a method that combines process and economic techniques so as to cover the manufacturing network as fully as possible. Geographical variations in data are partially accounted for, and when not, uncertainties induced by using national data estimated.

2. Methodology

Assessment of the net environmental impacts associated with delivering a product or service started in the 1970s with net energy analysis, which has since expanded to become a

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broader field known as life cycle assessment (LCA). The "life cycle" in LCA refers to the attempt to characterize environmental impacts from cradle to grave, starting from extraction of resources, following production of raw materials and parts, assembly, sales, to use and disposal of a product. There are two basic approaches to estimating life cycle requirements of materials and energy: process-sum and economic input–output (IO). The process-sum approach is based on using facility-level data describing industrial processes in terms of the material inputs of consumables, outputs of products, and emissions (*5*). Process-sum also implies a method: building the network of industrial activities piece and piece, stopping when either data limitations or other considerations make further expansion infeasible. This is termed setting the system boundary.

The other approach, economic input–output (IO), is based on IO tables that describe financial transactions between sectors in a national economy (*6*, *7*). The most detailed tables divide an economy into 400–500 aggregated sectors. One consequence of the completeness and mathematical simplicity of IO tables is that incorporating higher order flows (e.g. use for steel to produce the iron ore needed to make steel) can be easily accomplished using techniques developed by Leontief. The basic formula used to calculate the net energy used to produce a unit of economic output for economic sectors is

$$E^{SC} = E^{D}(1 - A)^{-1} \tag{1}$$

where E^{SC} is the vector of supply chain energy intensities (MJ/\$), E^{D} represents direct energy intensity, and A is the requirements matrix (A_{mn} = transaction from sector m to n/total economic output of sector n). The energy requirements to manufacture a given product is determined by multiplying the supply chain intensity of the relevant sector by the producer price of the product.

Both methods have advantages and disadvantages. Process-sum analysis can more accurately describe the particular technologies by which a product is made. Input–output tables aggregate many implementations and types of processes into one sector. For instance, production of copper, aluminum, zinc, lead, cadmium, tin, nickel, and other metals is usually combined into a single "nonferrous metals" sectors. Energy use to produce these different metals, however, does not correlate well with price. On the other hand, process-sum analyses often leaves out important contributions, especially due to production of capital goods and input of services, which are not easily accounted for in the mass-centric perspective of process-sum analysis.

Researchers have been exploring ways to leverage process and economic input–output methods such as to reduce the boundary cutoff error in the former and aggregation error of the latter. This is termed hybrid analysis, the basic premise of which was articulated by Bullard, Penner, and Pulati in 1978 (*8*). Their analysis focused on trying to identify what components of an IO analysis might have largest uncertainty for replacement with process data. Engelenburg and collaborators developed a method in which process data are supplemented by IO analysis estimating contributions from capital goods, services, and other missing processes, which was applied to the case of a refrigerator (*9*). Heijungs integrated process and IO frameworks into a unified mathematical form, which express the entire system via a mixed unit matrix containing environmental, mass, and economic data (*10*). Joshi, working within the IO method, used process data to further disaggregate certain economic sectors where aggregation error is expected to be significant (*11*).

Proposed Method for Separative Hybrid Analysis. The target of the current work is modification of the subset of "separative" hybrid methods. The starting point is the requirement that process-sum and IO correction can be expressed as the addition of two (separated) factors

$$\text{total energy} = \text{process-sum result} + \text{IO correction factor} \tag{2}$$

While more complex formulations in which process data are incorporated into generalized IO matrices (*10*, *11*) are also possible, there are cogent practical considerations favoring a separative form. While the data elements needed to perform an environmental IO analysis are publicly available (specifically the IO tables and direct sectoral energy consumption), building one up from scratch is extremely labor intensive. One advantage of a separative method is that the results of existing energy IO analyses (e.g. from the Green Design Institute at Carnegie Mellon University (*12*)) can be used with minor modifications. Also, simplicity eases evaluation of data and results and also makes the method more accessible to those not expert in the specialized field of IO analysis.

The key question is how to define the IO correction factor. One specific proposal is described below, in which the total IO correction factor is considered to be a sum of additive and "remaining value" terms:

$$\text{IO correction factor} = E_{A} + E_{RV} \tag{3}$$

E_A is the additive factor, which accounts for those industries for which specific economic (but not process) data on requirements per product is available. Let j be an index denoting sectors for which such economic data can be obtained. The additive correction factor is

$$E_{A} = \Sigma\, \text{Exp}_{j}\, E^{SC}{}_{j} \tag{4}$$

where Exp_j are expenditures in monetary terms on sector/activity j per unit product and $E^{SC}{}_j$ is the supply chain energy intensity (eq 1). Care must be taken not to double count activities such as materials production already covered in the process-sum analysis; these are subtracted from $E^{SC}{}_j$ by hand.

The "remaining value" factor, E_{RV}, estimates the contribution from those processes not included in either process-sum or additive IO terms, by accounting for how much of the total economic value of the product has been covered. Let k denote a set of processes treated in the process-sum analysis. The economic value covered by the process-sum analysis is defined as

$$V_{P} = \Sigma\, \text{Exp}_{k}\ \text{valuc-added share}_{k} \tag{5}$$

where "valuc-added" is a modified version of value-added as defined in the U.S. Annual Survey of Manufactures (*13*))

$$\text{valuc-added} = \text{shipments} - \text{materials (nonenergy)} - \text{services} - \text{capital} = \text{value-added} + \text{energy} - \text{capital} \tag{6}$$

The root of this definition is the observation that data for a given process usually cover direct energy use but not energy consumed in production of inputs materials, services, and capital goods. The term "valuc-added" is a mnemonic indicating that it differs from value-added by addition of e for energy and subtraction of c for capital. Valuc-added share is the ratio of valuc-added over total sector shipments.

