Energy Model for End-of-Life Computer Disposition

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Discussion

It has been postulated that recycling end-of-life computers and related components partially offsets the energy requirements of newly manufactured computers. This benefit can arise from

- 1) refurbishing and reselling components and systems,
- 2) "cannibalizing" computers of their high-grade parts such as sheet steel and aluminum, and
- 3) primary material source reduction through true recycling of clean and separated metals, plastics, and glass.

This research program undertook an effort to study and quantify this hypothesis.

Scope

A high level model was constructed to estimate and graphically depict the energy impact of a complete end-of-life computer disposition process. This is done by calculating the energy expenditure associated with producing a new (BOL) computer, both with and without maximum processing and disposition of the end-of-life computer that the new unit is in theory replacing.

Disposition Paths

The model assumes three possible disposition avenues for the end-of-life computer:

- 1) recycling (reduction of the computer to primary clean materials by mechanical or thermal processes, and reuse of these materials as feed stock in production of materials for new computers),
- 2) cannibalization (full or partial disassembly of end-of-life computers in order to take advantage of whole high grade-material parts, which can be more readily processed into new parts than can primary feed stock), and
- 3) refurbishing (reconditioning, repackaging, and resale of blemished, easily repaired, or slightly obsolete, but still viable components).

Application

The energy model runs on a desktop spreadsheet, using data from a variety of sources including process equipment, business practices, engineering estimates, rules of thumb, material databases, commodity value data, etc. Mass flows throughout the model are calculated at the constituent level. Transportation energy is included, with geographical factors assumed. The model assumes that tertiary energy can be recovered from waste plastic incineration.

The model is documented, configurable, and easily updated. A common nomenclature and data structure are shared with the process and business models discussed elsewhere. The model could be expanded to cover other end-of-life electronic products, such as video and communications devices, given the availability of applicable data.

Description of Model

The energy model flow diagram is shown in figure 1. This diagram shows mass flows possible for disposition of a typical end-of-life computer (or, generally, any electronic product), and also shows how re-circulation is possible between paths in order to account for all masses (for instance, a portion of the Recycled stream feeds the Refurbish stream, allowing for the use of valuable components in a computer that as a system is not worth refurbishing).

Inputs and Variables

Mass Distribution

Model calculations are made based on the mass make-up of a typical desktop personal computer. Mass assay data for such a device is given in table 1. This table lists elemental or compound constituents by mass percentage, and is based on aggregate data by representative computers. Such computers average a total mass of 31.7 kg (70 lb).

Definition of Inputs and Variables

Table 2 is a list of all energy model variables. The list includes variable name, description, primary and secondary units, and type. "Type" indicates whether the variable is an input or output variable--input variables can be considered independent variables and are manually or iteratively entered into the model, while output (dependent) variables are calculated by various algorithms in the model.

Specific Energy Data

The differential, or specific energy variables (DExxx) are input variables that represent the energies associated with processing material in the associated branch of the model, and are obtained from engineering handbook data or practical operating experience. The energy variables (Exxx) are calculated energy terms in units of kW-h.

DEPRI, DESEC

DEPRI and DESEC represent the primary and secondary material processing energy, respectively. These represent the total specific energy required to process the material from raw materials (ore, petroleum feedstock, etc.) followed by refining, forming, heat treating, or other process step, resulting in a finished material ready for use in manufacturing. Values for DEPRI and DESEC are estimated by calculating the appropriate energy densities for processing of glass,

metals, and plastics, and integrating these constituents into single estimates of DEPRI and DESEC that are representative of the complete desktop computer.

For glass, the model uses average process energy data for production of lighting, electronic, and technical glass. [2] The model uses 1976 data. We believe this will conservatively underpredict actual energy required because trendlines in 1976 indicated a 4% per year reduction in process energy. Process steps for which energy data breakdowns were reported are listed in table 3.

