ELSEVIER

Resources, Conservation and Recycling 38 (2003) 1–22

Resources Conservation & Recycling

www.elsevier.com/locate/resconrec

Emergy indices and ratios for sustainable material cycles and recycle options

M.T. Brown [a,*], Vorasun Buranakarn [b]

[a] Department of Environmental Engineering Sciences, Box 116350, University of Florida, Gainesville, FL 32611, USA

[b] Faculty of Architecture, Chulalongkorn University, Wangmai, Patumwan, Bangkok 10330, Thailand

Received 3 April 2001; received in revised form 27 June 2002; accepted 2 July 2002

Abstract

Emergy (spelled with an m) is the energy required to make a service or product expressed in energy of one form. The emergy used in the life cycles of major building materials as well as the emergy inputs to waste disposal and recycle systems were evaluated. Emergy per mass (expressed as solar emergy per gram [sej/g]) for building materials varied from a low of 0.88 E9 sej/g for wood to a high of 12.53 E9 sej/g for aluminum. Generally, emergy per mass is a good indicator of recycle-ability, where materials with high emergy per mass are more recyclable. Recycling added between 1 (cement) and 234% (wood) to the emergy inputs per gram of building materials. The analysis of materials suggested that recycle of wood may not be advantages on a large scale, but metals, plastic, and glass have very positive benefits. Two types of solid waste disposal systems were evaluated: municipal solid wastes (MSW), and construction and demolition wastes (C&D wastes). Expressed as emergy, the costs of collecting, sorting and landfilling (for 25 years) MSW were 251.0 E6, 8.2 E6 and 37.9 E6 sej/g, respectively. The costs of demolition, collection, sorting and landfilling C&D wastes were 49.0 E6, 21.7 E6, 6.7 E6, and 11.7 E6 sej/g, respectively. Three different recycle trajectories were identified and analyzed: (1) material recycle (the 'standard' recycle of a material where it is used again as the same material [i.e. glass bottles recycled and made again into glass bottles]); (2) by-product use (where a by-product from some process is used to make something entirely different [i.e. flay ash in concrete]); and (3) adaptive reuse (where a material after recycle is reused for an entirely different purpose [i.e. plastic milk cartons are converted into plastic lumber]). Three recycle indices measuring the benefits of various recycle systems suggested that materials that have large refining costs have greatest potential for high recycle

---

* Corresponding author

E-mail addresses: mtb@ufl.edu (M.T. Brown), vorasun.b@chula.ac.th (V. Buranakarn).

PII: S0921-3449(02)00093-9

benefits and that highest benefits appear to accrue from material recycle systems, followed by adaptive reuse systems and then by byproduct reuse systems.

Keywords: Emergy; Materials; Life cycle; Recycle; Solid wastes

---

1. Introduction

All systems recycle. The biosphere is a network of continually recycling materials and information in alternating cycles of convergence and divergence. As materials converge or become more concentrated they gain in quality, increasing their potentials to drive useful work in proportion to their concentrations relative to the environment. As their potentials are used, materials diverge, or become more dispersed in the landscape, only to be concentrated again at another time and place. Fitting the patterns of humanity to these material cycling pathways has become paramount in importance as our numbers and influence on the biosphere increases.

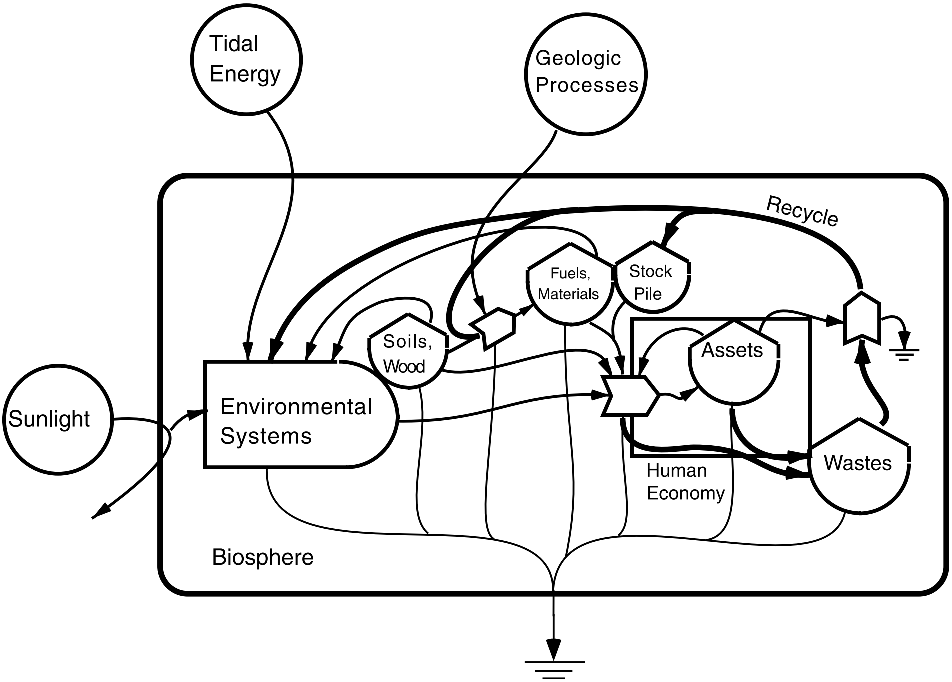


Fig. 1. The material and energy pathways of the biosphere showing the convergence of materials into the assets of humans and emphasizing the waste and recycle pathways. Numbered pathways of material recycle are as follows: (1) materials that are recycled back to the environment through land fills and litter; (2) materials recycled via geologic processes such as erosion and sedimentation; and (3) materials actively recycled into the stockpile of materials used by economic systems using nonrenewable energies.

The diagram in Fig. 1 illustrates the convergence of materials into human economic assets, their eventual disposal, and three pathways of recycle. Some materials are recycled back to the environment through landfills or disposed across the landscape (i.e. litter) shown by the pathway numbered one. Some materials are recycled via geologic processes through erosion sedimentation (pathway #2), and some are actively recycled into the stockpile of materials used by economic systems, for instance steel recycle (pathway #3). It is this third pathway that is the subject of this paper.

1.1. *Emergy-life-cycle-assessment*

Life cycle assessment is an important tool for evaluating the commitment of resources, energy, and human capital and the environmental degradation that results from choices regarding materials and products. The main drawback in life cycle assessment is that the rankings and indicators that result are of mixed units (e.g. CO_2 production, energy consumed, human capital required etc.). The mixed units often make comparative analysis between products or services difficult.

