Emergy Evaluation of Material Cycles and Recycle Options

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ABSTRACT

Emergy used in the life cycles of major building materials as well as the emergy inputs to waste
disposal and recycle systems were evaluated. The emergy per mass 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 advantageous 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 sej/g, 8.2 E6 sej/g and 37.9 E6 sej/g respectively. The
costs of demolition, collection, sorting and landfilling C&D wastes were 49.0 E6 sej/g, 21.7 E6 sej/g, 6.7
E6 sej/g, and 11.7 E6 sej/g respectively.

Three different recycle trajectories were identified and analyzed: 1) material recycle, 2) by­
product use, and 3) adaptive reuse. Four recycle indices measuring the benefits of various recycle
systems suggested that materials that have large refining costs have greatest potential for high recycle
benefits and that highest benefits appear to accrue from material recycle systems, followed by adaptive
reuse systems and then by byproduct reuse systems.

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.

The diagram in Figure 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 land fills, and disposal across the landscape (ie litter) shown by the pathway
numbered one. Some materials are recycled via geologic processes (pathway #2) through erosion
sedimentation, and some are actively recycled (pathway #3) into the stockpile of materials used by
economic systems, for instance steel recycle. It is this third pathway that is the subject of this paper.

Until very recently, humans gave little thought to the processes of recycle, using the free work of
the environment to dispose and dilute by-products and wastes from an ever expanding conglomeration of
technology, infrastructure and culture. However as humanity enters the 21st century and the limits to
both space and resources are felt, efficient use of resources becomes more important, and more attention
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Figure 1. The material and energy pathways of the biosphere showing the convergence in the assets of humans and emphasizing the waste and recycle pathways.

is given to recycle and reuse. The evaluations of materials and resource recycle systems in this study provide needed insight into the complex questions facing humanity concerning wise use. Relationships between resource quality and recycle-ability, the total life cycle emergy costs of materials, the costs of waste disposal and recycle, and their benefits to society were investigated in the hopes of providing perspectives and tools for decision making regarding material selection and recycle options in the future.

METHODS

Emergy in materials and the costs of construction, demolition, disposal, and recycle were evaluated using a variety of data sources and standard emergy evaluation techniques. In the interest of space, the full evaluations are not presented here. The full emergy evaluation tables including all calculations and data sources can be found in Buranakarn (1998).

Emergy Evaluation of Materials

The emergy of nine materials used in buildings were evaluated: Wood, concrete, cement, glass, clay brick, ceramic tile, steel, plastic, and aluminum. Emergy in materials was evaluated by analyzing national statistics from the Census of Manufacturers (1982 through 1992). All inputs of materials, energy and labor were expressed in emergy and summed to determine the total emergy per gram of material produced. The emergy of materials reported here includes human services (labor).
Emergy Evaluation of Construction, Demolition, and Disposal

Evaluation of construction was based on one building (10,900 sq ft) 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. The total emergy included labor.

Demolition emergy was evaluated using the total emergy in fuels, electricity, machines, and labor used in demolishing a 28,664 sq ft 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. The total emergy included labor.

Two different material disposal systems were evaluated: 1.) Municipal solid waste (MSW), and 2.) construction and demolition wastes (C&DW). 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 (50 year life span). Data for the C&DW 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 for 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. The total emergy included labor.

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 land fill divided by the total mass of material in the land fill. The total emergy included the emergy in human services.

Comparison of Major Building Materials

To compare different materials several, indices were calculated using emergy content, dollar costs, and useful life. 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/$). Price of building materials are usually given in varying units of measure such as dollars per board foot (lumber) dollars per cubic foot (concrete) and so forth. To standardize price and better utilize price information, prices were expressed as mass of material per dollar. First prices of materials from the literature and current cost estimate guides were compiled and expressed as units of material per dollar (ie board feet/$). Then mass units per reporting unit were calculated using average mass per unit from the literature (ie g/board foot). Finally dollars per unit mass were calculated by multiplying reporting unit per dollar by ratio of mass per reporting unit (ie. board feet/$ * g/board foot = g/$). The following indices were calculated for each material:

- **Price (P)** - the ratio of dollars paid to mass of material received. \( P = g/$

- **Emergy per mass** - the total emergy required to make a material per unit of mass.

- **Emprice** - the ratio of the emergy per mass to price. The units of emprice are sej/$.