The value covered in the additive IO analysis (E_A) is

$$V_{A} = \Sigma\, \text{Exp}_{j} \tag{7}$$

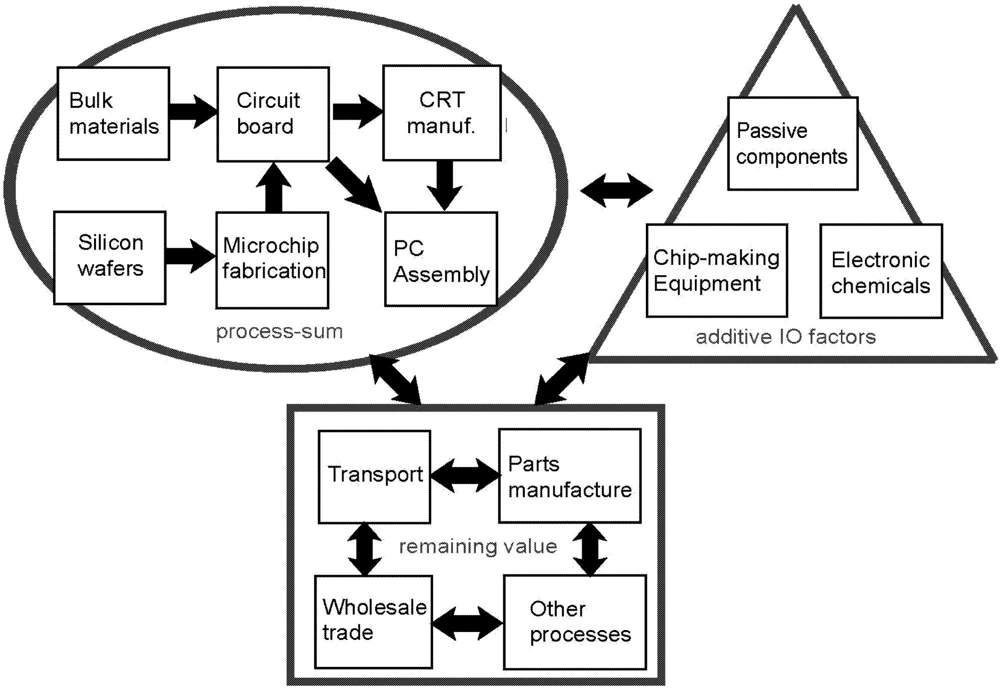

FIGURE 1. Generalized system boundary (some arrows indicating intersector flows have been abbreviated).

Thus, the total remaining value not yet covered is

$$\mathrm{RV} = \text{remaining value} = \text{producer price} - \mathrm{V_P} - \mathrm{V_A} \quad (8)$$

Given this, the manufacturing energy associated with the remaining value is estimated by

$$\mathrm{E_{RV}} = \mathrm{RV}\ \Sigma(\text{value share}_\mathrm{l})\mathrm{E^{SC}_l} \quad (9)$$

The sum is over a set of IO sectors (denoted by the index l) that excludes those already covered in the process and additive IO analyses, and value share is the relative fraction of supply chain purchases for each respective sector.

To sum up, the flow of the method is as follows: 1. Perform process-sum analysis via conventional means: $\mathrm{E_P}$. 2. For those processes for which product specific economic data are available, calculate additive IO corrections, $\mathrm{E_A}$, via [4]. 3. Estimate value covered in process-sum analysis, $\mathrm{V_P}$, via valuc-added [5, 6]. 4. Estimate value covered in additive IO analysis, $\mathrm{V_A}$, via [7]. 5. Calculate remaining value, RV, via [8]. 6. Estimate associated energy, $\mathrm{E_{RV}}$, via [9]. 7. Sum total energy = $\mathrm{E_P} + \mathrm{E_A} + \mathrm{E_{RV}}$.

While the above method is similar to existing work in its overall flow, the proposal to account for economic value via valuc-added is apparently new. The closest method is that of Engelenburg and collaborators (*9*). They allocate according to the full market price for raw materials full market price, and for manufacturing processes, only the price paid by firms for energy is subtracted. I argue that valuc-added (or even value-added) is a much more appropriate definition. Allocating the full price of materials assumes that those sectors imputing into materials production have been accounted for, which is generally not the case. Allocating energy costs for manufacturing sectors assigns near zero value to most of them, shunting most product value to the residual sectors. Yet it is clear in any economic accounting that manufacturing sectors have a nontrivial share of the value of a manufactured good. Using valuc-added addresses both of these points as well as treats all sectors covered in the process analysis symmetrically.

3. Case Study of a Desktop Computer

The case study applies the above methodology to assess the energy used in the chain of manufacturing processes yielding an "average" desktop computer with a 17 in. CRT monitor, produced in the year 2000. As the hybrid method combines process-sum and IO methods, the definition of the functional unit includes both physical and economic characteristics. These are to be detailed in later sections, but as a preview note that the average global producer price of a desktop system in 2000 was $1700 (*14*). A typical machine sold at that price in July 2000 was equipped with Pentium III 733 MHz processor, 128MB DRAM, and 30GB hard drive.

