EMERGY SYNTHESIS 3:
Theory and Applications of the Emergy Methodology

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The Center for Environmental Policy
Department of Environmental Engineering Sciences
University of Florida
Gainesville, FL
Historical Solar Emergy Use in the United States and its Relation to Technological Development

David R. Tilley

ABSTRACT

Technology development during the past two centuries has proceeded at an accelerating rate, synchronized to the quickened use of rich fossil fuels and bountiful natural resources. Technology, defined anthropologically as devices and the knowledge of how to use them, is a specialized form of social memory that requires input energies for development and maintenance, serving as a powerful and flexible agent for organizing subsequent energy and resource use. As an evolutionary process, technology development is greatly influenced by knowledge availability and previous innovation. Understanding how the dynamics of technology development are related to historical resource use is important in a resource restrained world with competing demands for those resources. Emergy evaluation, as a material-energy based accounting system that tracks the resources required to produce something, was used to quantify the total natural resources required (in solar energy equivalents) to develop and improve important communication technologies of the 20th Century. The solar emergy of a new technology includes the solar emergy used during its evolutionary path. Quantifying the solar emergy accumulated during the evolution of a technology required the use of dynamic emergy accounting principles. Ways to allocate the historical solar emergy use of the U.S. to the technological development of the satellite, the radio, the television and the telephone was explored. Historical time series of the solar transformity (ST) of each technology reveals decelerating rates of improvement in each, suggesting that there are macro-thermodynamic limits to improvements in each technology.

INTRODUCTION

Technological optimists commonly claim that the economic importance of physical materials will diminish in the future, while the prominence of information services will increase, possibly eliminating the need to consume natural resources altogether. Certainly, information processing has increased in many economic sectors and it has formed the basis of several new ones. Optimists point to the proportional increase in gross domestic product (GDP) that is attributed to the information sectors, the explosive increase in internet start-up companies, and the decline in the proportion that petroleum and agricultural industries represent in the U.S. GDP as proof of their assertions. Certainly, technological capabilities for processing information have improved in the past two centuries with the invention of numerous communications technologies like telegraphy, telephony, radio, television and the satellite.

But how well do we understand the energy basis of technology: its creation, usefulness, improvement and maintenance? Technology development is an evolutionary process; current successes depend on previous achievements and future innovations depend on current successes. Diamond (1997) argued that the rate of technology improvement is closely tied to a culture’s history, environment and geography, rather than on the work of particular geniuses. In his view, the general
theory of relativity, for which A. Einstein received much praise, would have been developed by someone else eventually. If Diamond’s view is appropriate, then two important questions concerning technology development are (1) what level of resource and energy consumption is necessary to achieve a certain rate of technological innovation and (2) how much energy and natural resources are required to maintain technologies?

The goal of this paper is to explore the relationship between the rate of resource and energy use in the U.S. (i.e., ‘national metabolism’) and the development rate of communication technologies. I estimated the total resources required to invent and maintain commonly used technologies. I translated all energy and resource requirements into units of solar emergy. Solar emergy is the total amount of solar energy required both directly and indirectly to make a product or provide a service (Odum 1996). Translation to solar emergy places all resource flows in the same units (solar embodied joules, sej), which allows them to be compared on a common basis. This is critical when attempting to measure national metabolism because the various units of natural resources, such as water, wood, soil, fossil fuels, and non-fuel minerals can be converted to a single system unit for aggregated addition and subtraction. Communication devices, like a telephone, consume a small amount of energy directly, but require vast amounts of energy and natural resources during their creation and improvement. The solar emergy required to create and improve per unit of energy consumed during use was calculated to compare the resource intensity of each technology. This ratio, the solar emergy required to the available energy used, was defined as the solar transformity (conjugation of transformation intensity) by Odum (1988). The solar transformity of solar radiation is defined as 1 sej per Joule (sej/J, Odum 1996).

Although communication devices consume a relatively small amount of power during use, the solar emergy required to create, support and improve them is potentially enormous. In a world struggling with a decline in resource availability, understanding how much energy and natural resources are required for our global communication activities is important and can add to the debate on the substitutability of information for physical goods. In addition, environmental historians, may be interested in relating past cultures’ rates of technological innovation to the availability of energy and natural resources.