- **Life Cycle energy intensity** - the sum of emergy required to make a building material, and dispose of it, either through recycle or landfilling. Units are sej/g.
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Recycling Indices

Figure 2 shows aggregated patterns of material use. In the top diagram, the refining of raw materials entering from the left requires an emergy input of fuels, goods and services \(A_j\). Transforming the refined materials into a material product requires emergy inputs of fuels, goods, and services \(B_j\). The emergy in the product is the sum of the emergy in the raw materials and the emergy inputs for refining and transforming \(R_j + A_j + B_j\). After use, the product is disposed of requiring emergy inputs of fuels, goods and services for collection and disposal \(C_j\). The emergy of disposal includes lifetime requirements for maintenance and operation of the landfill as well as the one time emergy used in

\[\text{Recycle System}\]

Conventional Solid Waste System

\[\text{Fuels, Goods, Service}\]

\[\text{Landfill}\]

**Figure 2.** Life cycle trajectory of material use. Conventional trajectory ends in landfill (top), while the recycle trajectory returns materials to that stage in the life cycle where their quality matches that of the resource quality.
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collection (Fᵢ). The emergy content of the waste product (Eᵢ), is the sum of all emergy inputs (Rᵢ+Aᵢ+Bᵢ+Cᵢ+Fᵢ).

An aggregated recycling system is shown in the bottom diagram in Figure 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 Figure 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 (Aᵢ) to the emergy used in recycle (Cᵢ+Fᵢ). $RBR = \frac{Aᵢ}{Cᵢ+Fᵢ}$

- **Recycle Yield Ratio (RYY)** – The ratio of emergy in recycled material (Rᵢ+Aᵢ+Bᵢ) to emergy used for recycle (Cᵢ+Fᵢ). $RYY = \frac{Rᵢ+Aᵢ+Bᵢ}{Cᵢ+Fᵢ}$

- **Landfill to Recycle Ratio (LRR)** – The ratio of emergy required for landfilling a material (Cᵢ+Fᵢ) to the emergy required for recycle (Cᵢ+Fᵢ). $LRR = \frac{Cᵢ+Fᵢ}{Cᵢ+Fᵢ}$

- **Recycle Efficiency Ratio (RER)** – The ratio of material and energy conserved, when recycled materials are used, to the emergy required for recycle. $RER = \frac{Rᵢ+Aᵢ+Bᵢ+Cᵢ}{Cᵢ+Fᵢ}$

****RESULTS****

**Emergy evaluation of building materials**

Given in Table 1 are the emergy and economic values for 9 primary building materials. In the second and third columns emergy per mass is from the evaluations by Buranakarn (1998) and Haukoos (1995). 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 for dollar. Earth materials (concrete, cement, clay bricks)

<table>
<thead>
<tr>
<th>Material</th>
<th>Buranakarn (1998)</th>
<th>Haukoos (1995)</th>
<th>Price ( (E9 \text{ sej/g}) )</th>
<th>Emprice ( (E9 \text{ sej/$}) )</th>
<th>Buyer Advantage ( \text{($/$)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>2.16</td>
<td>4.26</td>
<td>289</td>
<td>9.3E+11</td>
<td>0.8</td>
</tr>
<tr>
<td>Steel</td>
<td>4.13</td>
<td>2.77</td>
<td>510</td>
<td>1.8E+12</td>
<td>1.8</td>
</tr>
<tr>
<td>Ceramic tile w/ recycled glass</td>
<td>3.06</td>
<td>709</td>
<td>2.2E+12</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>Wood lumber</td>
<td>0.88</td>
<td>1.4</td>
<td>2628</td>
<td>3.0E+12</td>
<td>2.5</td>
</tr>
<tr>
<td>Aluminum</td>
<td>12.53</td>
<td>329</td>
<td>4.1E+12</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>Plastic (PVC)</td>
<td>5.85</td>
<td>1533</td>
<td>9.0E+12</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>Cement</td>
<td>1.97</td>
<td>2.37</td>
<td>7845</td>
<td>1.7E+13</td>
<td>14.2</td>
</tr>
<tr>
<td>Clay brick</td>
<td>2.32</td>
<td>7325</td>
<td>1.7E+13</td>
<td>17.0</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>1.54</td>
<td>1.28</td>
<td>20186</td>
<td>2.8E+13</td>
<td>23.7</td>
</tr>
</tbody>
</table>

b). Average of column 2 and column 3 times price (column 4)
c). Emprice (column 5) divided by average emergy per dollar for USA economy (1.2 E12 sej/\$)

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have the highest mass per dollar. In the fifth column, the average emprice is given. Emprice is the
emergy of the material (average of columns 2 and 3) divided by money paid for the product. Its units are
sej/$. Emprice is an expression of the emergy one receives in the material for each dollar paid for the
material. 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 $1.2 \times 10^12$ 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.