The average energy requirement for production of this class of glass was reported to be 27.2×106 Btu/ton (8.79 kW-h/kg). Using the breakdown by process steps, we calculate estimated model variables as follows:

$$\text{DEPRI (glass)} = 5.05 \text{ kW-h/kg}$$

$$\text{DESEC (glass)} = 3.74 \text{ kW-h/kg}$$

Total processing energy for finished plastic goods (average, all grades and tempers) is approximately 8.79 kW-h/kg. Complete plastic data by process step was not available; assuming that the breakdown between primary and secondary processing for plastic is similar to that for glass, we estimate:

$$\text{DEPRI (plastic)} = 5.05 \text{ kW-h/kg}$$

$$\text{DESEC (plastic)} = 3.74 \text{ kW-h/kg.}$$

While many metals can be recycled at energy costs only 10 to 20% as high as these extraction energies, aluminum is the most energy-intense metal because of the high electrical power required to refine bauxite ore by electrolysis. The smelting energy for various metals is shown in table 4. [3,4]

For metals, the model uses a weighted calculation based on mass constituency in a typical PC (table 5). The major metallic constituents are aluminum, iron (steel), copper, and nickel. The analysis uses the mass percentage of the individual metal in the typical PC, the metal's percentage relative to other metals, and the metal's primary energy requirement to calculate its primary energy contribution to the PC.

The weighted average primary energy content for metals (based on smelting energy requirements) in a typical PC is estimated to be:

$$\begin{aligned}\text{DEPRI (metals)} &= 9.780 \text{ kW-h/ton} \\ &= 10.78 \text{ kW-h/kg.}\end{aligned}$$

First order estimates of processing energy were generated by using weighted average of the calculations for the individual material constituents of the generic computer studied. Weighting coefficients were drawn up from the computer mass breakdown. Using this simple approach, we estimate:

$$\text{DEPRI} = 3.22 \text{ kW-h/kg}$$

$$\text{DESEC} = 8.29 \text{ kW-h/kg}$$

DETERT

On average, existing waste-to-energy (WTE) plants produce 451.3 kW-h net for every ton of municipal solid waste (MSW) produced.[5] Residual plastic contains heat value (recoverable internal energy) of approximately 20,000 Btu/lb, which equates to 12.9 kW-h/kg.[6]

DETRANx

The energy cost of transportation for PC materials was estimated from reported transportation costs and calculated fuel energy content, as follows. Average transportation costs

for recycled materials is \$0.12/mile-ton. [7] Using current fuel prices, specific gravity, and the lower heating value [8], the generalized transportation energy requirement is found:

$$\begin{aligned} \text{DETRAN}_x &= \left(\frac{\$0.12}{\text{mile} - \text{ton}} \right) \cdot \left(\frac{\text{gal}}{\$1.0} \right) \cdot \left(\frac{8\text{lb}}{\text{gal}} \right) \cdot \left(\frac{18,800\text{Btu}}{\text{lb}} \right) \cdot \left(\frac{2.205\text{lb}}{\text{kg}} \right) \cdot \left(\frac{\text{kW} - \text{h}}{3412.12\text{Btu}} \right) \\ &\quad \cdot \left(\frac{\text{mile}}{1.609\text{km}} \right) \cdot \left(\frac{\text{ton}}{2,000\text{lb}} \right) \\ &= 0.0036 \frac{\text{kW} - \text{h}}{\text{km} - \text{kg}} \end{aligned} \quad (1)$$

DEASBL

The specific energy term DEASBL is used to represent that energy expended in assembly of already-manufactured subcomponents into computer systems. This term is intended to describe near-final processing of beginning-of-life computers, and does not include energy of original processing, fabrication, and manufacture of parts and sub-assemblies.

The value chosen for this specific energy term for purposes of this model was derived from data supplied by Dell Computer Corporation.[9] Dell's business model involves outsourcing of most components and subassemblies that make up their product lines, and so plant energy expended in a Dell manufacturing cell very closely fits the definition of DEASBL.