The manufacturing network for almost any product encompasses firms in two or more nations. The production of computers, a highly globalized industry, is hardly an exception. This raises the question of whether data gathered in one region will apply to another. An equally valid concern is whether two different facilities will have similar environmental characteristics. Limitations on available data preclude tracking back the geographical and facility characteristics of each step and only using figures applying to that region or factory. As in previous environmental assessments, assumptions are made in which data for one region/facility are considered to be more general than is actually the case. For the process-sum analysis, every effort is made to gather international data so as to arrive at a reasonable global average for the industry. For the IO analysis, global producer prices are used, and it is assumed that the U.S. IO table is in fact a global one. This assumption no doubt leads to significant error, but in the absence of a generally available international IO table, necessary. In Section 8, the error induced by this assumption is estimated. Specifically, the Carnegie Mellon University calculations using the 1997 U.S. Benchmark table (*12*) are used throughout the IO analysis.

Process-sum life cycle assessment is based on the so-called system boundary, which delineates what processes are included in the analysis and which are not. For a hybrid analysis, the generalized system boundary describes how process and IO portions interrelate. This is graphically depicted in Figure 1. Energy use in production and distribu-

TABLE 1. Calculation of Energy Use Per Silicon Area from National Level Data

data source	year(s)	national gas use (billion MJ)	national electricity use (billion kWh)	national wafer use (billion cm²)	normalized direct fossil use (MJ/cm²)	normalized electricity use (kWh/cm²)
U.S. census	1995–2000	185	63.07	42.78	4.3	1.5
U.S. MECS	1998	21	13.34	6.32	3.3	2.1
Japan structural survey	1999	24	12.28	10.35	2.3	1.2

TABLE 2. Energy Use in Production Processes According to Different Data Sources and "Average" Values[a]

process	data type	year(s)	norm	direct fossil use (MJ/norm)	electricity use (kWh/norm)	global average direct fossil use (MJ/norm)	global average electricity use (kWh/norm)	source(s)
semiconductor	U.S. Census	1995–2000	cm² silicon	4.3	1.5	2.7	1.54	(*13*)
	U.S. MECS	1998		3.3	2.1			(*15*)
	Japan natl.	1999		2.3	1.2			(*16*)
	Facility (UMC)	1998–2001		n/a	1.4			(*17*)
circuit board	U.S. natl.	2000	m² board	93	28	116	34	(*13*)
	Japan natl.	2001		141	40			(*19*)
	Facility (anon.)	2001		190	27			(*20*)
CRT manufacture/ assembly	Japan natl.	1995	unit	113	21	210	13	(*21*)
	facility (anon.)	1997–2000		210	13			(*20*)
computer assembly	U.S. natl.	2000	unit	64	28	35	51	(*13*)
	firm (HP)	2000		35	51			(*22*)
bulk materials – control unit	process LCA databases	mixed	kg	85 (av)	n/a	85	n/a	(*23–25*)
bulk materials – CRT	process LCA databases	mixed	kg	51 (av)	n/a	51	n/a	(*23–27*)
silicon wafers	engineering literature	mixed	kg	n/a	2100	n/a	2100	(*2*)

[a] Notes: norm = normalization unit, n/a = not available, for definition of "average" process, see text and Supporting Information.

tion of energy itself as well as retail distribution/sales of computers are intentionally excluded from the analysis.

4. Process-Sum: E_P

The industrial activities covered in the process-sum analysis are as follows: 1. fabrication of semiconductor devices, 2. manufacture of printed circuit boards, 3. manufacture of cathode ray tube (CRT) monitors, 4. production of silicon wafers from raw materials (quartz, charcoal/coal), 5. production of bulk materials in computers and monitors (steel, plastic, aluminum, glass, etc.), 6. assembly of the computer from component parts.

These six are covered via process-sum analysis because they are the only ones for which data sources for both process energy use and content in the target product (e.g. kg of steel in a computer) were identified. The case of semiconductor fabrication is described below, and detailed treatment for other processes appears in the Supporting Information.

Inputs to semiconductor device manufacturing include silicon wafers, energy, a variety of chemicals (many toxic), prodigious quantities of water, and elemental gases. The main output is the finished microchip. Fabrication is known to be energy intensive and thus is expected to make a significant contribution to the overall energy consumed to make a computer. Data sources found describing energy consumption in semiconductor processing are the U.S. Census, the U.S. Manufacturing Energy Consumption Survey (MECS), the Japanese national survey of industrial energy use, and publicly reported data from a Taiwanese firm producing specialty integrated circuits (*13*, *15–17*). For comparison and analysis, all data must be translated into a common normalization. Energy use per area of input silicon wafer is chosen for this purpose. The first three sources reflect national consumption, and Table 1 details how energy use per wafer area is obtained from raw data. The comparatively low use of the Japanese industry does not necessarily imply higher energy efficiency, as a larger share of Japanese production is for wafer intensive discrete devices such as diodes. The global average value of energy use per square centimeter is estimated by adding use of U.S. (MECS) and Japanese industries and dividing by their combined wafer use, 16.7 billion cm^2 (*18*). The result is 2.7 MJ/cm^2 of directly consumed fossil fuels and 1.54 kWh/cm^2 of electricity. Data sources, energy use, and estimated global averages for all six groups of processes are summarized in Table 2.