METHODS

The philosophy for allocating historical solar emergy to technologies was grounded in the basic definition of solar emergy; namely that it is the total amount of solar energy required directly and indirectly to make a product. Emergy accounting for developmental processes is sometimes called dynamic emergy accounting (Tilley 1999, Odum 1996). Technology development is an evolutionary process with past innovations absolutely necessary for present and future innovations. This reasoning, taken to its fullest, would have us include the emergy of the Universe’s beginning, but our goals are less ambitious. Selecting the analytical boundary is largely arbitrary, but related, in this case, to readily available data and the date the country began. For the analysis presented here, 1790 was determined to be the best year to start the calculations. Figure 1 presents an energy systems diagram that gives the philosophy for how national emergy was allocated to technical innovations. The work of the nation’s entire ecosphere is required to create Technology #1, while subsequent innovations (i.e., Technology #2 and #3) required the solar emergy used to innovate Technology #1. This accounting philosophy leads to a mathematical model shown in Figure 2. Typically, emergy input from environmental energies is determined by only including the contribution of the largest renewable source to avoid double counting. Here, precipitation is taken as the single emergy source that is renewed on the time scale of a year. Soil loss and wood use were added to M_total under the assumption that they mostly consisted of solar emergy preceding 1790. A strong argument could be made that much of our latter-day domestic wood production is from secondary, regenerated forests, which consist of solar emergy from the post-1790 period. This is a detail that should be improved upon in subsequent historical emergy evaluations.
Chapter 18. Historical Solar Emergy Use...

Figure 1. Systems diagram of U.S. technology development.

Figure 2. Energy systems diagram with mathematical equations for estimating solar emery to create and improve technologies.

Where, $M_{create}$ is solar energy required to create a technology developed in creation year $t_c$; $M_t$ is annual national solar energy use in year $t$; $M_{improve}$ is solar energy used to improve a technology for the period $t_c$ to present year $t_p$; $R_t$ is annual revenue of a technology’s economic sector; $(sej/\$)_t$ is average annual solar energy to dollar ratio for year $t$; and $M_{total}$ is total solar energy accumulated in the technology.
Chapter 18. Historical Solar Emergy Use…

The rate at which solar emergy was contributed by the main types of resources and energy supplies was estimated annually for the period 1790 to 2000 for the United States. The solar emergy of an input was either the product of its energy use and solar transformity (sej/J), the product of its mass and its specific solar emergy (sej/g), or the product of its nominal dollar flow and the emergy-to-dollar ratio (sej/$) for that year. Almost exclusively, the energy, mass and dollar flow data were taken from published records of the U.S. Census Bureau. The specific solar emergy of a substance is the solar emergy required to process it into its current form per unit mass. The emergy-to-dollar ratio is the total annual emergy use divided by the gross domestic product, which makes it the mean solar emergy value of each dollar transacted in the economy. Solar transformities and specific solar emergies were taken from past emergy publications. Mean annual emergy-to-dollar ratios were estimated for the entire period of analysis.

Solar Emergy of Inputs

The methods and equations used to estimate the historical solar emergy use of the United States are presented for each type of input in the following sections.

Precipitation

The solar emergy of precipitation was found using Eq. 1.

\[ M_{pt} = L_t p_t S_{r} \]  

(1)

Where \( M_{pt} \) is solar emergy of precipitation of U.S. in year \( t \); \( L_t \) is land area for year \( t \); \( p_t \) is mean annual precipitation power; and \( S_r \) is solar transformity of precipitation.

Nation-wide precipitation rate for 1803 to 2000 was estimated as 915 mm y\(^{-1}\) (36 inches) based on visual interpolation of digital maps with color-coded monthly precipitation rates (Shinker 2003). The 1790 to 1803 precipitation rate was 1112 mm y\(^{-1}\). Changes to land area (\( L_t \)) were taken from Carter (1997) for the 1790-1970 period and from U.S. Census Bureau (2002) for post-1970. The Gibb’s free energy of freshwater precipitation was take as 5 J g\(^{-1}\)-water. The solar transformity of precipitation was a constant 18,200 sej J\(^{-1}\).

Soil Resources

The solar emergy of soil erosion in year \( t \) (\( M_{sr} \)) was found using Eq. 2.

\[ M_{sr} = F_t(5.68 \text{ MT ac}^{-1} \text{ y}^{-1})(0.03 \text{ g-org. matter g}^{-1}\text{-soil})*(22.6 \text{ kJ g}^{-1}\text{-O.M.})(63,400 \text{ sej J}^{-1}) \]  

(2)

Where \( F_t \) is farmland area in acres for year \( t \) (1 ac = 4000 m\(^2\)).