Life cycle emergy intensity measures the total emergy used for a material from “cradle to grave.”
Table 2 gives life cycle emergy intensities for the main building materials expressed as emergy per gram
(sej/g). Each column represents a different stage in the life cycle of the materials. The emergy required
to produce (including the emergy of the material itself) per gram of material produced is given in the first
column. The emergy used in construction (Column 3) was evaluated for an entire building, thus it is the
same for each material...it represents the average emergy used per gram of building, during
construction. The emergy used in demolition was calculated in the same manner so it represents the
average emergy used per gram of building demolished. Collection and landfilling are also averages. Of
interest is that costs of construction are over one order of magnitude larger than the emergy used in
demolition. Collection and landfilling are very small compared to construction costs as well.

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 (Buranakarn, 1998).
Steel has a life cycle emergy intensity about 39% of that of aluminum and glass has an emergy intensity
similar to that of steel. Earth materials like ceramic tiles, clay brick and cement, have intermediate life
cycle emergy intensities, while wood and concrete have the lowest.

Table 2. Life Cycle Emergy Intensity of Building Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Material product</th>
<th>Construction</th>
<th>Demolition</th>
<th>Collection</th>
<th>Landfill</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood lumber</td>
<td>0.88</td>
<td>1.4</td>
<td>2.14</td>
<td>0.15</td>
<td>0.022</td>
<td>0.01</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.54</td>
<td>1.28</td>
<td>2.14</td>
<td>0.15</td>
<td>0.022</td>
<td>0.01</td>
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<td>2.14</td>
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<td>0.01</td>
</tr>
<tr>
<td>Clay brick</td>
<td>2.32</td>
<td>-</td>
<td>2.14</td>
<td>0.15</td>
<td>0.022</td>
<td>0.01</td>
</tr>
<tr>
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</tr>
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<td>-</td>
<td>2.14</td>
<td>0.15</td>
<td>0.022</td>
<td>0.01</td>
</tr>
<tr>
<td>Aluminum</td>
<td>12.53</td>
<td>-</td>
<td>2.14</td>
<td>0.15</td>
<td>0.022</td>
<td>0.01</td>
</tr>
</tbody>
</table>

c). Table 3  
d). Average of column 2 plus sum of columns 3, 4, 5, and 6

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Emergy Evaluation of Waste Disposal

Two types of waste disposal systems were evaluated. Municipal solid wastes (MSW) and construction and demolition wastes (C&D). Table 3 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 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 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.

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 land fill)

Emergy Evaluation of Recycle Options

The recycle systems for each of the main building materials were evaluated to compare costs and benefits of recycle. We have identified three different recycle trajectories (Figure 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 per 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 non structural applications. This is considered material recycle.

Table 3. Emergy intensity of solid waste collection and disposal (after Buranakan, 1998)

<table>
<thead>
<tr>
<th>Service</th>
<th>Emergy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(E6 sej/g)</td>
</tr>
<tr>
<td><strong>Municipal Solid Wastes</strong></td>
<td></td>
</tr>
<tr>
<td>Collection</td>
<td>251.0</td>
</tr>
<tr>
<td>Separating</td>
<td>8.2</td>
</tr>
<tr>
<td>Landfilling</td>
<td>37.9</td>
</tr>
<tr>
<td><strong>Construction and Demolition Wastes</strong></td>
<td></td>
</tr>
<tr>
<td>Demolition</td>
<td>153.9</td>
</tr>
<tr>
<td>Truck transportation</td>
<td>21.7</td>
</tr>
<tr>
<td>Sorting</td>
<td>6.7</td>
</tr>
<tr>
<td>Landfilling</td>
<td>11.7</td>
</tr>
</tbody>
</table>
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Figure 3. Material and recycle trajectories. a) conventional material trajectory, b) material recycle trajectory, c) by-product use, and d) adaptive reuse.
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Clay brick with oil contaminated soil - 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.

Recycle plastic - 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.

Listed in the third through the seventh columns of Table 4 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).

Indices of Recycle-ability

Table 5 summarizes the recycle indices for the main building materials and their recycle systems. Four recycle indices are given: Recycle Benefit Ratio (RBR), Recycle Yield Ratio (RYR), Landfill Recycle Ratio (LRR) and the Recycle Efficiency Ratio (RER). Refer to Figure 2 for letter designations of pathways of emergy used to evaluate the various indices.