In this paper, we use an emergy-life-cycle-assessment methodology as a way of accounting for materials, energy, and human services, within the same quantitative framework. Emergy-life-cycle-assessment could add additional quantitative indices for comparison of materials within a life cycle assessment.

In the following sections, we summarize the general conceptual basis of the emergy methodology, describe the methodology for conducting an emergy evaluation, and then apply the evaluation to several materials and recycle trajectories.

1.2. *Energy and emergy*

The theoretical and conceptual basis for the emergy methodology is grounded in thermodynamics and general system theory. Evolution of the theory during the past 30 years was documented by Odum in *Environmental Accounting* (1996) and in the volume edited by Hall titled *Maximum Power* (Odum, 1995).

Emergy accounts for, and in effect, measures quality differences between forms of resources and energy. Emergy is an expression of all the energy (and resources) used in the work processes that generate a product or service in units of one type of energy. By definition, emergy is the amount of energy of one form (usually solar) that is required, directly or indirectly, to provide a given flow or storage of energy or matter. The ratio of emergy required to make a product to the energy of the product is called transformity. Solar emergy is expressed in solar emergy joules (called solar emjoules and abbreviated sej), while solar transformity is a ratio of solar emergy joules per Joule of output flow (sej/J). Materials are expressed as emergy per mass (sej/g).

In the most general sense, the total emergy driving a process is a measure of the activity required and converged to make that process possible. It is a measure of the work (in both the past and present) necessary to provide a given resource or service, be it the present stock of iron ore or oil deep in the planet or services provided by labor. Emergy content of major raw material resources of the earth are evaluated using the total emergy driving the biosphere and total quantities of global resources (Odum, 1996, 2000). Emergy of human services is evaluated using the total emergy required by workers for their support. The emergy of any product or process is the sum of the emergies used in both the past and present to make it.

Transformities of the main natural flows in the biosphere (wind, rain, ocean currents, geological cycles, etc.) are calculated as the ratio of total emergy driving the biosphere as a whole to the actual energy of the flow under consideration. The transformity of solar radiation is assumed equal to one (1). Transformities have been calculated for a wide variety of energies, materials, and services (Odum, 1996, 2000; Brown and Ulgiati, 1999; Ulgiati and Brown, 1999; Ulgiati et al., 1994).

Emergy quantifies energy and material resources as well as environmental and human services within a common framework. It reflects differences in the quality of energy and resources. Embodied in the emergy of products are the services provided by the environment, which are free and outside the monied economy Brown and Ulgiati, 2001; Ulgiati and Brown, 2001. By accounting for quality and free environmental services, resources are not valued by their money cost or society's willingness to pay, which are often very misleading, especially if decisions need be made regarding sustainability or environmental costs. They are misleading because in no way does society's willingness to pay reflect environmental costs or services. For a more full treatment of this topic see Brown and Ulgiati (1999).

2. Methods

2.1. Emergy evaluation

Emergy accounting (Odum, 1996) uses the thermodynamic basis of all forms of energy, materials and human services, but converts them into equivalents of one form of energy. Emergy accounting is organized as a top down approach where first systems diagrams of processes are drawn to organize evaluations and account for all inputs and outflows from processes. Tables of the actual flows of materials, labor and energy are constructed from the diagrams and all flows are evaluated. The different units for each flow are multiplied by transformities to convert them to solar emergy.

In practice, the use of emergy as a quantitative measure, allows comparison across disparate materials, energies and processes, that because of their different qualities (forms) are not usually directly comparable. Fig. 1 illustrates how emergy is assigned to an output flow, and how the transformity of an output flow is calculated. A material input from the environment on the left is 'up-graded' in the transformation process. The process has three inputs (two energy inputs and the material input) whose transformities are known from previous calculations. Therefore, the emergy of each input is its energy (E_0, E_1, E_2) multiplied by its transformity. The total emergy of the output is the sum of the emergy inputs, and the transformity of the output is its emergy divided by its energy.

The emergy in human services is estimated as the dollar costs of human services multiplied by the average ratio of emergy to money for the economy within which the process being evaluated is located. The emergy to money ratio for an economy is calculated by dividing the total emergy used in an economy by the total circulation of money in the economy estimated by Gross Domestic Product. To do this, an emergy evaluation of the economy is conducted as a separate exercise. In the USA for the period of these evaluations, the emergy to money ratio was 1.2 E12 sej/$ (Odum, 1996). Therefore, services were evaluated by multiplying dollars paid for service by 1.2 E12 sej/$.

2.2. Emergy evaluation of materials

The emergy of nine materials used in buildings were evaluated, including: wood, concrete, cement, glass, clay brick, ceramic tile, steel, plastic, and aluminum. Emergy in materials was evaluated by analyzing inputs of raw resources, energy, and labor obtained from national statistics for each material. Inputs of materials, energy and labor were tabulated and converted to emergy using emergy per mass, transformities, and emergy per dollar ratio (Odum, 1996, 2000). Emergy for each input was then summed to obtain the total emergy per gram of material produced.

2.3. Emergy evaluation of construction, demolition, and disposal

Evaluation of the emergy used in construction was based on one building (1012 m^2) on the University of Florida campus where total material take offs were used to evaluate the weights of various building materials used in construction, as well as fuels, electricity and labor. The resulting emergy per gram was the total emergy used in construction (fuels, electricity, machines, and labor) divided by the total mass of material in the building.

Demolition emergy was evaluated using the total emergy in fuels, electricity, machines, and labor consumed in demolishing a 2662 m^2 building on the University of Florida Campus. The resulting emergy per gram of demolished material was calculated as the total emergy used in demolition divided by the total mass of material in the building.

Two different material disposal systems were evaluated: (1) municipal solid waste (MSW); and (2) construction and demolition wastes (C&D wastes). Data for the MSW evaluation were obtained from the City of Gainesville, FL including the material, energy and labor costs of collection, sorting and landfilling (25-year life span) the annual solid waste load of the city. Data for the C&D wastes evaluation were obtained from a C&D sorting facility in Gainesville, FL, while transportation costs were averaged based on haul distance and emergy costs per mile.

Evaluation of the emergy used for land filling of MSW was based on data from the City of Gainesville, FL land fill and included total fuels, electricity, machines, and labor. The resulting emergy per gram of land filled material was calculated as the total emergy used by the land fill divided by the total mass of material in the land fill on an annual basis and including estimates for closure and maintenance after closure.