\( F_t \) was given by Carter (1997) for the period 1900-1970 and by the U.S. Census Bureau (2002) for 1971-2000. For the 1850-1900 period, Carter (1997) only reported decadal records. Therefore, we used straight-line interpolation to estimate inter-decade \( F_t \). Pre-1850 \( F_t \) was estimated as the product of population and the average per capita farmland for the 1850-1900 period (11.1 ac per person). The 5.675 MT erosion rate is a weighted average (by area) of cropland (7.5 MT ac\(^{-1}\) y\(^{-1}\)) and pasture (1.3 MT ac\(^{-1}\) y\(^{-1}\)). The average organic fraction of soil was assumed to be 3%.

Wood

The solar emergy of forestry product use in year \( t \) (\( M_{wt} \)) was found using Eq. 3a.

\[ M_{wt} = 544 \text{ MJ ft}^3(W_t)(41,000 \text{ sej J}^{-1}) \]  

(3a)

Where \( W_t \) is cubic feet of wood consumption (green weight); (1 ft\(^3\) = 0.0283 m\(^3\))

Total annual wood consumption was determined using Eq. 3b.

\[ W_t = W_p + W_f + W_i - W_e \]  

(3b)

Where \( W_p \) is industrial equivalent roundwood production, which includes logs, plywood, lumber, veneer, etc.; \( W_f \) is fuel wood consumption; \( W_i \) is imported roundwood equivalents; and \( W_e \) is exported roundwood equivalents.
Wood consumption for 1900-1970 was given by Carter (1997). Post-1970 Wt was given by Howard (1999). Pre-1900 lumber and total roundwood production were given on a decadal basis by Carter (1997). We used straight-line interpolation for interdecadal years. Per capita fuel wood consumption for the pre-1900 period was assumed to be 70 ft$^3$ per capita, which was multiplied by the population estimate to determine Wf. The 70 ft$^3$ per capita assumption was determined by extrapolating backwards in time the per capita use trend between 1900 and 1950. The solar transformity of forest products (41,000 sej J$^{-1}$) was taken from Tilley (1999), which was based on simulated values of a 200-year old forest.

**Immigration**

The annual solar emergy of immigrants arriving in the U.S. (Mit) was estimated using Eq. 4.

\[
Mit = (0.1 \times \text{U.S. per capita emergy use}) \times (\text{avg. immigrant age}) \times (\text{net immigration rate})
\] (4)

Eq. 4 assumes that the solar emergy per immigrant is accumulated at a rate equal to one-tenth of an American prior to their entrance to the U.S. The factor of 10% was based on the assumption that through the course of history, immigrants are largely compelled to immigrate based on the economic disparity between their home country and the U.S. Emergy evaluations of home countries could provide a more precise estimate of solar emergy per immigrant. The average age of immigrants was assumed to be 20 years, based on the fact that a majority of immigrants are young. The rate of net immigration was given by Carter (1997) for the period 1820-1970. Immigration prior to 1820 was not known so it was assumed to be zero, which is unlikely true. Post-1970 immigration was given by U.S. Census Bureau (2002, 1993).

**Fuels and Electricity**

Eqs. 5a through 5e were used to calculate the annual solar emergy of crude petroleum (Mpt), coal (Mct), natural gas (Mnt), hydroelectricity (Mht), and nuclear electricity (Mut) consumption, respectively. Pt, Ct, Nt, Ht, and Ut are, respectively, annual crude petroleum consumption in barrels, annual coal consumption in short tons (1 sh. Ton = 907.2 kg), annual natural gas consumption in cubic feet (1 m$^3$ = 35.3 ft$^3$), annual hydroelectricity consumption in kWh, and annual electricity consumption from uranium fission in kWh. The solar transformities were from Odum (1996).

\[
\begin{align*}
Mpt & = 6.28 \times 10^9 \text{ J/bbl} \times \text{Pt} \times 54,000 \text{ sej/J} \\
Mct & = 31.0 \times 10^9 \text{ J/short ton} \times \text{Ct} \times 39,000 \text{ sej/J} \\
Mnt & = 1.10 \times 10^6 \text{ J/cubic ft} \times \text{Nt} \times 48,000 \text{ sej/J} \\
Mht & = 3.606 \text{ J/kWh} \times \text{Ht} \times 160,000 \text{ sej/J} \\
Mut & = 3.606 \text{ J/kWh} \times \text{Ut} \times 160,000 \text{ sej/J}
\end{align*}
\] (5a - 5e)

**Non-fuel Minerals**

The solar emergy consumed as non-fuel mineral k (MNF Mk) for the 1790—1970 period was estimated for minerals listed in Table 1 using Eq. 6a.

\[
M_{NFMk} = C_{nfmk} \times m_{nfmk}
\] (6a)

Where \( C_{nfmk} \) is consumption of non-fuel mineral k in grams and \( m_{nfmk} \) is specific solar emergy of non-fuel mineral k in sej per gram.