Estimating energy use per desktop system requires information on both energy use per unit process and process "content" per product. For semiconductors, this must be done in an aggregate way, as data on manufacturing different devices (i.e. CPUs, DRAM, EPROM) and device content per product are inadequate. Total energy use required to manufacture the chips in one computer is estimated by first estimating energy consumption of the global semiconductor industry and then allocating a portion used in production of a desktop computer according to the value of semiconductor shipments used in computers. 49% of global semiconductor production in 2000 went to computer end-use markets (*28*). 60% of the value of total computer production was for desktop computers, and the number of desktops produced was 94.6 million (*14*). These data are combined via the formula

$$\begin{aligned}&\text{electricity use/computer [kWh/unit]} = \\ &\quad (\text{elec. per wafer area} \times \text{world wafer production} \times \\ &\quad \text{desktop share})/\text{computers produced} = \\ &\quad (1.54\ \text{kWh/cm}^2 \times 35.4\ \text{billion cm}^2 \times \\ &\quad 29.4\%)/94.6\ \text{million units} = 170\ \text{kWh per computer}\end{aligned} \tag{10}$$

The total energy to fabricate chips in one desktop is thus estimated at 170 kWh of electricity and 289 MJ of direct fossil

TABLE 3. Electricity, Fossil, and Total Energy Use in Computer Production (Total Energy ≡ Direct Fossil + 3.6·Electricity Use)

item	direct fossil (MJ)	electricity use (kWh)	total energy (MJ)
production			
process analysis (E_P = 3140 MJ)			
semiconductors	298	170	909
printed circuit boards	26.7	7.71	54.5
CRT manufacture/assembly	210	12.5	255
bulk materials − control unit	n/a	n/a	770
bulk materials − CRT	n/a	n/a	800
silicon wafers	n/a	38.1	137
computer assembly	35.3	51.2	220
IO analysis			
additive (E_A = 1100 MJ)			
electronic chemicals	381	18.5	448
semiconductor manufacturing equipment	392	29.4	498
passive components	109	10.3	146
remaining value (E_{RV} = 2130 MJ)			
disk drives and other parts	365	23	446
transport	338	3.5	351
packaging, documentation	120	4.8	137
other processes	973	61	1192
total production	3300	430	6400
use phase: home user (3 years)		420	1500
total production + use phase	3300	850	7900

fuels, and results for other processes (as well as from later sections of the article) are shown in Table 3.

5. Additive IO Correction Factor: E_A

The three processes treated as additive IO factors are as follows: specialized chemicals/materials for electronics manufacturing, semiconductor fabrication equipment, and manufacture of passive devices (e.g. resistors, capacitors). The large quantity of energy needed to produce silicon wafers suggests that production of other high-grade chemicals and materials may similarly be energy intensive and thus should be given special consideration. High-grade chemicals were not considered in the process analysis due to a lack of publicly available data on energy use in their manufacture.

To estimate the total value of electronics chemicals used to manufacture a typical desktop, note that the global market in 1999 for chemicals and materials in the semiconductor and circuit boards industries (excluding silicon wafers) totaled USD $16.8 billion (*29*). Alloting use per computer according to economic value, 49% of semiconductor production went to computers, and 60% of the computer market is held by desktops (*28*). Given 1999 production of 82.4 million units, the value of electronics chemicals per desktop is estimated at USD $61.

The next task is selection of a sector in the U.S. IO tables that best matches energy use per dollar of output for production of electronic chemicals/materials. A choice such as Other Miscellaneous Chemical Product Manufacturing seems natural at first. The supply chain energy intensity (E^{SC}) of this sector is 17.8 MJ/$. However, much of the activity of this sector is production of bulk chemicals, which consume significant energy with low price and profit margin. To guide the choice, note that process data on silicon wafers indicate that the ratio of electricity use to production value is 5 MJ/$ (*2*, *30*), much lower than for most bulk chemicals. Sectors such as Pharmaceuticals (($E^{SC} = 6.4$ MJ/$) and Photographic Film and Chemicals ($E^{SC} = 7.6$ MJ/$) have intensities much closer to this. The sector Photographic Film and Chemicals is chosen as a conservative estimate. To estimate energy use per computer, USD$61 in 1999 is deflated to 1997 dollar (a factor of 0.97) and multiplied by E^{SC}, as per formula 4. The results of this calculation are shown in Table 3 along with results of similar ones for contributions from production of semiconductor fabrication equipment and passive devices (*31*, *32*). Details appear in the Supporting Information.

6. Energy Associated with Remaining Value: E_{RV}

The first step in estimating remaining value is accounting for the "valuc-added" covered in the process analysis (V_P in eq 5). Table 4 shows the flow of the calculations. Global revenue of the sector is taken from consulting firm statistics (*33*−*36*). Value per desktop is derived as in eq 10, except that for bulk materials, value of contained product was estimated by multiplying respective weights by typical market material prices ((*37*) plus various Web sources for prices of plastics). Valuc-added is calculated from eq 6 from the U.S. Annual Survey of Manufactures (*13*). For example, shipments for the semiconductor sector 2000 were $93.3 billion, costs of materials (except energy) $18.9 billion, and capital expenditures $17.5 billion, leading to a valuc-added share of 61%. Results indicate that $1100 of the $1700 value of the average desktop has been accounted for in the process analysis. Remaining value (eq 8) is equal to

RV= $1700 − $1100 (process analysis) −
$61 (chemicals/materials) −
$74 (semiconductor equipment) −
$28 (passive devices) = $440

The energy associated with this remaining value is calculated according to eq 9, which allocates remaining value to IO sectors not yet covered according to supply chain purchases of the Electronic Computer Manufacturing sector. The top 24 sectors contributing to E^{SC} are chosen, not including those involved with energy production and distribution. Remaining sectors are a mix of activities from transport, packaging, and services to manufacture of parts and equipment as yet not covered, such as hard disk drives. There is the additional complication that the energy used to produce raw materials for parts has already been accounted for, and there is thus a risk of double counting if the supply chain IO factor for a parts-producing sector is used. This is corrected for by eliminating appropriate terms from E^{SC}_l by hand. Table 5 shows details of this calculation. The remaining value of $440 has been deflated to $420 1997 dollars.