The recycle benefit ratio measures the benefit of recycling a material that results in lower demand for raw material inputs and processing energy. It is the ratio of the emergy saved to the emergy costs of recycling. The higher the ratio the better. Highest RBRs 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.

The recycle yield ratio is the ratio of emergy value of recycled material to the costs of recycle. It measures the emergy value of recycle material received by society for the emergy invested. The larger the ratio the better yield for invested emergy. Significant yields 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.

The landfill recycle ratio is an index that measures the benefit of recycling verses landfilling. It is the ratio of the costs of landfilling (including the emergy in the material itself) to the costs of recycling. The higher the ratio the better, since it is an index of savings...the higher the ratio the more emergy is saved. Fly ash has the highest LRR followed by aluminum, recycled concrete aggregate, plastic and steel. Wood has the lowest LRR.

The last column in Table 5 is the recycle efficiency ratio (RER) which is a measure of efficiency by comparing the costs of producing a material from raw resources to the emergy costs invested in recycling. Again the higher the ratio the better. Fly ash, aluminum, and steel have the highest efficiencies. All the other material have intermediate RFRs with the exception of wood, which is less than one.
### Table 4. Emergy used in recycling materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Recycle System</th>
<th>Recycled material* (E6 sej/g)</th>
<th>Material savingsb (E6 sej/g)</th>
<th>Collection (E6 sej/g)</th>
<th>Sorting (E6 sej/g)</th>
<th>Disposal (E6 sej/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement with fly ash</td>
<td>By-product use</td>
<td>14000</td>
<td>1000</td>
<td>21.7</td>
<td>-</td>
<td>37.9</td>
</tr>
<tr>
<td>Concrete with recycled aggregate</td>
<td>Material recycle</td>
<td>4820</td>
<td>1000</td>
<td>175.6</td>
<td>16.6</td>
<td>11.7</td>
</tr>
<tr>
<td>Clay Brick - sawdust fired</td>
<td>By-product reuse</td>
<td>0.016</td>
<td>141.8</td>
<td>21.7</td>
<td>-</td>
<td>37.9</td>
</tr>
<tr>
<td>Recycled steel</td>
<td>Material recycle</td>
<td>3090</td>
<td>2830</td>
<td>175.6</td>
<td>6.7</td>
<td>11.7</td>
</tr>
<tr>
<td>Recycled aluminum</td>
<td>Material recycle</td>
<td>11965</td>
<td>11700</td>
<td>259.2</td>
<td>8.2</td>
<td>37.9</td>
</tr>
<tr>
<td>Recycled lumber</td>
<td>Material recycle</td>
<td>3219</td>
<td>879</td>
<td>175.6</td>
<td>2164</td>
<td>11.7</td>
</tr>
<tr>
<td>Plastic lumber from recycled plastic</td>
<td>Adaptive reuse</td>
<td>5578</td>
<td>879</td>
<td>259.2</td>
<td>8.2</td>
<td>37.9</td>
</tr>
<tr>
<td>Ceramic tile from recycled glass</td>
<td>Adaptive reuse</td>
<td>2160</td>
<td>1000</td>
<td>259.2</td>
<td>13.2</td>
<td>11.7</td>
</tr>
</tbody>
</table>

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

b). Emergy value of the material being replaced by the recycled material.
Chapter 12. Emergy Evaluations of Material Cycles and Recycle Options

Table 5. Recycle Indices of Building Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>RBR</th>
<th>RYR</th>
<th>LRR</th>
<th>RER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycled lumber</td>
<td>0.4</td>
<td>1.4</td>
<td>1.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Plastic lumber from recycled plastic</td>
<td>2.9</td>
<td>20.9</td>
<td>21.0</td>
<td>3.3</td>
</tr>
<tr>
<td>Ceramic tile from recycled glass</td>
<td>3.5</td>
<td>7.9</td>
<td>8.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Concrete with recycled aggregate</td>
<td>4.9</td>
<td>25.1</td>
<td>25.1</td>
<td>5.2</td>
</tr>
<tr>
<td>Clay Brick - sawdust fired</td>
<td>2.4</td>
<td>0.001</td>
<td>1.7</td>
<td>6.5</td>
</tr>
<tr>
<td>Recycled steel</td>
<td>14.6</td>
<td>17.0</td>
<td>17.0</td>
<td>15.5</td>
</tr>
<tr>
<td>Recycled aluminum</td>
<td>38.3</td>
<td>44.7</td>
<td>44.9</td>
<td>43.8</td>
</tr>
<tr>
<td>Cement with fly ash</td>
<td>16.8</td>
<td>645.2</td>
<td>646.9</td>
<td>46.1</td>
</tr>
</tbody>
</table>