Evaluation of the emergy used for land filling C&D wastes was based on data for the MSW land fill with the exception that drainage system and liner were not included. The resulting emergy per gram of land filled C&D material was calculated as the total emergy used by the landfill divided by the total mass of material in the landfill.

2.4. Comparison of major building materials

To compare different materials several indices were calculated using emergy content and dollar costs. The emergy content of each material was analyzed using standard emergy evaluation techniques. Total emergy commitment for material products was calculated as the sum of emergy content of the material and emergy of production. Life cycle emergy of materials was calculated as the sum of emergy in the material product with demolition, collection, and disposal costs.

Using building cost code calculators (RS Means, 1998) the dollar costs per gram of material were determined for each material and expressed as grams per dollar (g/$). Prices of building materials are usually given in varying units of measure such as dollars per board foot (lumber) dollars per cubic-foot (concrete) and so forth. To standardize price and better utilize price information, prices were expressed as mass of material per dollar.

The following indices were calculated for each material:

Price (P)—the ratio of dollars paid to mass of material received. $P = \text{g/\$}$.

Emergy per mass—the total emergy required to make a material per unit of mass. Units are sej/g.

Emprice—the ratio of the emergy to price. The units of emprice are sej/$. It is an expression of the emergy one receives in the material for each dollar paid for the material.

Buyer advantage—the emprice divided by the average emergy per dollar in the USA economy. Buyer advantage is the ratio of the emergy received to the average emergy represented by the money spent for the material.

Life cycle emergy intensity—the sum of emergy required to make a building material, and dispose of it, either through recycle or landfilling. Units are sej/g.

2.5. Recycling indices

We developed several emergy indices of recycle effectiveness. The indices are defined using the aggregated patterns of material use in Fig. 2. In the top diagram, the refining of raw materials entering from the left (R1) requires emergy inputs of fuels, goods and services (the sum of which is equal to A1). Transforming the refined materials into a material product requires emergy inputs of fuels, goods, and services (summed, they equal B1). The emergy in the product is the sum of the emergy in the raw materials and the emergy inputs for refining and transforming ($R1+A1+B1$).

After use, the product is disposed of, requiring emergy inputs of fuels, goods and services for collection and disposal (C1). The emergy of disposal includes lifetime requirements for maintenance and operation of the landfill as well as the emergy used in collection (F1). The emergy content of the waste product (E1), is the sum of all emergy inputs (R1 + A1 + B1 + C1 + F1).

An aggregated recycling system is shown in the bottom diagram in Fig. 2. Raw resources inflow and are refined requiring an emergy input of fuels goods and services (A2). At this point in the process, the recycled material is substitutable for the output from the refining stage; thus the input to the transformation stage is composed of some material from the raw resource pathway, and some material from the recycle pathway. Transformation requires an emergy input of fuels, goods and services (B2). The emergy in the product is the sum of the emergy in the raw materials and all the emergy inputs required to maintain the cycle of the material system (R2 + A2 + B2 + C2 + F2).

Several recycle indices were calculated for the materials evaluated. Using Fig. 2 as a guide the following indices were calculated and compared for each material and recycle pattern:

Recycle Benefit Ratio (*RBR*)—the ratio of emergy used in providing a material from raw resources (A1) to the emergy used in recycle (C2 + F2). RBR = A1/(C2 + F2).

Recycle Yield Ratio (*RYR*)—the ratio of emergy in recycled material (R2 + A2 + B2) to emergy used for recycle (C2 + F2). RYR = (R2 + A2 + B2)/(C2 + F2).

Landfill to Recycle Ratio (*LRR*)—the ratio of emergy required for landfilling a material (C1 + F1) to the emergy required for recycle (C2 + F2). LRR = (C1 + F1)/(C2 + F2).

2.6. Recycle trajectories

The recycle systems for each of the main building materials were evaluated to compare costs and benefits of recycle. We identified three different recycle trajectories (shown in Fig. 3), material recycle, by-product use, and adaptive reuse. Material recycle is a pattern in which materials are reused as part of the raw material inputs to produce the same or similar product. By-product use is a recycle pattern in which the by-product of a process is used in the production of another product. Adaptive reuse involves the reuse of a post consumer product as input for a different product. Each of the material recycle systems are described briefly below.

Cement with fly ash—in this material recycle system, fly ash from a coal fired power plant is substituted for a portion of the input cement. This type of recycle system is considered a by-product use. The benefit from fly ash use is a reduction in the amount of cement necessary in the final product. The costs associated with substitution are related to transport of the fly ash to the cement production facility.

Concrete with recycle concrete aggregate—in the recycle alternative, concrete is broken up and used for aggregate in the making of a lower grade of concrete suitable for nonstructural applications. This is considered material recycle.

Clay brick fired with wood waste—this system is considered a by-product use, since wood wastes (sawdust) are substituted for some of the fuel used in the making of bricks, lowering the amount of fuel necessary to fire the brick.

Steel recycle—steel is easily recycled. The conventional recycle systems for steel are considered a material recycle. The main recycle inputs are in transportation.

Aluminum recycle—aluminum is easily recycled. The conventional recycle systems for aluminum are considered material recycle. The main recycle inputs are in transportation.

Wood recycle—the wood recycle system is considered a material recycle. The recycle pathway is relatively intensive because of the labor and transport inputs.

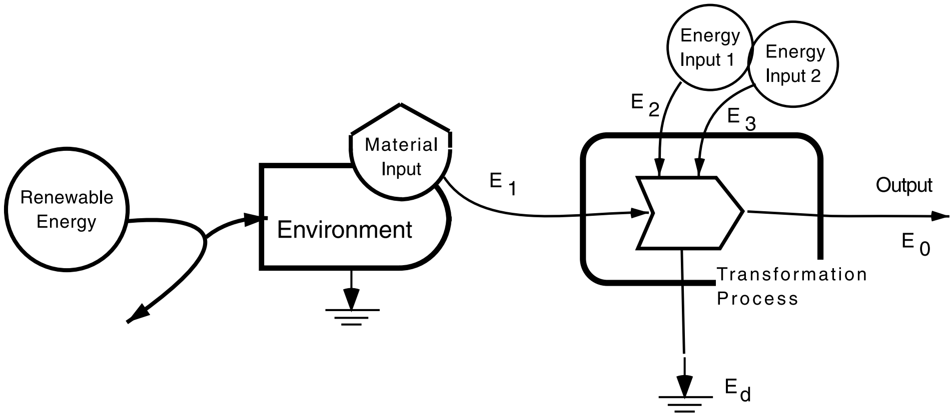
Plastic recycle—recycled plastic is made into plastic lumber. The production of plastic lumber is an adaptive reuse of post consumer paper and plastic. Significant amounts of emergy are used in collection, sorting and transport.