7. Total Energy and Fossil Fuel Use Associated with Owning a Desktop Computer

In this section, results for computer manufacturing are collected and compared with energy consumed in operation. Lifetime is one of the most important of variables determining the total energy associated with computer ownership. Measuring lifetime is complicated by the stockpiling of computers unused in closets: the number of years between purchase and disposal of a computer is often very different from the period it was actually used. Some writers claim that 70−80% are stockpiled in the United States before disposal (*39*). Data from a survey of 70 Japanese users show that 30% report that they store their old computer upon purchase of a new one (*1*). This survey also indicates an average period of 2.7 years between purchases of new computers. A separate survey of Japanese Web users (1350 respondents) reports an average 2-year span between purchases (*40*). Dataquest published results of a survey of U.S. business users reporting an average 3.44 year lifespan for an office computer (*41*). Although there is still a shortage of empirical evidence describing the distribution of computer lifetimes at the macrolevel, it is assumed in this analysis that a 3-year span of use for home users is representative.

TABLE 4. Valuc-Added Accounted for in Process Analysis

process	global sector revenue (billion $)	year	per desktop ($)	valuc added share (%)	accounted for in process analysis ($)	data sources
1. semiconductor	204	2000	634	61	387	(*28*, *33*)
2. circuit boards	42.7	2000	57	47	27	(*34*, *35*)
3. CRT monitor	19.5	2001	180	38	68	(*36*)
4. silicon wafer	7.5	2000	23	53	12	(*18*)
5. bulk materials	n/a	n/a	29	35	10	(*37*)
6. assembly	248	2000	1700	35	595	(*14*)
total					1100	

TABLE 5. Remaining Value Shares and Associated Value for IO Sectors

sector	supply chain purchases million $	RV share (%)	fossil intensity (MJ/$)	elec. intensity (kWh/$)	fossil/ comp. MJ	elec./ comp. kWh
Disk Drives and Other Parts						
computer storage device manufacturing	0.0950	11.9	4.22	0.233	210	11.6
other computer peripheral equipment manufacturing	0.0889	11.1	3.32	0.236	155	11.0
Transport						
air transportation	0.0127	1.59	20.2	0.206	134	1.37
couriers and messengers	0.0051	0.641	20.3	0.204	54.5	0.55
truck transportation	0.00884	1.10	9.35	0.207	43.3	0.96
rail transportation	0.00195	0.244	41.4	0.171	42.3	0.17
transit and ground passenger transportation	0.000936	0.117	67.6	0.154	33.1	0.075
scenic and sightseeing transportation and support activities for transportation	0.00288	0.360	20.1	0.277	30.3	0.42
Packaging, Documentation						
paper and paperboard mills	0.00878	1.10	18.4	0.694	84.6	3.19
commercial printing	0.00948	1.18	7.04	0.328	34.9	1.63
Other Processes						
wholesale trade	0.229	28.5	2.66	0.198	318	23.7
real estate	0.0298	3.72	8.72	0.550	136	8.59
software publishers	0.114	14.3	1.58	0.115	94.4	6.89
management of companies and enterprises	0.0704	8.79	2.39	0.240	88.0	8.85
waste management and remediation services	0.0144	1.79	8.56	0.175	64.4	1.32
other support services	0.0169	2.11	6.66	0.0980	58.9	0.87
plastics plumbing fixtures and all other plastics products	0.0123	1.54	7.19	0.310	46.4	2.00
sheet metal work manufacturing	0.0129	1.61	6.16	0.357	41.6	2.41
monetary authorities and depository credit intermediation	0.0202	2.52	2.90	0.120	30.6	1.27
maintenance and repair of nonresidential buildings	0.00524	0.654	10.9	0.311	29.8	0.85
telecommunications	0.0197	2.45	2.45	0.178	25.2	1.83
broadcast and wireless communications equipment	0.0109	1.36	3.52	0.251	20.1	1.43
scientific research and development services	0.0109	1.36	3.41	0.151	19.4	0.86
total	0.802	100			1795	91.8

A typical Pentium III system with 17-in. CRT monitor consumes on average 128 W when fully on (*38*). The usage pattern of a computer (i.e. number of hours used in what power mode) is a key determinant is energy consumption during operation. Given lack of publicly available data, it is assumed that average computer operation by a home-user is 3 h use per day full-on (no standby). There is clearly a need for further empirical work describing the usage patterns (lifetime, hours operated, standby modes, stockpiling, etc.). This is left as a task for future studies.

Based on the above assumptions, Table 3 combines results for production and use phases of a desktop computer, and the life cycle energy consumption for production and use is 7900 MJ. The annual life cycle energy use for a computer (3-year lifespan) is 2600 MJ, about 1.3 times the 2070 MJ required for a refrigerator (3500 MJ production energy, 510 kWh/year electricity use, 15 year lifespan) (*9*). The energy footprint of a computer is thus far more significant than its physical size would suggest. The energy used for the production phase is 81% of the total consumed for production and operation, a share much higher than for many other household appliances. For example, for a refrigerator only 11% of life cycle energy is consumed in production of the appliance (*9*).