Data for the consumption of non-fuel minerals after 1970 was not as easily available, so in an effort to complete the analysis we only evaluated the consumption of the three most common non-fuel minerals during this period. Iron ore (Fe), phosphate rock (P) and copper ore (Cu) were greater than 78% of total solar emergy of non-fuel minerals consumption for the 1950-1970 period, therefore, we used Eq. 6b to estimate total non-fuel mineral consumption for the 1971-2000 (MNF M2).

\[
M_{NFM2} = (M_{Fe} + M_{Cu} + M_{P}) / 0.78
\] (6b)

Where \( M_{Fe} \) is solar emergy of iron ore; \( M_{Cu} \) is solar emergy of copper ore; and \( M_{P} \) is solar emergy of phosphate rock.
Chapter 18. Historical Solar Emergy Use...

Table 1. Solar emergy per unit of energy and mass used.

<table>
<thead>
<tr>
<th>Item</th>
<th>Solar Transformity sej J⁻¹</th>
<th>Mass Specific Solar Emergy sej g⁻¹</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>18,200</td>
<td>Odum 1996</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>39,000</td>
<td>Odum 1996</td>
<td></td>
</tr>
<tr>
<td>Fuel Wood</td>
<td>41,000</td>
<td>Tilley 1999</td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>48,000</td>
<td>Odum 1996</td>
<td></td>
</tr>
<tr>
<td>Crude Petroleum</td>
<td>54,000</td>
<td>Odum 1996</td>
<td></td>
</tr>
<tr>
<td>Soil Erosion (O.M.)</td>
<td>63,400</td>
<td>Odum 1996</td>
<td></td>
</tr>
<tr>
<td>Petroleum Products</td>
<td>66,000</td>
<td>Odum 1996</td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>160,000</td>
<td>Odum 1996</td>
<td></td>
</tr>
<tr>
<td>Fish</td>
<td>2,000,000</td>
<td>Odum 1996</td>
<td></td>
</tr>
<tr>
<td>Phosphate Rock</td>
<td>3.90E+09</td>
<td>Odum 1996</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>3.42E+09</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
<tr>
<td>Chromium</td>
<td>4.07E+09</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>6.58E+10</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td>1.32E+14</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>2.04E+09</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>1.24E+10</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>1.07E+10</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
<tr>
<td>Molybdenum</td>
<td>7.13E+11</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>5.43E+10</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>3.29E+11</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>1.53E+11</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
<tr>
<td>Uranium</td>
<td>5.70E+11</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
<tr>
<td>Vanadium</td>
<td>1.02E+11</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>1.58E+10</td>
<td>Odum and Brown 1993</td>
<td></td>
</tr>
</tbody>
</table>

*Odum and Brown’s (1993) estimate for Mn was an order of magnitude greater than Fe-ore (the next largest emergy input). Since this did not correspond to the importance of Mn in the U.S. economy, we used the solar transformity of titanium, which had a crustal abundance similar to Mn.

Obviously, more detailed statistics exist for the 1971-2000 minerals use, so a subsequent analysis could be improved with this type of data.

Foreign Trade

Determination of the solar emergy of net balance of trade was found by multiplying net annual imports in US$ by estimates of annual mean US emergy-to-$ ratio (M$⁻¹). We used Eq. 7a to calculate the M$⁻¹ for 1869-2000 period and Eq. 7b for the 1790-1869 period.

\[
M_s^{-1}_t = \frac{M_i}{G_t} \text{ for } 1869 < t < 2000 \quad (7a)
\]

Where \(M_i\) is total annual solar emergy use in year \(t\); \(G_t\) is gross domestic product for \(t\).

\[
M_s^{-1}_t = 10^{(-0.0180t+48)} \text{ for } 1790 < t < 1868 \quad (7b)
\]

Eq. 7b is based on a least squares fit \((r^2=0.96)\) of the log transformed data series from the 1869-2000 period.