3. Results

3.1. Emergy evaluation of building materials

The emergy evaluation for cement given in Table 1 lists the inputs to the process, emergy per mass of inputs, total emergy (sum of emergy of inputs) and calculated emergy per mass for the annual production in the USA in 1995. Only the evaluation of cement is included here as an example. Complete emergy evaluations of the nine primary building materials may be obtained from the authors.

Emergy and economic costs for nine primary building materials are summarized in Table 2. In the second and third columns emergy per mass from the evaluations by Buranakarn (1998), Haukoos (1995) are listed. In the fourth column dollar costs for the building materials on a mass basis are given. It is important to note that the price given here is the amount of material received for money spent, thus the higher the number, the more material received per dollar. Earth materials (concrete, cement, clay bricks) have the highest mass per dollar. In the fifth column, emprice is the emergy of the material (average of columns 2 and 3) divided by money paid for the product. As with the price, earth materials have the highest emergy per dollar. The final column, buyer advantage, is the emprice divided by the average emergy per dollar in the USA economy. In essence, it is the ratio of the emergy received to the average emergy represented by the money spent for the material. On the average, a dollar in 1998 would purchase 1.2 E12 sej. So the number in the last column indicates how many times more emergy one receives for a dollars worth of the material than if the dollar was spent for an average mix of USA goods and services.



$$\text{Energy in} = \text{Energy out}\ldots(E_1 + E_2 + E_3 = E_d + E_0)$$

$$\text{Solar emergy output, } E_m = E_1{}^*Tr_1 + E_2{}^*Tr_2 + E_3{}^*Tr_3$$

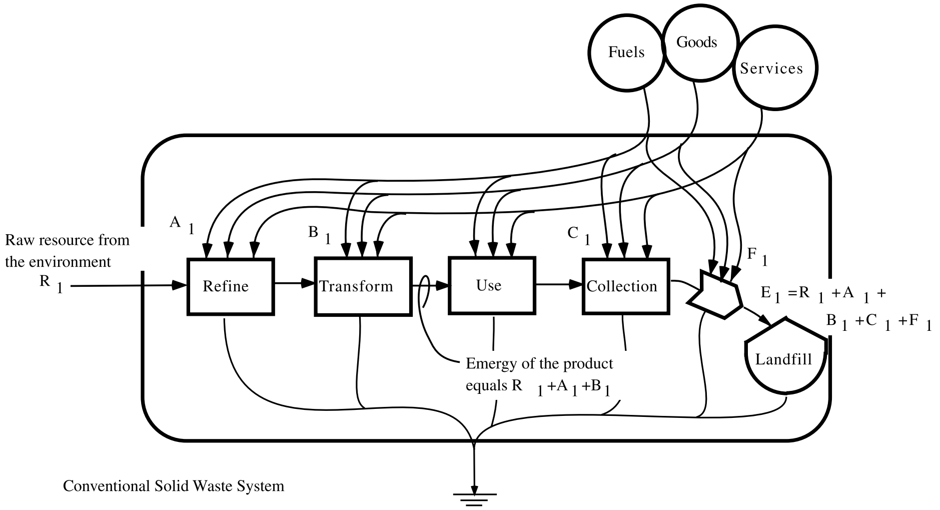
$$\text{Solar transformity of output} = \frac{\text{Solar emergy of output}}{\text{Energy of output}} = \frac{E_m}{E_0}$$

Fig. 2. Emergy accounting assigns the total emergy used in the past and present to the product of a transformation process. A material from the environment is transformed into a material product. Energy is conserved (i.e. energy input equals energy out). Solar emergy of the output is equal to the sum of the energy inputs (E_1, E_2, E_3) times their respective transformities (T_r). The solar transformity of the output is equal to its solar emergy divided by its energy content (E_o). E_d is the dispersed energy of the process (i.e. second law losses).

Life cycle emergy intensity measures the total emergy used for a material from ‘cradle to grave’. Table 3 lists life cycle emergy intensities for the main building materials expressed as emergy per gram (sej/g). By far, aluminum has the highest life cycle emergy intensity. The majority of emergy used is in the refining process (67%). Plastics have the next highest life cycle emergy intensity, Highest emergy inputs to the life cycle of plastics are in the raw resource (about 45% of total inputs. Both steel and glass have a life cycle emergy intensity about 39% of that of aluminum. Earth materials like ceramic tiles, clay brick and cement, have intermediate life cycle emergy intensities, while wood and concrete have the lowest. Of interest is that costs of construction are over one order of magnitude larger than the emergy used in demolition. Overall, collection and landfilling costs are very small compared to the emergy used in construction.

3.2. Emergy evaluation of waste disposal

Two types of waste disposal systems were evaluated. MSW and C&D wastes. Table 4 summarizes the emergy analyses of MSW and C&D wastes using the data from Buranakarn (1998). MSW is usually collected at curb-side, therefore the



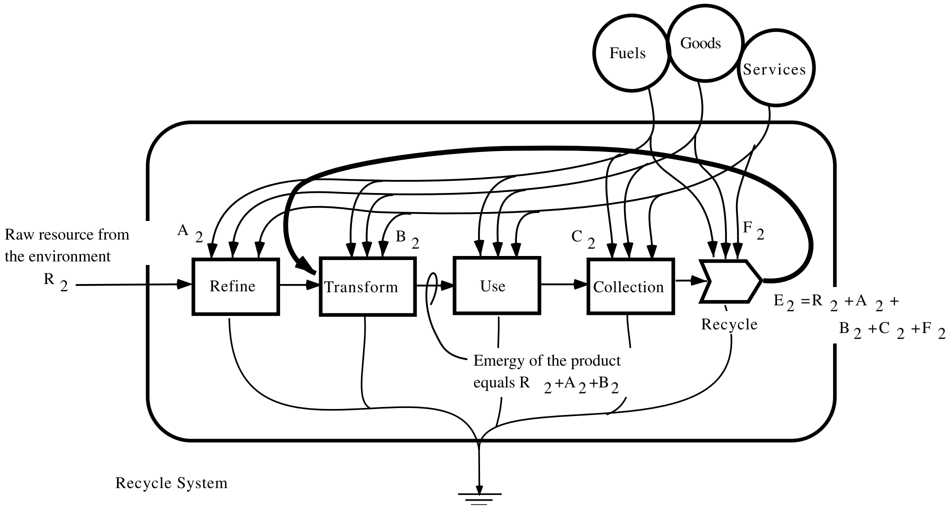


Fig. 3. Comparison of a conventional material trajectory (top) where a raw resource is upgraded through successive transformation and ends in a Landfill. The recycle trajectory (bottom shows the material recycle pathway where the material is reintroduced into the trajectory where its quality matches the quality of the material resource. Letters (A1, B1, C1, etc.) refer to the emergy of the inputs and are used to describe emergy recycle ratios in the text.

analysis includes significant amounts of truck transport and labor costs for collection (total costs = 251.0 E6 sej/g). Sorting costs were about 1/30th of collection costs, while the emergy costs of landfilling (includes the lifetime Operation & Maintenance [O&M] costs for 25-year life of the landfill) were almost 1/7th the collection costs. Obviously the emergy used in curbside collection dominates the emergy costs of MSW handling and disposal.