The ratio of fossil fuels consumed for production to the mass of the product is an indicator of energy intensity. It will not be possible to accurately estimate fossil fuel use (or carbon dioxide emissions, for that matter), as the carbon intensity of electricity varies from nation to nation. This does not pose an obstacle to calculation in principle, but, in practice, knowledge of the geographical distribution of different production stages is inadequate. The intention is simply to perform a crude estimate in which the computer manufacturing chain is assumed to be globally uniform, thus world averages can be used. Fossil fuels needed to produce a kilowatt-hour of electricity using the global average of technologies (e.g. fossil-fired, hydropower, nuclear) total 320 g per kWh (*42*). Using the International Energy Agency World Energy Statistics database, the average energy content of kilogram of fossil fuel consumed in the global industry sector is 39 MJ/kg (*43*). Also note that in Table 3 that energy to produce constituent materials is only expressed in terms of net energy use, there is no breakdown of fossil and electricity portions. To estimate the associated fossil fuel weight, dividing the world energy demand of raw material industries by the mass of fossil fuels consumed yields a conversion factor of 37 MJ/kg (*43*). Applying these conversion factors to the results of Table 3, manufacture of a desktop system is estimated to require 260 kg of fossil fuels (to two significant figures), some 11 times its weight. The ratio of fossil fuel use to product weight is high compared to other common goods such as an automobile (1−2), refrigerator (2), or aluminum can (4−5) (*44*, *9*). The author and collaborators in a previous work suggest that the high-intensity ratio for computers is due to additional processing needed to achieve the highly organized, low-entropy materials and environments associated with making high-tech goods (2).

8. Uncertainty and Caveats

I separate the discussion on uncertainties and caveats into two aspects: error in those factors considered in the analysis and issues not treated. With respect to the former, uncertainty in the process-sum and IO-based analyses are treated separately.

For process-sum analysis, values for energy use from different data sources are used as an indicator of uncertainty. I assume that different values are random errors, though in actuality they are a mix of random and system errors. Taking standard deviations yields fractional errors: semiconductor fabrication (±32%), circuit boards (±21%), CRT manufacture (±15%), and assembly (±79%). Variations in data for producing bulk materials and silicon wafers were not tracked down, and values of ±30% are assumed. Adding these different errors in quadrature (they are presumably uncorrelated) yields a total ±475 MJ error in the process sum result for manufacturing a desktop system.

In the IO based analyses (additive and remaining value based), the most significant uncertainty is probably due to the assumption that U.S. IO tables apply globally. Also, for some processes, in particular manufacture of chemicals for electronics, there is no clear choice of IO sector that matches these activities closely. Quantitative estimation of error is challenging for the same reasons the assumption was needed in the first place: lack of international economic and energy data. The reasons why using U.S. tables induces error is that energy efficiency varies from nation to nation as does value-added for similar sectors. Producer prices (and thus value of sector output) for similar goods are generally lower in China, for example.

The approach taken to error analysis for IO based factors is to use differences in national energy intensities of industry sectors to estimate lower and upper bounds for E_{SC}. Energy intensities for industry (as one overall sector) in the United States, Japan, China, and Malaysia in 2000 are 6.14, 3.73, 24.4, and 10.2 MJ/$ (year 2000 USD), respectively (*43*, *45*). The global industry average is 9.6 MJ/$ (year 2000 USD). The lower bound on IO uncertainty is obtained by assuming that all computer manufacturing takes place in Japan and that all Japanese energy intensities are lower than the U.S. ones by a factor of 0.61, the ratio of national level intensities. The upper bound is obtained via a similar assumption but using China, which leads to energy intensities a factor of 4 higher than the United States. These lead to upper and lower bounds for the sum of additive and remaining value IO corrections of 2000 and 13 000 MJ, respectively (base calculation using U.S. IO tables: 3200 MJ). This is clearly an *overestimate* of error because manufacturing is not focused in one region, and also international differences in energy intensities for computer related sectors are probably less than national industry averages.

The reader may well question why the analysis is based on industrial energy intensity at the national level. Would it not be more appropriate to narrow the error bound by using results for E_{SC} for individual sectors obtained from IO tables for Japan and China? This approach is indeed better in principle but faces the practical obstacles of data availability and differences in IO table definitions. While an energy IO analysis comparable to the U.S. one is available for Japan (*46*), this is not the case for China. Also, the definitions for (and numbers of) IO sectors differ greatly between the three nations, making comparison difficult. Addressing this is a challenging task beyond the scope of the current work. The above simplified analysis, however, serves its purpose of estimating lower and upper bounds on the error. This is because differences in E_{SC} of main contributing sectors to the IO correction are smaller than the wide margin granted by assuming single country production (a factor of 4 difference between the United States and China!).

To sum up, pessimistic assumptions on the accuracy of process-sum and IO parts of the analysis yield a possible range of 5000−16 000 MJ (base result: 6400 MJ) for the total energy required to manufacture a desktop system.