During a one-year production cycle (which accounts for seasonal variability), Dell consumed 3.066 million kW-h in a plant that produced 1.735 million desktop computer units. This energy does include so-called hotel loads (HVAC, lighting, appliances), both for the plant and support functions officed in the same building. While the latter does not represent energy used directly in assembly of product, it can be argued that any assembly operation will require similar ancillary activities, and that these require some energy.

Using Dell's data, the DEASBL term is estimated as:

$$\begin{aligned} \text{DEASBL} &= \left(\frac{3,066,000 \text{ kW-h}}{1,735,000 \text{ units}} \right) \cdot \left(\frac{\text{unit}}{70 \text{ lbs}} \right) \cdot \left(\frac{2.205 \text{ lb}}{\text{kg}} \right) \\ &= 0.056 \frac{\text{kW-h}}{\text{kg}} \end{aligned} \quad (2)$$

DEMFG

The specific energy term DEMFG is supposed to represent the total energy content required in subcomponent fabrication, manufacture, and assembly into computers. For example, in a truly vertical computer factory, DEMFG would include the energy content of the CPU and all other integrated circuit chips, printed wiring boards, chassis, cases, drives, and any other contained peripherals. Because no computer maker is truly vertical, it is difficult to extract the true energy content of a computer without having used modern life cycle analysis or design for environment (LCA/DFE) tools. Systematic use of such tools as part of new product development is only now becoming a near term priority for computer OEM's.

For the purpose of the energy model, DEMFG was estimated using published data from Compaq Computer Corp.[10] Compaq reported an average manufacturing energy content in 1994 of approximately 45 kW-h per computer. They also documented a 34% per year energy reduction trend, although it was not reported whether this trend is due to successful energy conservation designs and processes, or increased outsourcing of computer components. The latter is likely the bigger factor.

Still, using Compaq's data, and assuming continuation of their energy reduction trend, DEMFG for modeling purposes was estimated as:

$$\text{DEMFG} = 0.617 \text{ kW-h/kg}$$

DEREC, DEREf, DECAN

Utility consumption and throughput data from a private electronics recycling facility was used to estimate the energy required to recycle typical end-of-life computers. The resulting value used by the model is:

$$\text{DEREC} = 0.31 \text{ kW-h/kg.}$$

Refurbishment and cannibalization energy data is not readily available. The model uses the following assumptions:

$$\text{DEREF} = 1/2 \text{ DEMFG}$$

$$\text{DECAN} = 1/2 \text{ DEASBL}$$

Calculations

Mass

The mass coefficient variables are used to calculate the various fractional divisions in the flow of material through the energy model. All such variables actually represent a series of coefficients, corresponding to the mass constituent array, so all mass in the model is accounted for by constituent. Values for the coefficients are chosen based on engineering estimates from past performance of recycling operations, but real data from pilot plants can easily be incorporated when available.

The mass coefficients chosen for the first use of the model are given in table 6.

Energy

Individual energy terms are simply calculated by taking the product of the corresponding mass and specific energy. Table 7 summarizes the individual energy terms and their calculation, for the baseline case assumptions.

Benchmarking the Model

Assumptions

Two cases were established as a benchmark illustration of the model. Case 1 assumes that optimum use is made of end-of-life computer materials and components, using state of the art technology. This set of assumptions is embodied in the mass coefficients laid out in table 6, showing the relative proportions of the mass constituents going to the cannibalization, recycling, and refurbishment streams, plus waste. Case 2 simply assumes that the entire end-of-life computer is landfilled, except that plastic energy recovery through waste-to-energy incineration is allowed.

Results

The research presented here explored the energy conservation potential available if electronic products are recycled. The postulate held that beneficial direct re-use of materials would save significant amounts of energy by replacing source materials. Even accounting for the process energy required in recycling, the model tested this hypothesis for the benchmark case of a typical desktop personal computer.

Figure 2 illustrates the results of the benchmark model case comparison. Approximately 22% energy savings is realized in the Case 1 vs. Case 2 scenario. From the graph, it is apparent that most of this savings is in primary energy, with other significant savings in secondary energy and transportation energy. This is consistent with the expectation that the greatest benefit from recycling or other reuse of end-of-life computers is in primary source reduction for new (BOL) computers. Saved transportation energy for waste materials is also significant.