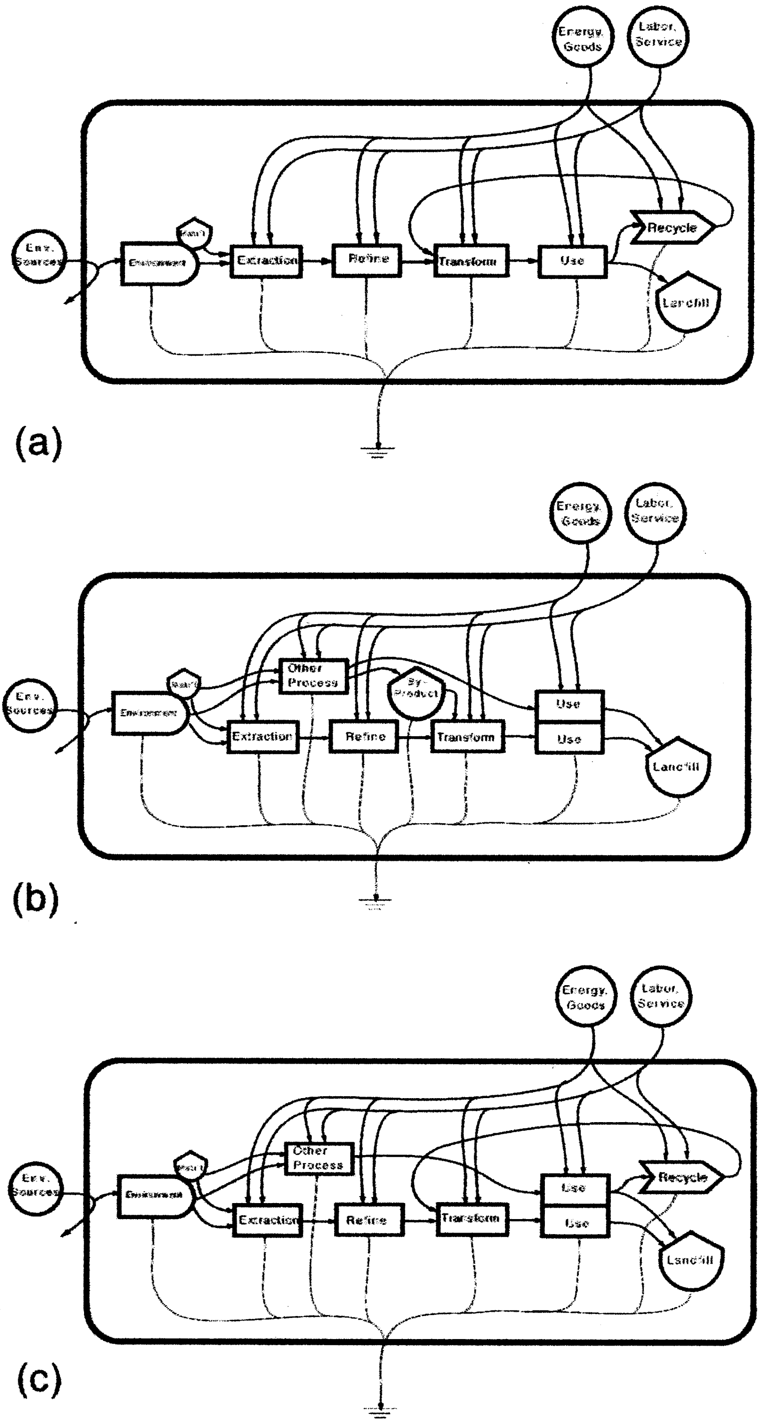

Energy, Goods
Labor, Service
Env. Sources
Environment
Mat'l
Extraction
Refine
Transform
Use
Recycle
Landfill
(a)
Energy, Goods
Labor, Service
Env. Sources
Environment
Mat'l
Other Process
By-Product
Extraction
Refine
Transform
Use
Use
Landfill
(b)
Energy, Goods
Labor, Service
Env. Sources
Environment
Mat'l
Other Process
Extraction
Refine
Transform
Use
Use
Recycle
Landfill
(c)

Fig. 4

Table 1
Emergy evaluation of annual cement production in the United States (1995)

Note	Item	Units	Input[a]	Solar emergy per unit[b] (sej/unit)	Solar emergy[c] (× E20 sej)
1	Limestone	g	8.01E+13	1.00E+09	801.0
2	Cement rock	g	2.42E+13	1.00E+09	242.0
3	Coral	g	6.80E+11	1.00E+09	6.8
4	Clay	g	4.29E+12	2.00E+09	85.8
5	Shale	g	4.38E+12	2.46E+09	107.7
6	Bauxite	g	9.67E+11	8.55E+08	8.3
7	Sand and sandstone	g	2.95E+12	1.12E+09	33.0
8	Iron ore	g	1.52E+12	1.32E+09	20.1
9	Gypsum	g	4.00E+12	1.00E+09	40.0
10	Coal	J	2.98E+17	4.00E+04	119.2
11	Natural gas	J	4.06E+16	4.80E+04	19.5
12	Oil	J	1.65E+15	6.60E+04	1.1
13	Liquid fuel, waste	J	2.30E+13	6.60E+04	0.02
14	Tires, waste	J	3.67E+15	2.10E+04	0.8
15	Electricity	J	3.97E+16	1.74E+05	69.1
16	Material transport (boat)[d]	Ton-mile	2.61E+08	1.17E+11	0.3
17	Material transport (rail)[d]	Ton-mile	3.44E+08	5.07E+10	0.2
18	Material transport (truck)[d]	Ton-mile	9.14E+07	9.65E+11	0.9
19	Labor[e]	$	6.16E+08	1.25E+12	7.7
	Total emergy				1563.4
20	Annual product yield[f]	g	7.55E+13	2.07E+09	1563.4

[a] Data are from USGS (1995): Tables 5, 6, 7 and 10 except where noted.