An important factor not considered here is technological change. As computers continue to evolve at a rapid pace, the net energy cost of manufacturing is a moving target. While one might be tempted to characterize trends by comparing this analysis with previous assessments (*3*, *4*), the method used in all are too different to allow meaningful conclusions to be drawn. No LCA study has yet to compare two generation of IT products using same methodology, though hopefully researchers will undertake such work in the future. However, it is important to emphasize that for a rapidly growing industry, efficiency improvements at the per product level do not necessary translate into reduction of environmental burdens of the industry overall. Any industry in the early phases of its life cycle also shows efficiency improvements. To whit, noting that in the 1920s that fuel mileage of a Ford model T was better than its predecessors would not have helped much to inform trends in the environmental burdens of automobiles. The key question is whether these efficiency increases are rapid enough to counteract growth. Examining growth rates in materials/energy input and product output suggests that for the computer industry, growth exceeds efficiency increases. For instance, the U.S. semiconductor industry grew an average of 15% per year over the period 1993−2000. Over the same interval electricity use of the industry grew 7.5% annually (*13*) and consumption of silicon wafers by 12% (*18*). That increases in input requirements for semiconductor manufacturing grows slower than economic output is an indicator of improvements in efficiency. However, these gains are insufficient to check increases in environmental burdens of the industry.

9. Implications for Environmental Assessment

The hybrid result of 6400 MJ required to produce a desktop system is considerably higher than the process sum result of the 1998 EU-sponsored study of 3630 MJ. This is not surprising: in general a hybrid analysis should yield a higher result than pure process-sum, as additional activities are included. A pure IO analysis of a desktop system on the other hand yields a total manufacturing energy of 7700 MJ (see the Supporting Information for details). A deconstruction of how and why IO and hybrid results are different is not attempted here. A key issue to resolve in the future is the degree to which aggregation error is reduced via hybrid analysis. Despite these remaining questions, the discussion in Section 2 on cutoff and aggregation error reiterates that increased adoption of hybrid analysis is important for improving the accuracy of LCA. I hope that the method developed here is sufficiently transparent and easily practicable such as to encourage future hybrid studies.

This study also considers how differences in data sources according to type and region affect LCA results. This is significant, ±15% for process and −32% to +300% for IO corrections. There is potential to greatly lower the error bounds on the IO portion, and future work to develop error analysis methods and compare international IO tables is needed. Even so, the analysis as it stands provides evidence that LCA results can change significantly according to the international character of the supply chain. "International corrections" are likely significant for a vast number of products and services on the market today, thus addressing geographical aspects is an important challenge for the future of life cycle assessment.

10. Implications for Societal Response

These results have bearing on how governments, firms, and civil society ought to perceive and respond to the environmental challenges posed by computers. There are two current areas of policy activity addressing computer impacts. One is one to try to keep toxic materials in computers out of landfills, as exemplified by European Union directives WEEE, which mandates recycling, and RoHS, which bans certain materials from being put into PCs. The second track is the mitigation of energy consumption in the use phase, and the most effective policy response thus far has been the Energy Star certification scheme run by the USEPA and USDOE. While these are worthy activities, the results here suggest that additional emphases are appropriate. First, the total life cycle energy associated with a computer is more significant than generally perceived: over the life cycle it is probably the most energy intensive of home devices aside from furnaces and boilers. The energy issue thus deserves more attention. Also, in contrast with many appliances, the bulk of life cycle energy use for many computers is in production, not operation, hence an emphasis on reducing energy use in the production phase is appropriate.

The fact that many computers are stored in closets for years and then thrown away while still perfectly functional suggests a "new" approach: extension of lifespan. Using computers longer via reselling or upgrading, for example, implies production of fewer new units in the first place. In addition to reducing life cycle energy use, this mitigates environmental impacts across the board. At first glance, the suggestion that computers ought to be used longer may seem facile, but the issue is actually quite complex. For instance, certain "noneconomic" obstacles constrain the market for used PCs: difficulties associated with transferring licenses for preinstalled software to secondary owners and lack of a proper blue-book of used computer prices stand out as two prominent ones (*1*). Extending lifespan is consistent with the traditional wisdom of waste management (e.g. Reduce, Reuse, Recycle) but has yet to be explicitly considered in the public response to the waste computer problem, which up to now has focused on ensuring proper treatment at the final end-of-life. Maximizing utility gained ought to be explicitly included in the agenda of activities addressing computer impacts and aggressively pursued by governments, firms, and civil society.

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Supporting Information Available