The solar emergy of net imports (\(M_i\)) was determined from Eq. 7c.

\[
M_i = M_s^{-1}_t \cdot N_{it} \quad (7c)
\]

Where \(N_{it}\) is annual net imports in dollars for year \(t\).

**Transformities for Technological Innovations**

The solar transformities of satellites, telephones, radios, televisions, and mail were defined as the total solar emergy required to create and improve the technology ($M_{total}$ in Figure 2) divided by the total power consumed by the total number of devices in operation. The critical variables for estimating $M_{total}$ were $t_c$ and $R_t$, which are given in Table 2. The power consumption used for each device is also given in Table 2. Obviously, there have been energy efficiency improvements in the power consumption of each communication technology during their lifetimes. We used the highest power efficiency for each device, which likely causes the ST to be overestimated in a technology’s early history (i.e., the denominator is less). Better estimates of device power consumption could improve the analysis in the future. Time series data on the number of devices in use came from the U.S. Census Bureau (1972, 1993, 2002) and Carter (1997). Although the U.S. Postal Service was created when the country began, we began our estimate of the solar transformity of mail in 1880. Since mail as a communication technology was created long ago, we did not attempt to include its creation emergy; we only included the Postal Service revenue to estimate its improvement emergy.

**RESULTS AND DISCUSSION**

**History of National Solar Emergy Use**

Total solar emergy use in the U.S. is shown in Figure 3a. Several changes in emergy use are remarkable. First, Thomas Jefferson’s purchase of the Louisiana Territory from Napoleon in 1803 corresponded to an increase of 36% in solar emergy availability to America (Table 3). A series of land acquisitions in the late 1840’s (Texas, Oregon and the Mexican Cession) was of greater emergy value (67% of annual use). The greatest period of decline in annual emergy use, on a percentage basis, was the 1930’s “Great Depression” (Figure 3a) with annual decline of 5.8%. The 1960’s, lead by war-time spending on the Vietnam War, was the period of greatest absolute increase in solar emergy use, with an average increase in the rate of growth of 14.7 E22 sej (3.4% per annum). Emergy use in the 1970’s was turbulent with large intra-decadal swings and little change from beginning to end. Since 1982, emergy use increased steadily with the exceptional years of 1990-91 when values decreased, but at a slower rate than the 1960’s.

Figure 3b and 3c break out the major components of total solar emergy use in the U.S. for the 1790-2000 period. Figure 3b shows the main renewable emergy inputs, while Figure 3c includes the most important non-renewable inputs. Precipitation has always been the largest renewable source of

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**Table 2.** Critical variables for estimating $M_{total}$ in Figure 2 and device power consumption.

<table>
<thead>
<tr>
<th>Technology</th>
<th>$t_c$</th>
<th>Device Power</th>
<th>$R_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td>1965</td>
<td>5.6 W per kg of payload</td>
<td>100% of U.S. GDP</td>
</tr>
<tr>
<td>Telephony</td>
<td>1870</td>
<td>1.0 W per set</td>
<td>Telephony sector estimated as 2.41% of GDP, which was the average share for period 1980-2000.</td>
</tr>
<tr>
<td>Radio</td>
<td>1922</td>
<td>10 W per set</td>
<td>Consumer spending for radio estimated as 0.02% of U.S. GDP, which was average rate from 1995-2000.</td>
</tr>
<tr>
<td>Television</td>
<td>1946</td>
<td>150 W per set</td>
<td>Consumer spending for TV estimated as 0.5% of U.S. GDP, which was average rate from 1995-2000.</td>
</tr>
<tr>
<td>Mail</td>
<td>n.a.</td>
<td>103 kJ per piece</td>
<td>U.S. Post Office revenue</td>
</tr>
</tbody>
</table>
Chapter 18. Historical Solar Emergy Use...

Figure 3. Historical solar emergy use in the U.S. (1790-2000), total (a), renewable (b), non-renewable (c).
energy to the U.S., while wood consumption and soil erosion were historically the next most important renewables (Figure 3b). In the last half of the 20th Century, decreased farmland area reduced soil consumption, while consumption of forest products increased so that it contributed 5.7% of total solar emergy use in 2000. Soil use, at 2-3% of total national emergy use in 2000, was equivalent to hydroelectricity consumption.