[b] Transformities are from Odum (1996, 2000).

[c] Product of input and emergy per unit (column 4 multiplied by column 5).

[d] Emergy per ton-mile from Buranakarn (1998).

[e] Data from USGS (1997). Emergy in labor is the product of emergy/dollar for the year of evaluation times the dollars paid for labor. Emergy/dollar in 1995 from Odum (1996).

[f] Emergy per mass is equal to total emergy (sum of last column) divided by mass of annual product (fourth column).

The largest emergy cost for C&D wastes is the cost of demolition, evaluated as 153.9 E6 sej/g. Hauling costs are about 1/7th this amount (21.7 E6 sej/g), while sorting amounts to about 4% of the demolition costs. We estimated the costs of landfilling C&D wastes, based on MSW costs without special drainage facilities and liners to be 11.7 E6 sej/g (assuming a 25-year life of landfill).

Fig. 4. Recycle trajectories are pathways of material reuse. Three recycle trajectories are shown: (a) material recycle; (b) by-product use; and (c) adaptive reuse. See text for explanation.

Table 2
Characteristics of building materials

Material	Buranakarn (1998) (E9 sej/g)	Haukoos (1995) (E9 sej/g)	Price[a] (g/$)	Emprice[b] (sej/$)	Buyer advantage[c]
Glass	2.16	4.26	289	9.3E+11	0.8
Steel	4.13	2.77	510	1.8E+12	1.8
Ceramic tile w/ recycled glass	3.06		709	2.2E+12	2.2
Wood lumber	0.88	1.4	2628	3.0E+12	2.5
Aluminum	12.53		329	4.1E+12	4.1
Plastic (PVC)	5.85		1533	9.0E+12	9.0
Cement	2.07[d]	2.37	7845	1.7E+13	14.2
Clay brick	2.32		7325	1.7E+13	17.0
Concrete	1.54	1.28	20 186	2.8E+13	23.7

[a] From Buranakarn (1998).

[b] Average of columns 2 and 3 times price (column 4).

[c] Emprice (column 5) divided by average emergy per dollar for USA economy (1.2 E12 sej/$).

[d] From Table 1.

Table 3
Life cycle emergy intensity of building materials

Material	Material product[a] (E9 sej/g)	Construction[b] (E9 sej/g)	Demolition[c]	Collection[c]	Landfill[c]	Total[d] (E9 sej/g)
Wood lumber	0.88 – 1.4	2.14	0.15	0.022	0.01	3.5
Concrete	1.54 – 1.28	2.14	0.15	0.022	0.01	3.7
Cement	1.97 – 2.37	2.14	0.15	0.022	0.01	4.5
Clay brick	2.32 –	2.14	0.15	0.022	0.01	4.6
Ceramic tile w/recycled glass	3.06 –	2.14	0.15	0.022	0.01	5.4
Glass	2.16 – 4.26	2.14	0.15	0.022	0.01	5.5
Steel	4.13 – 2.77	2.14	0.15	0.022	0.01	5.8
Plastic (PVC)	5.85 –	2.14	0.15	0.022	0.01	8.2
Aluminum	12.53 –	2.14	0.15	0.022	0.01	14.9

[a] Buranakarn (1998), Haukoos (1995).

[b] Buranakarn (1998).

[c] Table 4.

[d] Average of column 2 plus sum of columns 3, 4, 5 and 6.

Table 4
Emergy intensity of solid waste collection and disposal

Service	Emergy (E6 sej/g)
Municipal solid wastes	
Collection	251.0
Separating	8.2
Landfilling	37.9
Construction and demolition wastes	
Demolition	153.9
Truck transportation	21.7
Sorting	6.7
Landfilling	11.7

Data are from Buranakarn (1998).

3.3. Emergy evaluation of recycle options

Listed in the third through the seventh columns of Table 5 are data for the eight material recycle options. In the third column, the emergy of the recycled material is given. In the fourth column, the emergy of the material that is saved as a result of the recycled material is given. In most cases the recycled material has a higher emergy per gram than the material that is saved. The fourth column lists the collection costs. Lowest collection costs (21.7 E6 sej/g) are associated with materials that require only hauling. The intermediate collection costs (175.6 E6 sej/g) are associated with C&D wastes that require demolition and hauling, and the highest collection costs (259.2 E6 sej/g) are associated with materials that are collected as part of MSW. Sorting costs (sixth column) reflect the intensity of effort. For instance, wood recycle is very labor intensive as each piece of lumber must be handled, cleaned of nails etc., and potentially resawn. Finally, disposal costs are either in a lined MSW landfill (37.9 E6 sej/g) or an unlined C&D landfill (11.7 E6 sej/g).

3.4. Indices of recycle-ability

Table 6 summarizes the recycle indices for the main building materials and the four recycle indices: RBR, RYR, LRR and the Recycle Efficiency Ratio (RER). Refer to Fig. 2 for letter designations of pathways of emergy used to evaluate the various indices. Highest RBRs (the higher the ratio the better) were found for Cement with fly ash, aluminum, and Steel. The lowest ratio (in fact less than 1) is for the recycle of used lumber. Significant RYRs (the larger the ratio the better yield for invested emergy) are obtained with recycle systems for fly ash, aluminum, recycled concrete aggregate, recycled plastic and steel. Much lower, but still important is the RYRs for glass. Again wood has the lowest ratio.

Table 5
Emergy used in recycling materials

Material	Recycle system	Recycled material[a] (E6 sej/g)	Material savings[b] (E6 sej/g)	Collection (E6 sej/g)	Sorting (E6 sej/g)	Disposal (E6 sej/g)
Cement with fly ash	By-product use	14 000	1000	21.7	–	37.9
Concrete with recycled aggregate	Material recycle	4820	1000	175.6	16.6	11.7
Clay brick–sawdust fired	By-product use	0.016	141.8	21.7	–	37.9
Recycled steel	Material recycle	3090	2830	175.6	6.7	11.7
Recycled aluminum	Material recycle	11 965	11 700	259.2	8.2	37.9
Recycled lumber	Material recycle	3219	879	175.6	2164	11.7
Plastic lumber from recycled plastic	Adaptive reuse	5578	879	259.2	8.2	37.9
Ceramic tile from recycled glass	Adaptive reuse	2160	1000	259.2	13.2	11.7

[a] Emergy required to produce the recycled material. Does not include collection, sorting or disposal.