Data and assumptions used in the process-sum analysis, additive IO corrections, and a comparison of results with existing studies. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Kuehr, R.; Williams, E. *Computers and the Environment: Understanding and Managing their Impacts*; Kluwer Academic Publishers: Dordrecht, 2003.
(2) Williams, E.; Ayres, R.; Heller, M. The 1.7 kg microchip: Energy and chemical use in the production of semiconductors. *Environ. Sci. Technol.* **2002**, *36* (24), 5504.
(3) Microelectronics and Computer Technology Corporation. *Environmental consciousness: A strategic competitiveness issue for the electronics and computer industry*; 1993.
(4) Atlantic Consulting and IPU. *LCA study of the product group personal computers in the EU Ecolabel scheme*; 1998.
(5) Curran, M. *Environmental life-cycle assessment*; McGraw-Hill: New York, 1996.
(6) Bullard, C.; Herendeen, R. The energy cost of goods and services. *Energy Policy* **1975**, *December*, 268.
(7) Hendrickson, C. T.; Horvath, A.; Joshi, S.; Lave, L. B. Economic input−output models for environmental life-cycle assessment. *Environ. Sci. Technol.* **1998**, *32* (4), 184A.
(8) Bullard, C. W.; Pennter, P. S.; Pilati, D. A. Net Energy Analysis: Handbook for combining process and input−output analysis. *Res., Energy* **1978**, *1*, 267.
(9) Engelenburg, B. C. W.; van Rossum, T. F. M.; Blok, K.; Vringer, K. *Ener. Pol.* **1994**, *22* (8), 648.
(10) Heijungs, R. A generic method for the identification of options for cleaner products. *Ecol. Econ.* **1994**, *10*, 69.
(11) Joshi, S. Product environmental life-cycle assessment using input−output techniques. *J. Ind. Ecol.* **2000**, *3* (2), 95−120.
(12) Green Design Institute, Carnegie Mellon University, *Economic input−output life cycle assessment*, 2004. http://www.eiolca.net/.
(13) U.S. Census Bureau. *Annual survey of manufactures, statistics for industry groups and industries*, 1995−2000. http://www.census.gov/mcd/asmhome.html.
(14) eTForecasts. *Worldwide PC Forecast 1990−2007*, 2002. http://www.etforecasts.com/products/ES_pcww.htm.
(15) Energy Information Administration, U.S. Department of Energy. *Manufacturing Energy Consumption Survey*, 1998.
(16) Research and Statistics Department, Economic and Industrial Policy Bureau, Japanese Ministry of Economy, Trade and Industry. *The Structural Survey of Energy Consumption in Commerce and Manufacturing*, 1999. (in Japanese).
(17) UMC. *2002 Corporate Environmental Report*, 2002. http://www.umc.com/english/about/v.asp.
(18) *New metals databook*; Homat Ad: Tokyo, 2002. (in Japanese).
(19) Japan Circuit Board Association. *Status of the Printed Circuit Board Industry*, 2002. (in Japanese).
(20) Socolof, M.; Overly, J.; Kincaid, L.; Greibig, J. *Desktop Computer Displays: A Life-Cycle Assessment*; EPA document 744-R-01-004; U.S. Environmental Protection Agency: Washington, DC, 2002. http://www.epa.gov/oppt/dfe/pubs/comp-dic/lca.
(21) Electronics Industry Association of Japan. *Environmental vision for the electronics parts industry (Denshibuhinsangyou kankyou bijon)*, 1997. (in Japanese).
(22) Hewlett-Packard. *Social and Environmental Responsibility Report 2002*, 2002. http://www.hp.com/hpinfo/globalcitizenship/csr/csrreport02/hp_csr_full_lo.pdf.
(23) Boustead Consulting. *Boustead Model for life cycle inventory calculations, version 4.3*, 1999.
(24) Swiss Federal Office of Environment, Forests and Landscape and the Swiss Packaging Institute. *Economic Inventory of Packaging Database*, 1997.
(25) Design for Sustainability Program, Delft University of Technology. *IDEMAT Database*, 2001.
(26) WMC Resources Ltd. *Greenhouse challenge: Summary report 1998*, 1998. http://www.wmc.com.au/sustain/environ/greenhouse/greenhouse.pdf.
(27) Integrated Pollution Prevention and Control Office, European Commission. *Reference document on best available techniques in the glass manufacturing industry*, 2001. http://www.sepa.org.uk/guidance/ippc/bref/PDFs/glass.pdf.
(28) World Semiconductor Trade Statistics Organization. *WSTS End-Use Survey*, 2001.
(29) Van Arnum, P. Electronic materials. *Chemical Market Reporter* **2000**, *11 December*, FR8.
(30) Williams, E. Forecasting material economic flows in the global production chain for silicon. *Technol. Forecasting Soc. Change* **2003**, *70* (4), 341−357.
(31) Semiconductor equipment monitor. *Semiconductor Int.* **1999**, *22* (8), 326.
(32) Passive Component Consumption in the Computer Industry, 2001. *Passive Compon. Ind.* **2001**, *May/June*, 7.
(33) Semiconductor Industry Association, *Industry statistics*, 2002. http://www.sia-online.org/pre_statistics.cfm.
(34) PWB and flex circuit production up. *Circuits Assembly* **2001**, *12* (9), 16.
(35) Hassman, J. A record year. *PC Fab* **2001**, *24* (9), S16−S17.

(36) Chin, S. CRTs creeping up on LCDs as prices fall. *EBN* **2001**, *1288*, 50.

(37) United States Geological Service. *Mineral Industry Surveys*, 2001. http://minerals.usgs.gov.

(38) Roberson, J.; Homan, G. K.; Mahajan, A.; Nordman, B.; Webber, C. A.; Brown, R. E.; McWhinney, M.; Koomey, J. G. *Energy use and power levels in new monitors and personal computers*; Lawrence Berkeley National Laboratory: Berkeley, CA, 2002 http://enduse.lbl.gov/Info/LBNL-48581.pdf.

(39) Goldberg, C. Where do computers go when they die? *The New York Times* **1998**, *12 March*, 12.

(40) *Statistical databook of the IT Society 2002*; Seikatsu Jouhou Center: Tokyo, 2002. (in Japanese).

(41) Smulders, C. *Watching Rome Burn: PC Empires Threatened by Extending Life Cycles*; Doc. AV-14-1972; Gartner, Inc.: Stamford, CT, 2001.

(42) International Energy Agency. *Key World Energy Statistics*, 2003. http://www.iea.org/bookshop/add.aspx?id=144.

(43) *World Energy Statistics and Balances: Basic Energy Statistics – Non OECD Member Countries, Release 1*; International Energy Agency: Vienna, 2002.

(44) MacLean, H.; Lave, L. A life-cycle model of an automobile. *Environ. Sci. Technol.* **1998**, *32* (13), 322A.

(45) *World Development Indicators 2003*; World Bank: Washington, DC, 2003.

(46) Moriguchi, Y.; Nansai, K. *Energy Consumption and Carbon Emission Intensities based on the Input–Output Analysis*; National Institute of Environmental Studies: Tsukuba, Japan, 2003.

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