Non-renewable emergy use was dominated early in the country’s history by coal. Total non-fuel mineral use was the second largest contributor up until the 1920’s when it was overtaken by petroleum (Figure 3c). Coal use was replaced by petroleum use as the #1 non-renewable emergy input in 1949. Nine years later in 1958, natural gas use replaced coal use as the #2 non-renewable input. The emergy of petroleum use was first greater than precipitation in 1948. In 2000, petroleum made up 40% of the non-renewable emergy input and 31% of total emergy use. Nuclear power electricity has increased dramatically in the past 35 years to where it provided over 5% of total emergy consumption in 2000. Global trade has always been an important part of the U.S. economy dating back to colonial times. The importation of goods, excluding fuels and minerals, at 4% of total emergy use in 2000, has become a substantial component of U.S. emergy consumption (Figure 3c). The solar emergy of non-fuel minerals peaked, as a percentage of total solar emergy in the 1940-50 period at about 12%, but continue to provide 8% of total emergy consumption.

In the U.S., cumulative total solar emergy use grew continuously from 1790 to 2000 (Figure 4). The continuously increasing, rather smooth, cumulative emergy use curve highlights the fact that the U.S. has never stagnated in its emergy use for any appreciable length of time. Noteworthy is the cumulative value in 2000 (505 E24 sej), which is equivalent to 53 years of the Earth’s annual endowment of input solar emergy (9.44 E24 sej y⁻¹). In this sense the U.S. has consumed 53 total earth-years of solar emergy in 210 years, although it only occupies about 5% of the Earth’s surface.

The pattern of change in the U.S. emergy use to gross domestic product (emergy-to-$) was calculated for the period 1869-2000. For the prior period (1790-1869), the emergy-to-$ ratio was estimated from the regression equation developed from the 1869-2000 data. The log transformed emergy-to-$ ratio decreased linearly with time (Figure 5). For the 131 year period from 1869 to 2000, the emergy-to-$ ratio showed a remarkable decrease of slightly more than two orders of magnitude. In 1869, it was 150 E12 sej/$ but by 2000 it was only 0.78 E12 sej/$. In 1790, each U.S. dollar was backed by 6,030 E12 sej, nearly 8,000 times its 2000 value.

The long-term, regularly decreasing emergy-to-$ ratio indicates that the circulation of money in the economy, as measured by gross domestic product, increased at a faster rate than emergy use. At
Chapter 18. Historical Solar Emergy Use...

By the end of the Korean War, from 1952 to 1971, the rate of change in emergy-to-$ was a consistent 0.25 E12 sej S^{-1} y^{-1}$ (Figure 5), which is slower than the high inflation period of the 1970’s when the rate of decrease was 0.33 sej S^{-1} y^{-1}, but faster than during the 1990’s when the decrease was only 0.04 sej S^{-1} y^{-1}.

The percent of the U.S. solar emergy derived from renewable supplies (% renewable) declined slowly from 1790 to 1875, dived rapidly between 1875 and 1905, and continued a regressive drop until the year 2000 at which time its value was 9.9% (Figure 6). The drop was heavily influenced by the emergence of fossil fuel use. The mean annual Environmental Loading Ratio (ELR) of the U.S., a measure of economic intensity relative to environmental capacity, steadily increased from 0.10 in 1790 to 9.7 in 2000 (Figure 7). In general, the ELR tracked total solar emergy use (Figure 3a).

![Figure 5. Measured and simulated solar emergy per U.S. dollar (1790-2000).](image)

![Figure 6. Historical percentage of total solar emergy use in U.S. derived from renewable sources (1790-2000).](image)
Per capita solar emergy use is a measure of living standard. Nations with a high per capita solar emergy generally have a populous that is wealthy, educated and healthy. On an annual basis, per capita emergy use in the U.S. started at a phenomenal 90,000 E12 sej in 1790, but declined steadily until 1890 when it began to fluctuate about a mean (Figure 8). For the next 70 years, until 1960, the per capita emergy use ranged between 16,900 and 24,600 E12 sej with an average of 22,100 E12 sej. The minimum occurred early in the “Great Depression” in 1932. In the most recent period (1970-2000), the average rose to 27,800 E12 sej with a maximum of 29,800 E12 sej in 1978. Most recently (2000) it stood at 28,200 E12 sej.

Figure 7. Historical Environmental Loading Ratio (non-renewable to renewable solar emergy use) of U.S. (1790-2000).