[b] Emergy of the material being replaced by the recycled material.

The landfill recycle ratio (LRR) is an index relating the benefit of recycling verses landfilling. Fly ash has the highest LRR (the higher the ratio the larger the benefit to society) followed by aluminum, recycled concrete aggregate, plastic and steel. Wood has the lowest LRR.

4. Discussion

4.1. Emergy and building materials

Emergy of building materials includes all the emergy required to make the material, including the emergies of the environment that were necessary to concentrate the raw material by natural processes. Materials investigated had emergy per mass that ranged from 0.88 E9 to 12.5 E9 sej/g. The general pattern was that the more refined the material product, the higher the emergy per gram. Thus steel, aluminum, plastics and float glass had emergy per mass that ranged from about 4 E9 to 12.5 E9 sej/g, while wood, concrete, ceramic tile, and bricks ranged from 0.8 E9 to 3 E9 sej/g.

Quality and versatility of a material may be related to emergy per mass. The larger the emergy per mass, the more valuable and versatile the product. The highest emergy per mass are associated with aluminum (12.5 E9 sej/g) and plastic (5.9 E9 sej/g). These materials may be the most versatile and may have the greatest potentials for recycle.

Price has long been the single most important comparative tool for evaluating materials. In Table 2 the price of materials expressed as mass per dollar (g/$) were

Table 6
Recycle indices of building materials

Material	RBR	RYR	LRR
Recycled lumber	0.4	1.4	1.4
Plastic lumber from recycled plastic	2.9	20.9	21.0
Ceramic tile from recycled glass	3.5	7.9	8.0
Concrete with recycled aggregate	4.9	25.1	25.1
Clay brick–sawdust fired	2.4	0.001	1.7
Recycled steel	14.6	17.0	17.0
Recycled aluminum	38.3	44.7	44.9
Cement with fly ash	16.8	645.2	646.9

RBR, recycle benefit ratio: ratio of the emergy used in providing a material from raw resource (A1) to the emergy used in recycling the material (C2+F2). The larger the ratio the greater the advantage of recycle. RBR = A2/(C2+F2). RYR, recycle yield ratio: ratio of the emergy in the material (R2+A2+B2) to the emergy used to recycle (C2+F2). A large ratio indicates greater yield. RYR = (R2+A2+B2)/(C2+F2). LRR, landfill to recycle ratio: ratio of emergy used to land fill a material to the emergy used to recycle the material. The higher the ratio the larger the benefit from recycling. LBR = (C1+F1)/(C2+F2).

given. The larger the number the more mass is obtained for the expenditure of a dollar, and as might be expected, the more finished a material, the lower the mass purchased per dollar. Therefore, glass, steel, and aluminum have relatively low mass per dollar prices since they are more finished. On the other hand, concrete, cement, and clay brick have the largest mass per dollar. Price is directly related to human service, so those materials that have the lowest mass per dollar are most often those that have large inputs of human service in their production.

Emprice (emergy-price) is the emergy received for each dollar paid for a material. The fifth column in Table 2 gives the emprice for the evaluated materials. The emprice varies from a high of 28 E12 sej/$ (concrete) to a low of 0.93 E12 sej/$. The emprice is an indicator of the amount of human service that is required in the production process of a material. Very high emprices (17–28 E12 sej/$) are associated with raw resources and primary building materials, which require relatively smaller amounts of human service in production, while low emprices (1.0 E12 sej/$) are indicative of materials having large demands for human service in production. Buyer advantage represents relative ‘emergy advantage’ because it is a ratio of what one receives when purchasing a material to what one would receive for an average dollar expenditure in the economy. The higher the emergy advantage, the more value one receives and the more work processes it can drive. Generally, raw resources have higher emergy advantage while finished products are lower.

The life cycle emergy intensity, given in the last column of Table 3, is the total emergy used in the life cycle of a material (expressed as sej/g), including the emergy required to make it and that necessary to collect and dispose of it. Comparison between the emergy per mass and life cycle emergy for each material indicates the relative portion of the total emergy that is necessary for collection and disposal. Raw resources have a greater percentage of their total life cycle emergy intensity in the construction phases, while more finished products have more of their life cycle emergy in the material production phases. Comparison of the emergy associated with the various stages shows the relatively small percent of a material’s life cycle that is involved in the demolition, collection and landfilling phases.

The relationship between emergy per mass of the conventional material process and that required for recycle as a percent of the conventional process suggests the likelihood of recycle becoming a significant aspect of a material’s cycle. Using the emergy per gram in Table 2 and the emergy required for recycle in Table 5, the percent of total material cycle required for recycle can be calculated. For instance, it requires only an additional 2.1% emergy input to recycle aluminum while the increase to recycle wood lumber represents an increase of 234% emergy commitment over the conventional process. Steel requires an additional 6.1% emergy input for recycle, while plastic from recycled post consumer plastic requires and additional 4.6% emergy input.

4.2. Recycle indices

Several recycle indices were developed to evaluate the appropriateness of different recycle systems. Taken together, these recycle indices provide information regarding the appropriateness of a particular material recycle system. It is quite apparent that steel and aluminum exhibit high ratios across all the indices. Primary materials like cement, concrete and clay brick exhibit moderate values for the ratios across all indices. Wood, on the other hand exhibits index values less than 1.0, calling into question the potential for large scale recycle of wood lumber.

Individually, the recycle indices provide comparative analysis to evaluate various recycle systems relative to each other. The RBR provides information relative to the potential savings that can result if a material is recycled and substituted for a raw resource. All the materials evaluated in this study, with the exception of wood lumber had very high RBRs. The RBR for wood was less than 1.0 suggesting that there is little benefit from recycling. Although this value represents an average value. In some cases, either where wood is scarce, or the quality of the wood is very high, recycle would probably show positive RBRs.

The recycle yield ratio evaluates the net benefit that society receives for recycling. It is a measure of what society gets in emergy for its emergy investment in recycle. Very high yields result from a small investment of emergy to transport aluminum and plastics and recycled concrete as aggregate. Recycled steel has a relatively high ratio as well, while the recycle of lumber is only 1.4/1 and sawdust does not provide a positive net yield. The recycle of fly ash has an extremely high RYR because the emergy of fly ash is ver large. The RYR is similar in concept to the Emergy Yield Ratio (EYR) used to express the net benefits to society from energy sources (Brown and Ulgiati, 1997). Generally fossil fuel energy sources have EYR's of about 10/1. Several of the material recycle systems have yield ratios more than twice those characteristic of the fossil fuels.