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 = A₁/ (C₂+F₂)

RYR = Recycle Yield Ratio = ratio of the emergy in the material (R₁+A₁+B₁) to the emergy used to recycle (C₂+F₂). A large ratio indicates greater yield.  
RYR = (R₁+A₁+B₁) / (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.  
LRR = (C₁+F₁)/ (C₂+F₂)

RER = Recycle Efficiency Ratio = ratio of material and energy conserved (R₁+A₁+B₁+C₁) to the emergy required for recycle (C₂+F₂) when a recycled material is substituted for a raw resource.  
RER = (R₁+A₁+B₁+C₁) / (C₂+F₂)

DISCUSSION

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. The total required emergy, expressed as emergy per mass (sej/g) was given in Table 1. Materials investigated had emergy per mass values that ranged from 0.88 E9 sej/g to 12.5 E9 sej/g. The general pattern is that the more refined the material product, the higher the emergy per gram. Thus steel, aluminum, plastics and float glass have emergy per mass values that range from about 4E9sej/g to 12.5E9 sej/g, while wood, concrete, ceramic tile, and bricks range from 0.8E9 to 3E9 sej/g.

Emergy theory suggests that 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 values 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 1 the price of materials expressed as mass per dollar (g/$) were 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
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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 1 gives the emprice for the evaluated materials. The emprice varies from a high of 28 E12 sej$/ (concrete) to a low of 0.93 E12 sej$/ (wood). 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 is another way of describing emprice. It represents relative "emergy advantage" in that 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. In essence 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 2, 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. The higher the number the higher the commitment of emergy over the life time of a material. 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 1 and the emergy required for recycle in Table 4, percent of material cycle 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.

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's 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
energy of fly ash is very large. The RYR is similar in concept to the Emergy Yield Ratio (EYR) used to express the net benefits to society from energy sources. Generally fossil fuel energy sources have EYR's of about 10^11. Several of the material recycle systems have yield ratios more than twice that 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 to recycle are significant suggesting that it costs society between 1.5 and 650 times the emergy to land fill material 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.

Comparing the emergy used in a recycle pathway to the emergy saved by substituting a recycled material for a raw product is one way of measuring efficiency. In this study this comparison was achieved as a ratio and was termed recycle efficiency ratio (RER). It was defined as the ratio of the emergy costs of recycling the emergy of a material product from the raw resource that was not used because the recycled material was substituted for it. High efficiencies can be achieved through recycling...anywhere from 3.3/1 if recycled plastic is used in place of lumber, to 46/1 if fly ash is substituted for cement. The general trends are that metals have the highest efficiencies while earth materials have efficiencies between 3/1 to 6/1.

Recycle Trajectories

It is apparent that there are several different material recycle trajectories. Three different recycle trajectories were identified and analyzed:

1) material recycle
2) by-product use, and
3) adaptive reuse

Judging effectiveness of recycle is the same for each trajectory, i.e. the recycle of a material 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.

Evaluating recycle patterns and looking for general trends suggests that the highest benefits to society appear to accrue from material recycle trajectories, followed by by-product reuse trajectories, and finally by adaptive reuse. Material recycle trajectories have high overall values for most of the recycle indices because material reuse substitutes directly for raw resources and refining energy. By-product reuse, 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.

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. Quality and versatility of a material are related to emergy per mass. The larger the emergy per mass, the more valuable and versatile the product and the greater the potential for recycle.

4. Price, expressed as mass per dollar is inverse to the amount of human service inputs to a material's production.

Recycle indices were developed that have the potential to provide insight regarding material trajectories within recycle patterns. Three recycle patterns were identified that had different material trajectories. Four recycle indices were developed to evaluate recycle patterns as provide needed information on the appropriateness of recycle options. The following conclusions were drawn from the analysis of recycling patterns:

1. Materials that have large refining costs have greatest potential for high recycle benefits, as recycled materials are substituted for raw resources.

2. It appears that materials that require fewer inputs in their refining stages are less likely to exhibit positive recycle benefits.

3. The highest benefits to society appear to accrue from material recycle trajectories. The benefits from adaptive reuse and by-product reuse trajectories are varied, but still positive.

4. 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.

5. 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.

REFERENCES