Figure 8. Per capita solar emergy on an annual basis (annual solar emergy per person) and historic accumulation basis (cumulative solar emergy use per person).
Chapter 18. Historical Solar Emergy Use...

While an annually based per capita index may capture total resource use and indicate well-being, a new per capita emergy index is proposed that uses the cumulative solar emergy used since the country began. We call this the per capita cumulative consumption of solar emergy (CCSE). We believe the CCSE may more fully capture the importance of the pathway to affluence. In the U.S., the CCSE increased rapidly during the first 40 years from 90,000 E12 sej to 1,480,000 E12 sej in 1827 (Figure 8). After a 70-year period of decline (1827-1897) the CCSE increased steadily with only one period of stagnation (1946-1964). In the year 2000, the CCSE stood at 1,800,000 E12 sej.

People living today must attribute a large proportion of their knowledge, wealth and affluence to the work of their forbearers. The CCSE would be particularly useful for comparing the affluence of different countries or cultures throughout history. For example, some European and Asian countries with much longer histories than the U.S., may have accumulated more historic emergy, but currently use less on annual basis, which supports their ability to wield influence globally. Britain, for example, through its colonization and control of a vast amount of the world over the past centuries, presumably accumulated a large amount of solar emergy. Emergy used in the past is stored in institutions of learning and government, which is then used to control energies in today’s society. Historic emergy accumulation is a means of measuring information storage as a capital stock. One could take the emergy accumulation in the U.S. as an investment in democracy with emergy showing its value.

A fair and important question is, how is the historically used solar emergy stored? Is it in written manuscripts, periodicals and books? Is it stored in the customs and mentality of the people? In technologies? We believe it is ultimately stored in many information processing and storage devices and the high transformity mental capacities of humans. As long as there is a temporal continuum that connects historic events to people of the current age, then most, if not all of the historically used solar emergy should accumulate. There is a question concerning the lag period with which historic emergy use is added to current emergy use. Does emergy used in 1980 accumulate instantly in 1981? Say a scientist publishes a paper in 1980 that possesses a large amount of historic solar emergy because it drew heavily upon scientific knowledge produced within the last 50 years. The paper is read infrequently for the first 10 years after publication, but suddenly finds large readership in 1990. In the time interval between 1980 and 1990, the emergy stored with the content of the paper is not contributing to knowledge production, so it should not be added to energy accumulated. However, after 1990 it is contributing significantly to scientific progress, which indicates that its emergy should be added to accumulated emergy. The question in dynamic emergy accounting is to determine the length of the lag period, if it exists at all.

**Solar Transformity of Communication Technologies**

The development and proliferation of technologies in the U.S. and the world during the past two centuries is unprecedented in human history (Figure 9). The U.S. instituted a Patent Office shortly after forming its constitutional government in the late 1700’s. In the first year there were 3 patents issued; 210 years later there were a record 158,014 issued in single year. Figure 9 shows that patent growth has accelerated, especially in the late 1990’s, presumably fueled by the inter-networking of computers known as the World Wide Web. The typical household has five to six radios and nearly two TV’s. The rate of increase in total payload launches for the U.S. satellite industry increased continuously from 1965 to 2000. Presently, the U.S. has about 1,200 working geostationary communication satellites in orbit (Figure 9).

Figure 10 shows that the solar transformity of all five communication technologies decreased since their commercial introduction. The solar transformity of geostationary communication satellites decreased rapidly from 4,700 E12 sej/J in 1965 to 4.8 E12 sej/J in 2000. The solar transformity of telephone communication dropped slightly more than two orders of magnitude during its first thirty years, from 1,410 E12 to 11.5 E12 sej/J, and dropped another 96% over the next 100 years. The solar transformity of television set output decreased rapidly from 58 E12 sej/J in its inaugural year (1946) to 12.6 E9 sej/J in 1955, and continued to decrease through year 2000 (0.72 E9 sej/J). The solar transformation of written communications and telegraphs decreased rapidly from 2700 sej/J in 1870 to 350 sej/J in 1900, and dropped another 99% over the next 100 years. The solar transformity of internet communications decreased rapidly from 4,700 E12 sej/J in 1965 to 4.8 E12 sej/J in 2000. The solar transformity of computer hardware decreased rapidly from 4,700 E12 sej/J in 1965 to 4.8 E12 sej/J in 2000. The solar transformity of computer software decreased rapidly from 4,700 E12 sej/J in 1965 to 4.8 E12 sej/J in 2000.
Chapter 18. Historical Solar Emergy Use...