The landfill recycle ratios (LRR) for all the material recycle systems studied, were greater than one, indicating that investments in recycling these materials are beneficial in the long run. The LRR is calculated by adding the emergy used for landfilling to the emergy of the material, since if landfilled, a material is lost to society and represents a cost. The long term benefits of recycle are significant suggesting that it costs society between 1.5 and 650 times the emergy to land fill materials than to recycle them. The costs to society for landfilling plastics, steel, and aluminum are between 21 and 45 times what it costs to recycle them.

4.3. Recycle trajectories

Judging effectiveness of recycle is related to the recycle trajectory. A material recycle should result in a net savings of energy and resources. Criteria to judge appropriateness is related to whether the recycle of a material requires more energy, resources, and/or service than processing raw material to produce a product. The savings might include less transportation, less nonrenewable energy required for refining, and lower landfill costs. Added costs include collection and separation, as well as transportation.

The general trends of recycle trajectories are that the highest benefits to society appear to accrue from material recycle trajectories, followed by by-product use trajectories, and finally by adaptive reuse. Material recycle has high overall values for most of the recycle indices because material reuse substitutes directly for raw resources and refining energy. By-product use, is often used as disposal, and therefore the by-product incorporated into a new product remains as a small percentage of the total material input. Yet because by-products often have very high emergy their disposal within a recycle pathway can often be very beneficial. This is the case for fly ash. Saw dust on the other hand has relatively low emergy, so its recycle is not as beneficial. Adaptive reuse systems vary, depending on the material substitution. In general they are at the low end of the material trajectories evaluated.

4.4. Accuracy and sensitivity of data

Emergy evaluations of building C&D as well as MSW and C&D waste collection, sorting and landfilling are all based on one example each. Data were collected from a single constructed building and an average construction emergy calculated and expressed as emergy per gram of building. Demolition was calculated and expressed in the same manner. We had very good, accurate data for each of these evaluations. Our purpose was not to compare different ways of constructing or demolishing, but to evaluate in a relative way the emergy intensity of different stages in the life cycle of building materials. Thus a single evaluation is sufficient to provide the information. While more work could be done in this area, and more evaluations could strengthen these numbers, our task here was to give relative values.

We understand that to accurately estimate the emergy to construct a wood wall verses a concrete wall, for example, it is necessary to evaluate the materials separately. However, it is equally relevant to express the total emergy to construct a building as the emergy used in constructing the entire building divided by the total weight of materials in the building. This value is an average emergy per gram of building for construction. In a completed building it would be nearly impossible to evaluate each material separately, as costs for construction are not itemized to that degree.

Consider that when a building is demolished the materials are not taken down one at a time, but instead the building is torn apart and hauled off en masse. Seldom is it sorted if it is being land filled. Thus the emergy costs of demolition were expressed as an average for all materials. Curb side collection of MSW is done en masse and sorted at a central facility. Thus a single value for all materials is appropriate. Finally, land fill costs were calculated based on total solid wastes and total costs. A land fill is composed of many materials, thus it is impossible to assign portions of the operation and maintenance to separate materials, so an average is appropriate.

The data in Table 3 for emergy intensity of construction, demolition, collection and landfilling reflect the above considerations. Averages for each life cycle stage were used Fig. 4.

5. Summary and conclusions

The following conclusions regarding materials and material quality were developed:

1) Emergy per mass may be a good indicator of recycle-ability. It appears that materials with high emergy per mass are more recyclable.
2) The emprice (emergy received for money spent) is highest for primary building materials like concrete and clay brick, and lowest for materials that contain more human services.
3) Materials that have large refining costs have greatest potential for high recycle benefits, as recycled materials are substituted for raw resources.
4) The highest benefits to society appear to accrue from material recycle trajectories while the benefits from adaptive reuse and by-product use trajectories are varied, but still positive.
5) The landfill recycle ratios for all the material recycle systems studied were much larger than one (with the exception of wood), indicating that investments in recycling materials yield very positive returns when compared with landfill alternatives.
6) The yields from recycling are extremely high, for the most part, far greater than the yields that society obtains from energy sources indicating the very important contributions that effective recycling systems will have in the long run.

The use of emergy accounting may provide life cycle indices of materials and recycle trajectories that lead to ease of comparability and with the added benefit of providing quantitative metrics of some aspects of sustainability.

References

Brown MT, Ulgiati S. Emergy based indices and ratios to evaluate sustainability: monitoring technology and economies toward environmentally sound innovation. Ecological Engineering 1999;9:51–69.

Brown MT, Ulgiati S. Emergy evaluation of natural capital and biosphere services. AMBIO September 1999;28(6):486–93.

Brown MT, Ulgiati S. The role of environmental services in electricity production processes. Journal of Cleaner Production 2001;10:321–34.

Buranakarn V. Evaluation of recycling and reuse of building materials using the emergy analysis method. Ph.D dissertation, Department of Architecture, University of Florida, Gainesville, FL, 1998, p. 257.

Haukoos DS. Sustainable architecture and its relationship to industrial building. Masters thesis, Department of Architecture, University of Florida, Gainesville, FL, 1995, p. 274.

Odum HT. Energy systems and the unification of science. In: Hall CAS, editor. Maximum Power. Niwot, CO: University of Colorado Press, 1995:365–72.

Odum HT. Environmental Accounting: Emergy and Environmental Decision Making. New York: John Wiley and Sons, 1996:370.

Odum HT. Emergy of Global processes. Handbook of Emergy Evaluations, Folio #2. Center for Environmental Policy, P.O. Box 116450, University of Florida, Gainesville, FL 32611, 2000.

RS Means. Building Construction Cost Data, 56th ed.. Kingston, MA: R.S. Means Company, Inc., 1998.

Ulgiati S, Odum HT, Bastianoni S. Emergy use, environmental loading and sustainability. An emergy analysis of Italy. Ecological Modeling 1994;73:215–68.

Ulgiati S, Brown MT. Emergy accounting of human-dominated, large scale ecosystems. In: Jorgensen, Kay, editors. Thermodynamics and Ecology. Elsevier, 1999.

Ulgiati S, Brown MT. Emergy evaluations and environmental loading of alternative electricity production systems. Journal of Cleaner Production 2001;10:335–48.

USGS. Minerals yearbook, vol. 1: Metals and Minerals. US Government Printing Office # 024-004-02447-0, 1995. p. 952.

USGS. Minerals Commodity Summaries 1997. US Government Printing Office # 024-004-02443-7, 1997. p. 197.