Energy Impact

In the framework of the above discussion, it is possible to talk about the "recoverable energy content" of an end-of-life electronic product. Table 8 gives a rough mass breakdown of the typical desktop computer system, along with approximate energy savings available through proper disposition.

The model predicts that a total of approximately 2,130 kW-h is required to manufacture a new desktop computer system. This could be considered "Case 0"; comparison with the model results shown in Figure 2 then predicts a energy savings per new computer of 69 kW-h when only tertiary energy is recovered (Case 2) and 530 kW-h when all recycling avenues are used most effectively (Case 1).

Approximately 13.7 million PC's will be either recycled, stockpiled, or landfilled from all US sources in 1997.[11] If the electronic products recycling industry were able to absorb this volume efficiently, the energy model predicts a total energy savings of 7.26 billion kW-h.

Future Improvements

This is a coarse model in that specific energies and mass inventories are not calculated at the individual material level, but are aggregated by similar materials (metals, glass, plastic). Also, much remains to be gained in more complete energy data for specific metal alloys, plastic grades, and process activities. These are closely related to the functionality included in modern design for environment (DFE) and life cycle assessment (LCA) methodology. In planned future research programs, the authors hope to improve and expand energy analyses for electronic products through the use of DFE and LCA tools specifically tailored for this purpose.

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Table captions

Table 1. Mass breakdown of a typical desktop computer

Table 2. Coefficients and variables used in model

Table 3. Energy distribution by glass process steps

Table 4. Smelting energy requirements for various metals

Table 5. Calculation of average primary energy density requirements for metals

Table 6. Mass coefficients used in calculating model mass streams

Table 7. Energy term calculations

Table 8. Energy conservation "content" of a typical end-of-life desktop personal
computer

Figure captions

Figure 1. Math models for flow in end-of-life computer disposition. Each submodel (DEPRI, DEREK, etc) is described in text

Figure 2. Energy model – case 1 and case 2 comparison

Table 1. Mass breakdown of a typical desktop computer

Item	Percent by Mass
plastic	22.9907
lead	6.2988
aluminum	14.1723
germanium	0.0016
gallium	0.0013
iron	20.4712
tin	1.0078
copper	6.9287
barium	0.0315
nickel	0.8503
zinc	2.2046
tantalum	0.0157
indium	0.0016
vanadium	0.0002
terbium	0
beryllium	0.0157
gold	0.0016
europium	0.0002
titanium	0.0157
ruthenium	0.0016
cobalt	0.0157
palladium	0.0003
manganese	0.0315
silver	0.0189
antimony	0.0094
bismuth	0.0063
chromium	0.0063
cadmium	0.0094
selenium	0.0016
niobium	0.0002
yttrium	0.0002
rhodium	0
platinum	0
mercury	0.0022
arsenic	0.0013
silica	24.8803