Figure 9. Historical rate at which popular technologies accumulated in the U.S. from 1850 to 2000 (television sets, wire-based telephones, radio sets, cumulative patents issued since 1780, cumulative geostationary communication satellites launched successfully).

The transformity of radio output decreased by over two orders of magnitude during its first ten years of existence, but only dropped by only 9% during the most recent 10 year period (1990-2000) to a value $8.11 \times 10^9$ sej/J. The solar transformity of mail decreased from $15 \times 10^6$ sej/J in 1890 to $2.5 \times 10^6$ sej/J in 2000 (83%).

Odum (1988) proposed that the solar transformity measured the position an energy form occupied in the global hierarchy of energy transformation processes. Forms of energy small in quantity are often high in quality. Higher quality energy forms produce more effect on system performance per unit of their dissipation than lower quality forms. For the communication technologies evaluated here, satellites occupied the highest position in the energy hierarchy (i.e., highest solar transformity), while the other technologies were ordered as (high to low): telephony, radio, television and mail (Figure 10). Satellites are the most global of the communication devices evaluated, allowing information to be communicated between any two points on Earth with only millisecond delay. Mail, on the hand, is also used to communicate globally, but its transmission rate is several orders of magnitude slower (days rather than seconds). The rank order of the technologies fits our preconceived notions except for TV and radio. We would have expected TV to have a higher ST than radio mainly due to the apparent influence TV has had on American culture and the typical citizen’s daily intake of information via TV.

The most remarkable feature about the historical change of the technologies' transformities was their common regression toward lower levels (Figure 10). With the exception of mail, the technologies exhibited similar paths of rapid decrease early in their existence, followed by slower declines. Part of the reason for a decrease in ST was that the number of devices in use increased from the time the technology was introduced, which increased total power output making the denominator in the ST larger. The increase in units would also have allowed for 'economies-of-scale' to be achieved; lowered total resource consumption per unit operated. For example, the nation’s number of TV’s (and their total power consumption) grew faster than the television industry’s costs of creating and broadcasting TV programs. We assumed the highest efficiency for power consumption of each device, so there was no temporal change in this variable. The fact that each technology’s decline in ST approaches a minimum indicates that there are system limits to the amount of solar emergy required to
operate communication technologies. In other words, at the system scale of a nation, there appears to be a thermodynamic limit to how much solar emergy is required to transmit information.

Does modern information technology increase a nation’s solar empower without necessarily increasing its power consumption? In other words, do modern technologies increase the ratio of empower to power? This is analogous, although not equivalent, to a type of system efficiency, i.e., getting more for less. This is difficult to answer for the U.S. because total power has not leveled; it continued to increase to the year 2000. The question concerns two hypotheses about the temporal behavior of a nation’s power spectrum (Figure 11). In the first case, a change from the original

![Figure 10](image1.png)

**Figure 10.** Time series of the solar transformity of communication satellites, telephony, radio, television, and mail.

![Figure 11](image2.png)

**Figure 11.** Two hypotheses about the temporal dynamics of power spectra as system empower increases.
spectrum to a new spectrum occurs as a complete ‘shift’ with the slope remaining the same. In the second case, the new spectrum is generated by a ‘rotation’ about the y-intercept. In each case power and empower increase, but the ratio of empower to power increases more under rotation. In rotation, use of high transformity energies (e.g., information) increases tremendously, whereas use of low transformity energies (e.g., soil and fuels) increases only slightly. In a shifted spectrum, high and low transformity energies increase in similar proportions. The implications of which hypothesis is correct provide clues as to whether technological progress can continue in an energy limited world. In an Odumesque “prosperous way down” view, the more important question may be, “how does the power spectrum change when resource availability and use is shrinking?” Theoretically the higher transformity units have longer turnover times than lower transformity ones, which would cause the power spectrum to exhibit wave properties as a system develops. The wave starts on the left of the spectrum with relatively high use of low transformity energies (e.g., water), propagates to the right through mid-level transformities (e.g., fuels) to high transformity energies (e.g., information), and remains on the right side while the left shrinks. This fits with Odum’s (1988, 1996) idea that shared information has a longer turnover time. Memories remain long after the creating event has disappeared. The question for humanity is: “Are we creating the most memorable parts of the system?”

REFERENCES