Table 2. Coefficients and variables used in model

Name	Description	Primary Unit	Secondary Unit	Type
Ccan	coeff. of cannibalized stream, start (by material)	--	--	Input
Ccan1	coeff. of cannibalized stream, final (by material)	--	--	Input
Ccan2	coeff. of cannibalized stream, diverted (by material)	--	--	Input
Crec	coeff. of recycled stream, start (by material)	--	--	Input
Crec1	coeff. of recycled stream, final (by material)	--	--	Input
Crec2	coeff. of recycled stream, diverted (by material)	--	--	Input
Cref	coeff. of refurbished stream, start (by material)	--	--	Input
Cwas	coeff. of total waste stream (by material)	--	--	Input
Cwas1	coeff. of waste recovered (by material)	--	--	Input
Cwas2	coeff. of waste disposed (by material)	--	--	Input
DEASBL	sp. energy spent in assembling BOL computer components	kW-hr/kg	Btu/lb	Input
DECAN	sp. energy for processing cannibalized stream	kW-hr/kg	Btu/lb	Input
DEMFG	sp. energy spent in manufacturing BOL computer components	kW-hr/kg	Btu/lb	Input
DEPRI	sp. energy spent in processing new materials from primary form	kW-hr/kg	Btu/lb	Input
DEREC	sp. energy for processing recycled stream	kW-hr/kg	Btu/lb	Input
DEREF	sp. energy for processing refurbished stream	kW-hr/kg	Btu/lb	Input
DESEC	sp. energy spent in processing new materials from secondary form	kW-hr/kg	Btu/lb	Input
DETERT	energy recovered from incineration of waste stream	kW-hr/kg	Btu/lb	Input
DETRANP	sp. energy spent in transporting primary recycled stream stream	kW-hr/kg-m	Btu/lb-mi	Input
DETRANS	sp. energy spent in transporting secondary recycled stream stream	kW-hr/kg-m	Btu/lb-mi	Input
DETRANW	sp. energy spent in transporting waste stream	kW-hr/kg-m	Btu/lb-mi	Input
mama	mass assay master array (by material)	kg	lb	Input
EASBL	energy spent in assembling BOL computer components	kW-hr	Btu	Output
ECAN	energy for processing cannibalized stream	kW-hr	Btu	Output
EMFG	energy spent in manufacturing BOL computer components	kW-hr	Btu	Output
ENET	net energy differential	kW-hr	Btu	Output
EPRI	energy spent in processing new materials from primary form	kW-hr	Btu	Output
EREC	energy for processing recycled stream	kW-hr	Btu	Output
EREF	energy for processing refurbished stream	kW-hr	Btu	Output
ESEC	energy spent in processing new materials from secondary form	kW-hr	Btu	Output
ETERT	energy recovered from incineration of waste stream	kW-hr	Btu	Output
ETRANP	energy spent in transporting primary recycled stream stream	kW-hr	Btu	Output
ETRANS	energy spent in transporting secondary recycled stream stream	kW-hr	Btu	Output
ETRANW	energy spent in transporting waste stream	kW-hr	Btu	Output
Mcan	mass of cannibalized stream, start (by material)	kg	lb	Output
Mcan1	mass of cannibalized stream, final (by material)	kg	lb	Output
Mcan2	mass of cannibalized stream, diverted (by material)	kg	lb	Output
Mrec	mass of recycled stream, start (by material)	kg	lb	Output
Mrec1	mass of recycled stream, final (by material)	kg	lb	Output
Mrec2	mass of recycled stream, diverted (by material)	kg	lb	Output
Mref	mass of refurbished stream, start (by material)	kg	lb	Output
Mwas	mass of total waste stream (by material)	kg	lb	Output
Mwas1	coeff. of waste recovered (by material)	kg	lb	Output
Mwas2	mass of waste disposed (by material)	kg	lb	Output

Table 3. Energy distribution by glass process steps

Process	Process Step	Percent Total Energy
Primary	Batch Handling	1
	Refining/Melting	55
Secondary	Forming	13
	Post-Forming	19
	Product Handling	4
	Space Conditioning	8

Table 4. Smelting energy requirements for various metals

Material	Energy Required [kW-h/ton]
Iron Ore (smelting)	1650-2400
Steel (melting)	450-700
Steel (melting + refining)	600-750
Lead	40-50
Tin	35-50
Zinc	80-100
Copper/Brass	250-400
Aluminum	22,000-27,000

Table 5. Calculation of average primary energy density requirements for metals

Metal	% Total PC (wt) [%]	% Total Metal (wt)[%]	Primary Energy Requirement [kW-h/ton]	Primary Energy Contribution [kW-h/ton]
Aluminum	14	33	25,000	8250
Iron	20	48	2,000	960
Nickel	0.8	02	26,000	520
Copper	7	17	300	50
TOTAL				9780

Table 6. Mass coefficients used in calculating model mass streams

Material	CAN	can1	can2	REC	rec1	rec2	REF	WAS	was1	was2
Plastics	0.05	0.05	0	0.7	0.35	0.2	0.25	0.15	0	0.15
Aluminum, Iron, Copper	0.7	0.7	0	0.2	0.2	0	0.1	0	0	0
All Other Metals	0	0	0	0.8	0.7	0	0.2	0.1	0.1	0
Glass	0	0	0	1	0.5	0.2	0	0.3	0.3	0

Table 7. Energy term calculations

Term	Case 1	Case 2
ECAN	(MCAN)(DECAN)	0
EREC	(MREC+MCAN2)(DEREC)	0
EREF	(MREF+MREC2)(DEREF)	0
ETERT	(MWAS2)(DETERT)	0
ETRANW	(MWAS1)(DETRANW)(dW)	(MTOT)(DETRANW)(dW)
ETRANP	(MREC1)(DETRANP)(dP)	0
ETRANS	(MCAN1)(DETRANS)(dS)	0
EPRI	(MTOT-MREC1-MCAN1)(DEPRI)	(MTOT)(DEPRI)
ESEC	(MTOT-MCAN1)(DESEC)	(MTOT)(DESEC)
EMFG	(MTOT)(DEMFG)	(MTOT)(DEMFG)
EASBL	(MTOT)(DEASBL)	(MTOT)(DEASBL)

Table 8. Energy conservation "content" of a typical end-of-life desktop personal computer

MATERIAL	MASS [kg]	ENERGY SAVINGS		AVAILABLE VIA...		TOTAL
		<i>Cannibalization</i>	<i>Recycling</i>	<i>Refurbishment/ Reuse</i>	<i>Recovery</i>	
Primary metals (aluminum, copper, steel)	13.2	132.0	37.7	18.9	0	188.6
Primary Plastics (ABS, polycarbonate)	6.2	2.6	36.0	12.8	0	51.4
Other metals	3.3	0	66.1	0	0	66.1
Other Plastics	1.1	0	0	0	12.5	12.5
Glass	7.9	0	52.4	0	0	52.4
Total Mass [kg]	31.7		Recoverable Energy Density [kW-hr/kg]			11.7
			Recoverable Energy [kW-hr]			371.1

1002.0046

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Born in Austin, Texas, Mr. Aanstoos served in the United States Navy for six years as a supervisor of nuclear-powered ship propulsion systems. Since graduation in 1980, he has been a member of the CEM-UT engineering staff. As Project Engineer for industrial applications at CEM-UT from 1980 to 1990, he conducted analytical and experimental research in pulse welding, pulse heating, pulse consolidation, high energy forming, and other high energy rate processes. He rebuilt the 10 MJ disk-type homopolar generator system at CEM-UT as the primary power supply in these areas. He also participated in the design and commissioning of the 900-MA, 60-MJ modular homopolar generator.

In addition, Mr. Aanstoos designs and tests high current, rapid-response fixtures and controllers, high current density collectors and switches, and auxiliary systems. He models iron- and air-core homopolar generator systems and conducts related parametric studies. He has served as Project Engineer for the design, testing, and implementation of a 5.0-MA, 500-MJ high current switching and energy dissipation system, and for design and fabrication of a 200-MJ rotor failure test bunker. He designed and fabricated a 100-kw low voltage dc traction motor for electric vehicles.

Mr. Aanstoos was a member of a research team tasked with gathering and characterizing energy use and intensity data for all State of Texas owned and leased buildings. As part of a research effort in energy conservation potential in recycling of electronic products, he conducted energy modeling and simulation studies in the analysis of disposition strategies for end-of-life computers. He organized and hosted the Glass Roundtable, an informal association of stakeholders in the responsible disposition of leaded cathode ray tube glass.

Mr. Aanstoos is the author of more than 40 technical articles and reports. In 1985, he was awarded the American Welding Society's A.F. Davis Award for machine design. He holds a patent in homopolar welding technology. He has served on various panels including the Manufacturing Technology Group of the Strategic Defense Initiative Organization. He has served on various University committees and as a reviewer for the IEEE Transactions on Magnetics, and is a Member of the American Society of Mechanical Engineers.

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